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(Eds.)

# Advances in Production Management Systems

## Production Management for the Factory of the Future

IFIP WG 5.7 International Conference, APMS 2019
Austin, TX, USA, September 1–5, 2019
Proceedings, Part I

1 Part I

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# Preface

The revolution in the information and communication technology (ICT) is rapidly transforming our world. The manufacturing industry is not an exception and it has already gone through profound changes due to the technological advancements in information technology. The digitization of production systems has been the most influential trend in the manufacturing industry over the past few years. The concept of Cyber-physical Production System (CPPS) is now being increasingly adopted in various sectors of the manufacturing industry to promote further intelligence, connectivity, and responsiveness throughout in the product value chain. There are several enablers of the vision of digitized, cyber-enabled, sustainable, and smart production system, including big data analytics, artificial intelligence, virtual and augmented reality, digital twin, and Human-Machine Interaction (HMI). These are the key components of the fourth industrial revolution and the main research thrusts in smart manufacturing and Industry 4.0 research community. The core challenge is how to improve the effectives and efficiency of production systems and, at the same time, enhance their sustainability and intelligence. Also, redefining the role of human in the new generation of automated production systems is a major challenge faced by researchers and practitioners.

APMS 2019 in Austin, Texas brought together leading international experts from academia, industry, and government in the area of production systems to discuss globally pressing issues in smart manufacturing, operations management, supply chain management, and Industry 4.0. A large international panel of experts reviewed all the papers and selected the best ones to be included in these conference proceedings. The topics of interest in APMS 2019 included Smart Supply Networks, Knowledge-Based Product Development, Smart Factory and IIOT Data-Driven Production Management, Lean Production, and Sustainable Production Management.

The proceedings are organized in two parts:

- Production Management for the Factory of the Future (Volume 1)
- Towards Smart Production Management Systems (Volume 2)

The conference was supported by the International Federation of Information Processing (IFIP) and was organized by the IFIP Working Group 5.7 on Advances in Production Management Systems and Texas State University. We would like to thank all contributors for their high-quality work and for their willingness to share their innovative ideas and findings. We are also indebted to the members of the IFIP Working Group 5.7, the Program Committee members, and the Scientific Committee members for their support in the review of the papers. Finally, we appreciate the

generous support from our sponsors, namely, Texas State University - College of Science and Engineering, the University of Texas at Dallas - Naveen Jindal School of Management, AlphaNodus, and PennState Service Enterprise Engineering.

September 2019

Farhad Ameri
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# Total Quality Management and Quality Circles in the Digital Lean Manufacturing World

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**Abstract.** In this paper, the authors present practical insights in order to propose a Quality Management Framework for Digital Lean Manufacturing. The rationale behind this proposed framework is that the individual ISO 9000:2015 Quality Management pillars are rather different when it comes to their objectives and their tasks at hand when using Human capabilities and/or Digital technologies capabilities in a strategic way for (i) Quality Planning, (ii) Quality Control, (iii) Quality Assurance, and (iv) Quality Improvement in the context of the emerging paradigm of Digital Lean Manufacturing Systems.

**Keywords:** Digital manufacturing · Smart manufacturing · Lean Manufacturing · Digital Lean Manufacturing · Digital lean enterprise · Cyber-Physical Production Systems · Industry 4.0 · Quality Control Circles · Total Quality Management

## 1 Introduction

Today's manufacturing enterprises have to operate and thrive in highly competitive global environments where the highest quality, lowest cost, and shortest lead-time determine manufacturing competitiveness [1]. In this context, emerging paradigms such as *Digital Lean Manufacturing (DLM)* [2] offer an increase in the productivity and efficiency of manufacturing processes. In particular, DLM leverages the potential of *cyber-physical quality management systems* (i.e. tools, techniques, and practices) by increasing the stability and performance of such processes towards (near-)zero defect manufacturing [3].

According to Romero et al. [2], *Digital Lean Manufacturing (DLM)* "builds on new data acquisition, data integration, data processing and data visualization capabilities [4] to create different descriptive, predictive and prescriptive analytics applications [5] to


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detect, fix, predict and prevent unstable process parameters and/or avoid quality issues inside defined tolerance ranges that may lead to any type of waste within the cyber- and physical- worlds". Such capabilities contribute to support important *feedback loops* for quality improvement and the *digitalization* of quality management.

In this paper, we propose a *Quality Management Framework for Digital Lean Manufacturing* based on the four ISO 9000:2015 pillars [6] of Quality Management: (i) Quality Planning, (ii) Quality Control, (iii) Quality Assurance, and (iv) Quality Improvement (see Fig. 1). Critical to this is the *Lean principle* of '*respect for people*', which recognizes the unique contribution of human creativity, ingenuity and innovation (represented by the work of *Quality Managers* and their *Quality Circles*) to quality planning, quality control, and quality assurance tasks, and in particular to quality improvement duties, given the onset of *digital technologies* in combination with the new practices of quality management.

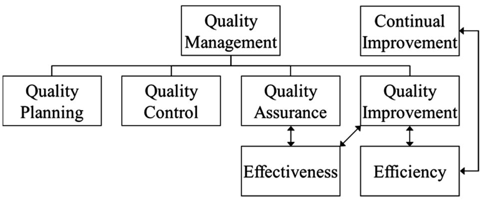


**Fig. 1.** A quality management framework by ISO 9000:2015 [6]

The literature often argues that *Quality Management (QM)* practices in general, and the role of the *Quality Manager* in particular, will be substantially disrupted by the Fourth Industrial Revolution (a.k.a. The Industry 4.0 paradigm). Similar to the First Industrial Revolution, skilled craftsman or in the current case Six Sigma (6σ) Black Belts will be substituted by 'technology' that can be operated by cheaper, less-skilled labour. In contrast, in this research, we seek to explore the still highly relevant roles of the *Quality Manager,* and his/her *Quality Circles,* in the QM practices of the future. In doing so, we distinguish between the four individual QM pillars of the ISO 9000:2015 framework [6] in order to discuss and propose how a sensible, balanced, and value-adding *Quality Management Framework* could look like in an emerging "Digital Lean Manufacturing World".

## 2 Towards a Quality Management Framework for DLM

*Total Quality Management (TQM)* can be defined as a method, a continual process or a practice of detecting, reducing and eliminating errors in manufacturing processes in order to enhance their quality and productivity [7–9]. This can be done by streamlining workers' competencies through education and training programmes, statistical process controls, suppliers' controls and quality engineering controls (such as parameters and tolerances), so as to reduce manufacturing costs, and therefore waste, and increase customer satisfaction through continuous improvement [7–9]. Furthermore, *Quality*

*Control Circles (QCC),* or simply *Quality Circles,* are small groups of workers that voluntarily and periodically meet to discuss production, quality, and related problems with the aim of collaboratively (cf. *Nemawashi*[1]) establishing productivity and quality goals and specifications as well as proposing improvements and corrective actions for those causes and issues constraining their achievement and compliance [10–12].

From a DLM perspective, TQM and QCC have evolved over the decades. In the following *QM continuum,* this progress is loosely clustered building on the defining characteristics of the four Industrial Revolutions:

- *QM 1.0 practices* – based on human supervision of manufacturing processes and random physical inspection of products; and shop-floor meetings between workers for collaborative problem-solving.
- *QM 2.0 practices* – based on Statistical Process Control (SPC) [13] tools and techniques, using 'sampling-based measurements', to monitor, control, and improve a manufacturing process by early detection of its deterioration in order to safeguard product quality; and still face-to-face shop-floor meetings, with some 'phone-call' communications, between workers for collaborative problem-solving.
- *QM 3.0 practices* – based on Six Sigma (6$\sigma$) [14] statistical techniques and tools to identify and eliminate fluctuations in a manufacturing process in order to guarantee a uniform quality output; and first possibilities of virtual meetings between on-site and remote workers for collaborative problem-solving.
- *QM 4.0 practices* – based on (Big) Data Analytics and Machine Learning (ML) methods [15] capable of offering early alarms and fault diagnosis of problematic (manufacturing) processes, and therefore products, as well as optimisation parameters for optimized process settings. Moreover, advanced virtual meetings can now allow a true 'digital presence' of remote workers thanks to new interactive technologies such as mixed reality and haptics [16] for 'see-what-I-see', 'hear-what-I-hear' and even 'feel-what-I-feel' real-time collaborative problem-solving between remote and on-site workers.

In the context of *QM 4.0 practices,* Romero et al. [2] have defined *Digital Quality Management (DQM)* as "the semi-automated or automated digital governance of cyber-physical production assets like smart products, smart operators and smart machines, aimed at offering real-time tracking and reporting of such intelligent assets performance towards compliance with predefined quality standards and proactively alerting in case of potential deviations from them to prevent quality problems (viz. defects) before they materialize". A similar concept to DQM is *Virtual Quality Management (VQM)* [17, 18], which in addition to production assets information, also considers environmental factors that can have a potential influence on manufacturing processes and on their quality outputs. It uses modelling and simulation techniques in order to try, test and optimize virtual process chains prior to setting-up the real manufacturing processes in the factory [18]. Hence, emerging *Digital Lean Cyber-Physical Production Systems*

[1] In the Lean Manufacturing jargon, is the process of bringing problems and potential solutions to all those affected to gather their ideas and get agreement on a solution.

*(CPPSs)* [2, 19], characterized by their real-time feedback loops, offer a huge potential for DLM and VQM implementations.

The following sub-sections (see Sects 2.1 to 2.4) describe an enhanced QM framework with *Lean principles* and *Digital technologies* (e.g. Industrial Internet of Things (IIoT), (Big) Data Analytics, Cyber-Physical Systems (CPSs), Machine Learning (ML), Edge Computing) in order to introduce a *Quality Management Framework for DLM.*

The rationale behind this proposed framework is that the individual QM pillars are rather different when it comes to their objectives and their tasks at hand when using *Human capabilities* and/or *Digital technologies capabilities* in a strategic way.

### 2.1 Quality Planning for Digital Lean Manufacturing

Based on ISO 9000:2015 [6], the first pillar of QM is 'Quality Planning'. This activity is focused on "setting quality objectives and specifying necessary operational processes and resources to fulfil these quality objectives". It requires the agreement of relevant stakeholders, including internal and external customers, to ensure that their expectations for quality requirements and legal compliance are correctly identified. In this context, even though *digital technologies* (e.g. advanced modelling, simulation, and (big) data analytics tools [20]) have made a lot of progress as 'supporting tools' for quality planning, *Quality Managers,* and their *Quality Circles,* still play an important role. This vital role includes but is not limited to, their human touch (i.e. sensitivity) when it comes to identifying and understanding customer requirements (i.e. the Voice of the Customer [21]), setting quality criteria, and defining quality standards. Since expressed quality specifications will never cover exactly all the quality aspects expected by the end-user as highlighted by [22], there is a distinction between 'relevant quality', also known as *service quality,* covered by crucial *technical quality specifications,* and 'cosmetic quality', synonym of *specified quality,* covered by crucial *customer quality specifications.* Moreover, if we use only technology for quality planning, we will limit our human capabilities to conduct this important QM activity manually, and we will not be able to properly teach the workers about quality.

### 2.2 Quality Control for Digital Lean Manufacturing

ISO 9000:2015's [6] second pillar of QM is 'Quality Control'. This activity is focused on "fulfilling quality requirements". It is responsible for determining whether quality acceptance criteria have, or have not, been met according to quality specifications, using different inspection and testing techniques. *Quality Control Systems* benefit from new, and improved *digital technologies,* such as (big) data-driven industrial process monitoring, fault-detection and diagnosis technologies [23, 24], machine (computer) vision inspection systems [25], and edge computing processes [26]. Supervised, semi-supervised and un-supervised machine learning algorithms [27] are capable to identify quality deviations early in the process, potentially enabling rework of problematic parts and thus reducing scrap (waste). While this reduces the direct involvement of (human) *Quality Experts,* such as replacing human operated visual inspection stations, there are other areas that emerge that may need to be staffed with the humans' unique skills. For example, insightful management of ‘data quality’ is still an issue that causes problems with automated, (big) data-driven industrial process monitoring, fault-detection and diagnosis systems [23], and *Quality Managers,* and their *Quality Circles* are key for addressing these data quality challenges today.

### 2.3 Quality Assurance for Digital Lean Manufacturing

ISO 9000:2015’s [6] third pillar of QM is ‘Quality assurance’. This activity is focused on “providing confidence that quality requirements will be fulfilled according to planned activities and results”. It validates the consistent use of quality control procedures and standards and ensures that human and artificial quality control systems have the correct capabilities to fulfil their responsibilities. *Quality Assurance* builds on the insights from the collected information and data of production operations. Here a combined approach between qualified *Quality Managers* and (big) data analytics are often the method of choice when it comes to dealing with the production complexity. (Big) data-driven approaches provide the input, within a variety of degrees, yet the *Quality Managers* are the ones putting the data into context and interpreting it, and drawing the conclusions that lead to quality improvement actions. Thus, at all times, the *Quality Experts* need to have a solid understanding of what the data means (i.e. interpreting correctly the data to infer the right information from it in order to properly answer questions and/or take actions), and of what the (big) data-driven systems actually do and how their results are developed (i.e. explain the functioning of the data analytical models). *Black-box systems* are powerful, yet problematic in a “Digital Lean Manufacturing Systems Environment” where workers are supposed to constantly pursue continuous learning and product-processes quality improvement(s). Therefore, employees commitment to continuous learning will remain a critical factor for ensuring quality. This is because the workers will continue to control operations or rather take the decisions on quality. Consequently, *Quality Circles* are key to deal with (production) uncertainty and to create a sustainable quality assurance strategy, since manufacturing enterprises cannot only rely on non-explainable ‘artificial intelligence(s)’ [see 28] and/or external experts when it comes to the know-how to perfect (i.e. to make *lean* and *digitalize*) their manufacturing processes for operational excellence and high-quality standards. *Quality Managers,* and their *Quality Circles,* should always be part of the journey of perfecting any manual or semi-automated process before it becomes to be fully automated in order to avoid the “black-box problem”, since anyone could buy quality control and quality assurance systems, but the knowledge of how to use them strategically and effectively must be acquired and developed by the employees.

### 2.4 Quality Improvement for Digital Lean Manufacturing

ISO 9000:2015’s [6] fourth pillar of QM is ‘Quality Improvement’. This activity is focused on “increasing (recurrently) the ability to fulfil quality requirements as they evolve”. It drives the quality continual improvement by using the information provided by the quality assurance and the quality control activities to improve effectiveness and efficiency. Moreover, Quality Improvement can be generally divided into two types: (i) incremental quality improvements (cf. Kaizen) – driven by (real-time) optimization techniques of processes [29], and supported by humans, and (ii) breakthrough quality improvements (cf. Kaikaku) – driven by human creativity, ingenuity and innovation, and supported by digital technologies. In this context, even though 'technology' has gone far with advanced modelling, simulation, and optimization techniques as well as with Machine Learning (ML) algorithms, machines may learn something that the ML algorithms' developers did not initially program or set, consequently, machine-learned results should be validated by humans, even if unexpected. Therefore, it is important to not underrate the humans' creativity and ingenuity. Moreover, without these human capabilities, a 'smart factory' may remain stuck at the same stage of development as the optimization techniques reach their limits and improvements become marginal. Therefore, *Quality Managers* and their *Quality Circles* are key for true continuous quality improvements and for the development of quality competitive advantages. Hence, we need to continue investing in and empowering our employees, our *Quality Experts* and their ideas and skills, even when digital technologies seem to be very progressive.

## 3 Discussion and Reflections

The aim of this paper is to explore the still highly relevant roles of the *Quality Manager,* and his/her *Quality Circles,* in the QM practices of the future, framed in light of the four individual QM pillars of the ISO 9000:2015 framework [6]. We discuss and propose how a sensible, balanced, and value-adding *Quality Management Framework* could look like in an emerging "Digital Lean Manufacturing World" [2]. In general, although the pillars of Quality Control and Quality Assurance indeed have the potential to become highly automated in light of (smart) digital technologies [30, 31], Quality Planning and Quality Improvement pillars may potentially require more human creativity, ingenuity and innovation than ever before, combining traditional skills of continuous improvement and QM techniques with the (new) smart capabilities presented by *digital technologies.*

Figure 2 represents our proposed *Quality Management Framework for DLM,* built on the four pillars of QM [6], where we highlight the *Human (H)* or *Automation (A)* heavy nature of the pillars in the QM practices of the future, given the onset of (smart) digital technologies and the Industry 4.0 paradigm.

Quality Planning – is expected to have a continued reliance upon human creativity, ingenuity and innovation regardless of the degree of (smart) digital technologies used. Quality planning is a customer-sensitive task, and even though humans may be able to benefit from greater use of advanced modelling, simulation, and (big) data analytics tools, the quality planning task will remain human-intensive in future QM practices. On the other hand, Quality Control – will almost certainly become automation-heavy. The onset of (smart) digital technologies for process monitoring, process control, fault-detection and fault-diagnosis in addition to low-cost visual inspection systems provide manufacturers with incentives to automate quality control tasks. This also stands true for Quality Assurance tasks – drawing on the same technologies as quality control. However, quality assurance will continue to draw on the creativity and ingenuity of the human, where *Quality Managers,* and their *Quality Circles,* define and execute

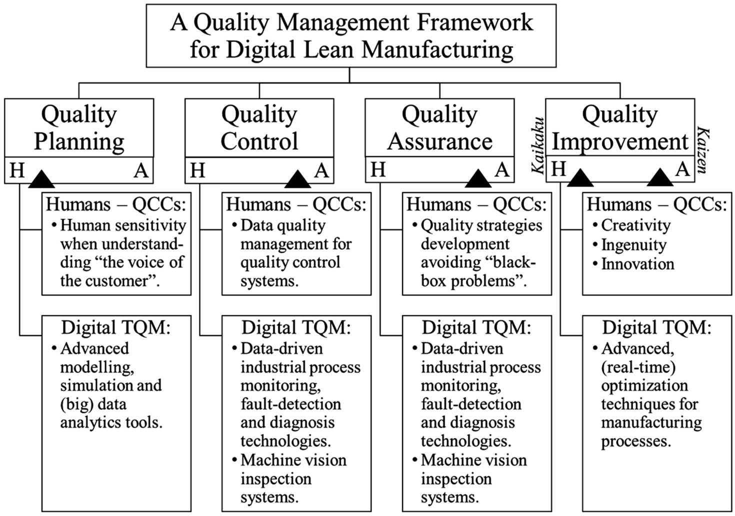


**Fig. 2.** Towards a quality management framework for digital lean manufacturing

strategies for effective quality assurance. Finally, the role of the *Quality Manager,* and his/her *Quality Circles,* is set to become even more essential in Quality Improvement – given the current shift towards the Industry 4.0 paradigm, where time saved by automating the quality control and quality assurance tasks can be much better spent on quality improvement, enabling manufacturing enterprises to successfully operate and thrive in highly competitive environments where the highest quality, lowest cost, and shortest lead-time determine an organisation's ultimate manufacturing competitiveness. In Quality Improvement, small, continuous process improvements can be automated to a higher degree through smart process optimization technology. However, larger improvement possibilities, radical innovations, will be realized to a greater extent through harnessing human creativity, ingenuity and innovation applied to problem-solving in DLM environments.

## 4 Conclusions

Industry 4.0 presents manufacturing enterprises with a plethora of new technologies [31] that promise greater competitiveness through higher quality, lower cost, and shorter lead-times. However, following the true spirit of *Lean Manufacturing,* firms should not neglect the power of the *'respect-for-people' principle,* even though the promise of automation is extremely attractive.

In this paper, we highlight several avenues in which the QM practices of the future can benefit from new (smart) digital technologies when combined with greater levels of human creativity, ingenuity and innovation – utilizing their unique capability for collaborative problem-solving. At this stage, the analysis relied mainly on insights from literature as well as from scholarly and industry experts and is more explorative and theoretical in nature. This limitation should be addressed through rigorous empirically grounded work, assessing the elements of this *QM Framework for DLM* based on data collected from QM departments of various industries.

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# Practical Boundary Case Approach for Kanban Calculation on the Shop Floor Subject to Variation

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**Abstract.** Determining the number of kanban in a pull production is essential for a good system performance. While this is simple in a static case, it becomes much more challenging if the system is subject to variations, as all practical systems are. The paper presents a novel boundary case approach to determining the number of kanban subject to a desired delivery performance. The approach is compared with the well-known Toyota formula. An extensive simulation-based approach verification for different coefficients of variations for the replenishment time and the customer takt was used to verify this boundary case approach also in comparison with the Toyota formula. The presented approach handles variation much better and determines a much more suitable number of kanban. This approach can also be adapted to practical everyday use in industry with little additional effort and with only a limited understanding of the underlying randomness of the key variables.

**Keywords:** Kanban formula · Pull production · Random variation · Replenishment time · Lean manufacturing

## 1 Introduction

Lean production is one of the best approaches for promoting business excellence through continuous improvement [1]. One of the key concepts is pull production. The idea of pull production is based on limiting the maximum number of products or jobs processed in the system at the same time. The most common approach to implement pull production is through kanban, especially for high-volume low-mix products. In setting up a kanban system, the number of kanban cards has to be determined. There exist a variety of different kanban formulas. All of them are based on the relation between the replenishment time and the customer takt as shown in (1), where RT is the replenishment time, TT is the customer takt, NPK are the number of parts per kanban, and K is the number of kanban.


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$$K = RoundUp\left[\frac{RT}{TT \cdot NPK}\right] \quad (1)$$

As we will see below, this equation works well for a static system, but presents a challenge for dynamic systems that include random variations. Unfortunately, all real-world systems are dynamic, and these random variations cannot be ignored. This paper will look at the relation between replenishment time, customer takt, and the number of kanban using both theoretical and experimental approaches.

## 2 Theoretical Approach

### 2.1 Static Situation

In the first part we assume a static situation with no random fluctuations. This of course is a widely optimistic and unrealistic assumption for practical use. However, it is useful to understand the theoretical foundations. A key variable here is the customer takt. It represents the average demand of the customer during a time period. To calculate it, you divide the available working time by the customer demand during that time, as shown in Eq. (2) [2], where TT is the customer takt, AT is the available work time, and CD is the customer demand during that time:

$$\mathrm{TT} = \frac{\mathrm{AT}}{\mathrm{CD}} \quad (2)$$

**Customer Takt Slower than or Equal to Replenishment Time**
If the customer takt is larger than the replenishment time, one Kanban card will suffice for production. If the customer wants a product, he receives the single piece in stock, and then we reproduce it to increase stock again to one piece. Hence, the behavior of the inventory over time may look like Fig. 1. As the RT is faster than the TT, the product is always completed before the customer requests the next one. This concurs with Eq. (1) above.

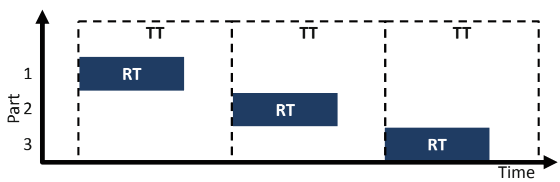


**Fig. 1.** Theoretical behavior if customer takt is slower than the replenishment time

**Customer Takt Faster than Replenishment Time**
If the customer takt is larger than the replenishment time, we would need multiple Kanban cards as calculated in Eq. (1). An example is shown in Fig. 2, where the

replenishment time is almost three times as long as the customer takt. Hence, we would need three kanban to have one part ready before the customer demands it.

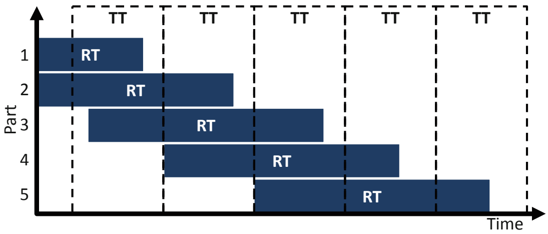


**Fig. 2.** Theoretical behavior if customer takt is faster than the replenishment time

## 2.2 Dynamic Situation

In reality both the replenishment time and the customer takt have random variations. The distribution of customer takts can often be approximated using exponential or log-normal distributions. For replenishment times we also often find log-normal distributions, Weibull, Gamma, or Pearson type 5 distributions. Overall, the Eq. (1) would now consist not of discrete numbers but random variables. Hence, Eq. (1) would change to Eq. (3).

$$K = \frac{RT}{TT \cdot NPK} \tag{3}$$

There are methods available to calculate the division of probability functions. The general ratio distribution is shown in Eq. (4), where $p_K(k)$ is the probability density function of the number of kanban needed [3].

$$p_K(k) = \int_0^{\infty} |TT| \, p_{RT,TT}(k \cdot tt, tt) dtt \tag{4}$$

However, this requires independence of the variables, which is not given in our case. The replenishment time depends on the customer takt, as more orders increase the replenishment time. Furthermore, the replenishment time also depends on itself, as, for example, a part with a long replenishment time is usually followed by another part with a long replenishment time. Finally, the option of buffering parts in a supermarket is not included in this simplified model. Hence, the theoretical approach has unrealistic assumptions and cannot be used. Therefore the problem in determining the number of kanbans is how to deal with these uncertainties.

## 3 Simulation Approach

We have also analyzed manufacturing systems using a simulation-based approach. In this simulation, a single process is controlled using a kanban system in order to supply parts to a customer. The customer demand is modeled using a lognormal distribution. The processing time is modeled using a Pearson Type V distribution. Due to the large number of possible variables, an exhaustive search is prohibitive. Nevertheless, we simulated a wide range of different systems, varying three primary variables:

- The relation of the customer takt to the process cycle time, which effectively changes the utilization of the process
- The standard deviation of the customer takt
- The standard deviation of the process cycle time.

Additionally, the number of kanban cards was varied exhaustively between 1 and 50, with additional simulations having up to 1000 kanban cards to also test for systems with extremely large number of kanban cards. Each simulation was repeated 30 times for statistical validity and to allow the calculation of confidence intervals. Two primary results were measured:

- Work in process inventory: how many parts were in the system
- Delivery performance: what percentage of the customer request were fulfilled immediately. Not immediately fulfilled request were fulfilled when the next part became available.

The full details of the simulation experiment can be found in [4]. Figure 3 shows the location of the kanban cards in the system for different number of kanban cards for both the customer takt and the cycle time having a coefficient of variation of 1, with a mean customer takt of 12 and a mean cycle time of 10. Showing all results from [4] would exceed the scope and space available within this paper.

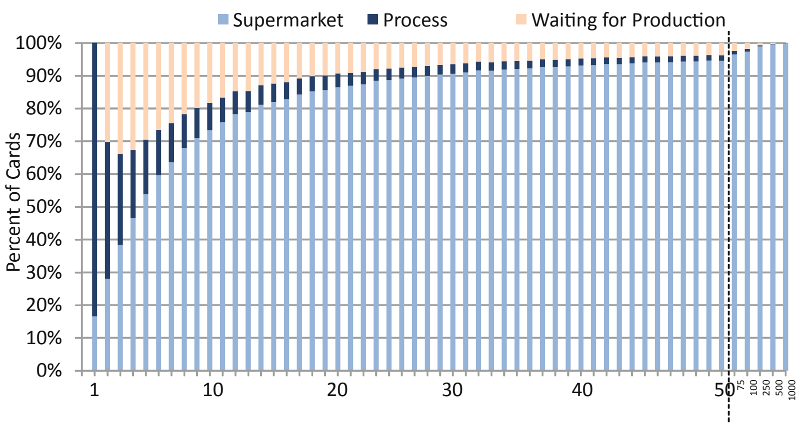


**Fig. 3.** Location of the kanban cards for a system with the customer takt and the cycle time having a coefficient of variation of 1, a mean customer takt of 12 and a mean cycle time of 10. The system was simulated for all kanbans up to 50, and then for selected kanbans up to 1000.

# 4 The Toyota Formula

The formula used by Toyota to calculate the number of kanban is called the Toyota Formula, and is widely used in literature, e.g. [5–7]. This approach calculates the number of kanban based on the average daily demand *DD*, the replenishment time (called lead time, but includes the times for collecting kanban), the container capacity (i.e., the number of parts per kanban *NPK*), and a safety factor α as shown in Eq. (5).

$$K = \frac{DD \cdot RT}{NPK} \cdot (1 + \alpha) \tag{5}$$

As the daily demand DD is merely the inverse of the customer takt TT, Eq. (5) translates into Eq. (3) with an additional safety margin. The safety factor α is to account for uncertainties, and is generally recommended to be no more than 10%. We verified this Toyota formula using the simulation and the resulting data from [4]. For full details on the simulation data please refer to [4]. The average for the simulated systems was a delivery performance of 71.3%, which is still far from acceptable for a functioning production system.

# 5 A Practical Boundary Case Kanban Approach

## 5.1 Description of the Boundary Case Kanban Approach

The boundary case approach for calculating the number of kanban is based on Eq. (1). However, instead of using the mean value for the replenishment time and the customer takt, we now use boundary cases. This is not the extreme case, as customer takts and process times are time-based and hence have boundaries of [0,∞], which would give us an infinite number of Kanban in the worst case. More practically, we will be using the values for selected percentiles of the distribution. For the replenishment time we want to cover all but the slowest replenishment times. Similar is true for the customer takt, but now we want to cover all but the fastest customer takt. The selected percentile depends on the desired reliability and delivery performance of the kanban system.

## 5.2 Simulation Verification of the Boundary Case Kanban Approach

Using the same simulation data as from the verification of the Toyota formula, we now verified the boundary case approach. We selected to verify this approach for 80% percentiles, 90% percentiles, and 95% percentiles on both all but the slowest replenishment time and all but the fastest customer takts. Tables 1, 2, and 3 show the resulting number of kanban for a coverage of 80%, 90%, and 95% respectively for the customer takt and the replenishment time for different coefficients of variation.

**Table 1.** Number of kanban for different coefficient of variations, covering 80% of the customer takt and replenishment time

| | | Customer Takt | | | | |
|---|---|---|---|---|---|---|
| | CV | 0% | 25% | 50% | 75% | 100% |
| Production Process | 0% | 1 | 2 | 3 | 7 | 14 |
| | 25% | 2 | 2 | 4 | 8 | 16 |
| | 50% | 3 | 4 | 6 | 11 | 20 |
| | 75% | 5 | 6 | 9 | 15 | 23 |
| | 100% | 6 | 8 | 13 | 19 | 31 |

**Table 2.** Number of kanban for different coefficient of variations, covering 90% of the customer takt and replenishment time

| | | Customer Takt | | | | |
|---|---|---|---|---|---|---|
| | CV | 0% | 25% | 50% | 75% | 100% |
| Production Process | 0% | 1 | 2 | 4 | 9 | 19 |
| | 25% | 2 | 3 | 6 | 11 | 23 |
| | 50% | 3 | 5 | 9 | 16 | 31 |
| | 75% | 5 | 8 | 12 | 23 | 38 |
| | 100% | 8 | 11 | 19 | 30 | 51 |

**Table 3.** Number of kanban for different coefficient of variations, covering 95% of the customer takt and replenishment time

| | | Customer Takt | | | | |
|---|---|---|---|---|---|---|
| | CV | 0% | 25% | 50% | 75% | 100% |
| Production Process | 0% | 1 | 2 | 5 | 12 | 26 |
| | 25% | 2 | 3 | 7 | 15 | 33 |
| | 50% | 4 | 6 | 11 | 22 | 44 |
| | 75% | 6 | 9 | 17 | 33 | 56 |
| | 100% | 9 | 14 | 25 | 43 | 78 |

The resulting delivery performance is shown in Tables 4, 5, and 6. Overall, the performance is much more satisfactory. If both the customer takt and the replenishment time is set to cover 80% of the slowest and fastest times respectively as shown in Table 4 the average delivery performance across all tested situations is 87,8%. Similarly, for a coverage of 90% as shown in Table 5, the average delivery performance is 93.3%. Finally, for a coverage of 95% as shown in Table 6, the average delivery performance is 95.4%.

**Table 4.** Delivery performance for different coefficient of variations using the boundary case approach covering 80% of the customer takt and replenishment time

| | | Customer Takt | | | | |
|---|---|---|---|---|---|---|
| | CV | 0% | 25% | 50% | 75% | 100% |
| Production Process | 0% | 100,0% | 96,9% | 82,4% | 89,4% | 92,9% |
| | 25% | 96,2% | 84,1% | 86,3% | 90,2% | 94,1% |
| | 50% | 82,2% | 85,8% | 86,1% | 90,2% | 95,3% |
| | 75% | 78,3% | 81,4% | 85,8% | 89,0% | 92,0% |
| | 100% | 71,6% | 80,0% | 85,2% | 87,9% | 92,4% |

**Table 5.** Delivery performance for different coefficient of variations using the boundary case approach covering 90% of the customer takt and replenishment time

| | | Customer Takt | | | | |
|---|---|---|---|---|---|---|
| | CV | 0% | 25% | 50% | 75% | 100% |
| Production Process | 0% | 100,0% | 96,9% | 92,2% | 93,7% | 96,9% |
| | 25% | 96,2% | 96,0% | 95,9% | 95,8% | 98,2% |
| | 50% | 82,2% | 91,2% | 95,4% | 96,8% | 99,1% |
| | 75% | 78,3% | 89,1% | 91,3% | 96,5% | 98,6% |
| | 100% | 78,2% | 87,0% | 93,1% | 95,4% | 97,6% |

**Table 6.** Delivery performance for different coefficient of variations using the boundary case approach covering 95% of the customer takt and replenishment time

| | | Customer Takt | | | | |
|---|---|---|---|---|---|---|
| | CV | 0% | 25% | 50% | 75% | 100% |
| Production Process | 0% | 100,0% | 96,9% | 96,2% | 97,9% | 99,0% |
| | 25% | 96,2% | 96,0% | 97,5% | 97,9% | 99,8% |
| | 50% | 90,2% | 94,4% | 97,4% | 98,9% | 99,8% |
| | 75% | 83,0% | 90,5% | 96,5% | 98,4% | 99,5% |
| | 100% | 80,5% | 87,2% | 96,6% | 95,9% | 98,4% |

Overall, the calculated number of kanban is much more suitable for the needs of the industry. Delivery performances of 87%, 93%, or 95% for the different percentile boundaries are much more acceptable than an average delivery performance of 71% using the Toyota formula. The level of coverage can also be influenced by the percentile of the boundary case. Covering 95% of the fastest and slowest cases for the replenishment time and customer takt respectively will give a higher number of kanban and hence an overall better delivery performance than a coverage of only 90%, which in turn will again be better than a coverage of 80%.

### 5.3 Practical Application of the Boundary Case Kanban Approach

The boundary case approach to determine the number of kanban works very well as verified using extensive simulation data. For a practical application, however, these 80%, 90%, or 95% percentiles are difficult to determine. While the mean customer takt or mean cycle time are usually well known on the shop floor, the shape of the distribution of this random variable is usually unknown. Hence, there is usually insufficient data to determine an 80%, 90%, or 95% percentile.

However, there is usually either historic data or – more commonly – personal experience of "bad days," where either the customer demand or the replenishment time was exceptionally difficult, meaning very fast or very slow respectively. Therefore, while sacrificing some accuracy, we propose for practical purposes to select the worst case that has to be covered either from data or from the experience of the personnel.

In personal experience, shop floor supervisors seek safety in numbers and may want to cover worse situations but change their opinion once they see the resulting number of kanban and hence potential inventory. Therefore, we also propose that this selection of the boundary cases to be covered is not done in independence, but should involve a back and forth of selecting boundary cases and determining the number of kanban until a suitable compromise of boundary case coverage and number of kanban is achieved. Thus we achieve a suitable tradeoff between a high delivery performance (lots of kanban) and low inventory (fewer kanban).

## 6 Summary

The presented boundary case approach uses the well-known relation of the replenishment time to the customer takt as in Eq. (1) to determine the number of kanban. However, rather than mean values, this approach uses boundary cases (i.e., the largest replenishment time and the smallest customer takt that the system has to cover). This can be either expressed as a percentile of the distribution function if the function is known, or more practically based on the boundary cases known from experience or historic data that the system has to cover. The approach is intuitive, and requires little knowledge of statistics, hence making it suitable for everyday shop-floor use. Nevertheless, the approach has been extensively verified based on simulations, and returns much better delivery performances with much less outliers than the conventional Toyota formula. This information can be used to aid with the implementation of the Kanban system, regardless if it is a paper Kanban, a digital Kanban (where the time for the information flow is usually significantly less), or any other form of Kanban.

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# Options for Maintaining Weak FIFO in Parallel Queues

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**Abstract.** Maintaining a FIFO sequence is a common aspect of manufacturing, especially in lean manufacturing. This can easily be realized by having FIFO lanes, where items are added at one end and removed at the other end. This maintains their FIFO sequence. In industry, however, there is often the situation that the required quantity of items would result in a very long single FIFO lane. This creates subsequent problems with available floor space. Hence, a practical solution is often to have multiple parallel FIFO lanes. However, a separate system is now needed to maintain the FIFO sequence across multiple parallel FIFO lanes. Ideally this would not require much additional managerial overhead and high investment costs. This paper investigates different options on how to manage parallel FIFO lanes, and measures their sequencing performance.

**Keywords:** FIFO · Pull production · Storage · Lean manufacturing

## 1 Introduction

The sequence of material flow in manufacturing and other processing systems is relevant for overall performance. About the most common method used is FIFO (First In, First Out). The oldest material is always used first. The primary advantage of FIFO is that it reduces the fluctuations of the lead time for individual items. All items will have a similar lead time in a FIFO lane. In contrast, a LIFO (Last In, First out) will create vastly different lead times for different items. The first item in will have the longest lead time, and the last item added will have the shortest lead time. LIFO is generally not advisable, but may sometimes be used due to the nature of storage. Both principles are shown in the following Fig. 1.

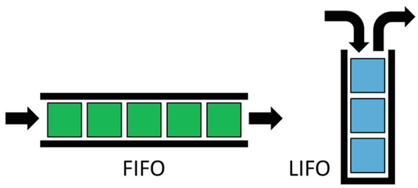


**Fig. 1.** Simplified illustration of FIFO and LIFO


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FIFO is most of all a buffer inventory to decouple fluctuations between the arrival and departure processes. By limiting the maximum inventory, it also prevents excess build up of material. FIFO also has other advantages, as it allows better traceability. If there is a systematic product quality issue, or if there is a design change, it is much easier to track the items that have to be changed. It is also much easier to use up the items of the “old” design before switching over to the “new” design [1]. Furthermore, FIFO represents a transparent material storage, because the information flow is ensured through the materials in the FIFO lanes.

## 2 Problem Statement

This paper is based on a master thesis [2]. In this paper, we will discuss possibilities for managing parallel FIFO lanes. In theory, it is often assumed to have a single FIFO lane in a certain length that is needed. There are different academic methods to determine the FIFO size (for example [3–7]). These can be used to design capacities of FIFO lanes and production areas. In practice, however, limitations on the floor space and storage system often make it difficult or impossible to place all required items into one FIFO lane. One option is to have random-access storage and track the FIFO sequence using an overarching ERP system. Another option commonly seen in industry is to use multiple parallel FIFO lanes, what is being investigated in this article.

An example of multiple parallel FIFO lanes is shown in Fig. 2. The items arrive in sequence. An adding logic decides in which of the multiple parallel FIFO lanes an item is stored. Naturally, this has to be a FIFO lane that is not yet completely full. In addition, there is also customer demand, where the customer requests items periodically. A removing logic decides from which of the multiple parallel FIFO lanes an item will be removed. Similar to the adding logic, this has to be a FIFO lane that is not yet completely empty. If all FIFO lanes would be full, no more items could be added. The system is blocked. Otherwise, if all FIFO lanes are empty, no more items could be removed. The system is starved.

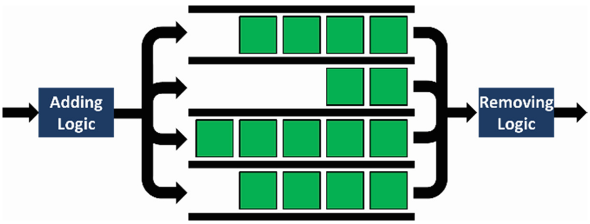


**Fig. 2.** Example of four parallel FIFO lanes each with a capacity of five items

Hence through the adding and removing logic, it is possible to maintain FIFO [8]. Here we have to distinguish between two definitions. First, a strict FIFO where the items leave the system in exactly the sequence they arrived. Second, a weak FIFO sequence where the items leave the system approximately in the sequence they arrived [8]. While within this paper we analyze weak FIFO sequences in particular, we would first briefly introduce the approach for a strict FIFO sequence.

## 3 Strict FIFO Sequence Approach

There are three basic approaches in multiple parallel FIFO lanes that are able to maintain a strict FIFO sequence. The first is to create a digital or physical timestamp of the time when the item was added into the parallel FIFO system. Alternatively, a number could be used to indicate the sequence. If an item is needed, the item with the oldest timestamp is used. The disadvantage of this method is the effort in creating a timestamp and the effort in searching for the oldest item during removal. Nevertheless, this approach is used, in particular in combination with a digital MES (manufacturing execution system) or ERP (enterprise resource planning) system.

A second approach is to fill the parallel FIFO lanes sequentially (i.e. fill the first FIFO lane, then the second FIFO lane, etc.). This is followed by the removal of parts by emptying the first FIFO lane, then the second FIFO lane, etc. The major caveat of this approach is that the filling process must not overtake the emptying process. This is visualized in Fig. 3, where for your understanding the parts are numbered in the sequence of arrival. On the left image the filling process is about to fill a lane before the lane assigned for emptying. In the right image this lane is now full, and the filling process switches to the next lane. This, however, breaks the sequence.

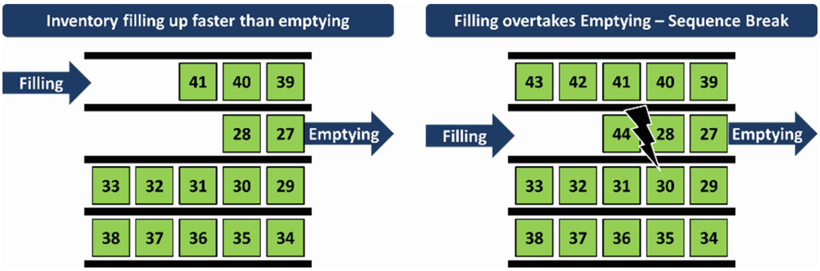


**Fig. 3.** Problem of filling overtaking the emptying process

This breaking of the sequence not only breaks the strict FIFO sequence, but due to the nature of the break we now no longer even have a weak FIFO sequence. Depending on the subsequent arrivals and departures, the items in the other FIFO lanes may remain in the buffer for a very long time while filling and emptying use only one FIFO lane.

This problem can be avoided by blocking the filling of the FIFO lane that is currently emptied. In this case, however, the usable buffer space is less than the total buffer space, and the buffer capacity fluctuates. On the shop floor it would also require very stringent enforcement of standards to prevent, for example, a forklift driver from dropping a part in the only available space just because something indicates he should not place it there.

Another option is to have a signal (red sign, dummy part, etc.) in between the two non-sequential parts. This would be, for example, parts 28 and 44 in Fig. 3. The challenge here is to know when to add this signal, which may not be obvious to the person adding the items. This does have potential for mistakes.

A third option is to always fill the next part into the next FIFO lane adjacent to the previous adding. For removal, the part from the next FIFO lane is removed adjacent to the previous removal. This is also modeled below in the *Add Cyclic & Take Cyclic* combination.

Overall, it is possible to maintain a strict FIFO in parallel systems without the use of timestamps. However, this may require some effort. For example, it can be imagined that a forklift driver would have to get off his forklift to move a signal – and we all know that forklift drivers usually prefer not to get off their vehicle. Furthermore, this may not use the entire available space. Additionally, if a mistake is made, the items can potentially be very badly out of sequence. Especially the second approach above is hence not very robust, and small mistakes may have significant consequences.

In many situations, however, a weak FIFO sequence is sufficient (e.g., if the surrounding system does not include traceability, or in general the advantages of a strict FIFO are not utilized). In this case it may be better to maintain only a weak FIFO with less effort. In the following we compare possibilities for a weak FIFO sequence that are

- more robust against mistakes;
- do not require complex signals within the FIFO; and
- use all of the available space in the FIFO.

## 4 Methods for Adding and Removing

We will consider five different strategies for adding and removing items from multiple parallel FIFO lanes, which are presented below.

### 4.1 Adding Methods

One method for adding items is **Add Random**. In this case, the items arriving are randomly assigned to one of the empty FIFO lanes. The assignment is equally distributed, with only non-full FIFO lanes being used as addition possibilities.

Another method is **Add Max**, where the item is added to the FIFO lane with the largest non-full inventory. If more than one FIFO lane has the largest non-full inventory, the method prefers the FIFO lane that was used for the last addition. If this no longer has the largest non-full inventory, sequentially the next FIFO lane from these equally largest non-full inventories will selected for the addition process.

A further method represents **Add Min**, where the item is added to the FIFO lane with the smallest inventory. If more than one FIFO lane has the smallest inventory, the method prefers the FIFO lane that was used for the last addition. If this no longer has the smallest inventory, sequentially the next FIFO lane from these equally smallest inventories is selected.

The fourth method is **Add Repeat**, where items are repeatedly added in the same FIFO lane until it is full. After this FIFO lane is full, the next non-full FIFO lane is selected. Items are added into this new FIFO lane until it is also full. Then the process is repeated. Please note that if this method includes a signal in case of an overlap, then this *Add Repeat* and corresponding *Take Repeat* would maintain a strict FIFO as presented in Sect. 3.

Finally, **Add Cyclic** is used as the fifth method, where each item is added to the next non-full FIFO lane from the previous one. Doing this, the first item is added to FIFO lane 1, the second to FIFO lane 2, and the third to FIFO lane 3, etc. This will continue until an item has been added to the last FIFO lane, after which the cycle begins again with FIFO lane 1. If during this procedure a FIFO lane is full, it is skipped.

## 4.2 Removing (Taking) Methods

Similar methods are used for removing items. One of these is the **Take Random** method, which takes an item randomly from one of the non-empty FIFO lanes. The random removal is with equal probability from the non-empty FIFO lanes.

The **Take Max** method removes the item from the FIFO lane with the largest inventory. If more than one FIFO lane has the largest inventory, the method prefers the FIFO lane that was used for the last removal. If this no longer has the largest inventory, sequentially the next FIFO lane from these equally largest inventories will be selected for the addition process.

The **Take Min** method removes an item from the FIFO lane, which contains the smallest non-zero inventory. If more than one FIFO lane has the smallest non-zero inventory, the method prefers the FIFO lane that was used for the last removal. If this no longer has the smallest non-zero inventory, sequentially the next FIFO lane from these equally smallest inventories.

The **Take Repeat** method removes items repeatedly from the same FIFO lane until it is empty. After this FIFO lane is empty, the next non-empty FIFO lane is selected, and items are removed from this FIFO lane until it is also empty. Then the process is repeated. The sequence of the FIFO lanes for the removal is identical for the sequence of the FIFO lanes for adding if the adding method has a sequence (*Add Repeat*, *Add Cyclic*).

The fifth method is **Take Cyclic**, where each item is removed from the next non-empty FIFO lane from the previous one. In this case, the first item is removed from FIFO lane 1, the second from FIFO lane 2, and the third from FIFO lane 3, etc. By analogy to *Add Cyclic*, this will continue until an item has been removed from the last FIFO lane. After this the cycle begins again with FIFO lane 1. If during this procedure a FIFO lane is empty, it is skipped. The sequence of the FIFO lanes for the removal is identical for the sequence of the FIFO lanes for adding if the adding method has a sequence (*Add Repeat*, *Add Cyclic*). Please note that the combination of *Add Cyclic* and *Take Cyclic* would give a strict FIFO sequence.

There would also be another method, **Take Oldest**, where the oldest item in the parallel FIFO lanes is removed. This would ensure a strict FIFO, where the removal of the items is exactly in the sequence they are added. This is regardless of the method in which they were added to the FIFO lanes. However, this would require a data system or a comparison of the first item in all parallel FIFO lanes to find the oldest one. While best for the sequence, it is not always practical due to the effort in determining the oldest item and the amount of investment costs incurred.

### 4.3 Combination Adding and Removing (Taking) Methods

Within the scope of selecting FIFO lanes, we have five methods for adding items and five for removing items (excluding *Take Oldest*). Hence, we have a total of 25 combinations of adding and removing methods as shown in Fig. 4. Please note again that combination 25 gives a strict FIFO sequence.

| | Add Random | Add Max | Add Min | Add Repeat | Add Cyclic |
|---|---|---|---|---|---|
| Take Random | 1 | 2 | 3 | 4 | 5 |
| Take Max | 6 | 7 | 8 | 9 | 10 |
| Take Min | 11 | 12 | 13 | 14 | 15 |
| Take Repeat | 16 | 17 | 18 | 19 | 20 |
| Take Cyclic | 21 | 22 | 23 | 24 | 25 |

**Fig. 4.** 25 combinations of adding and removing strategies, with #25 having a strict FIFO sequence

## 5 Simulation Approach

We simulated all 25, adding and removing combinations for a system with 10 parallel FIFO lanes with a capacity of 10 each. The inter-arrival and inter-departure times were exponentially distributed. The system was tested under three different load conditions. A low load had an on average 0.5% less items arriving than demanded (i.e., the customer frequently had to wait and the inventory was frequently empty). A high load had on average 0.5% more items arriving than needed, resulting in a mostly full inventory. Finally, a medium load had on average as many items arriving as consumed. We measured the sequencing quality as the root mean square error (RMSE) of the difference between the position in the arrival sequence and the position in the departure sequence. For each simulation this was calculated as shown in Eq. (1), where $i$ is the i$^{th}$ item in the arrival sequence out of $n$ items in total, and $T_i$ is the position of the item $i$ in the departure sequence.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(i - T_i)^2} \quad (1)$$

Each simulation processed 10,000 items. Furthermore, each simulation was repeated 52 times for statistical accuracy. This resulted in almost 4,000 simulations to determine the mean RMSE and its confidence interval.

## 6 Simulation Results

Below are exemplary of the results of all 25 combinations for inter-arrival and inter-departure times with same parameters, including its 2.5% confidence interval. The results in the following Fig. 5 are sorted by the removing methods. Full results can be found in [2].

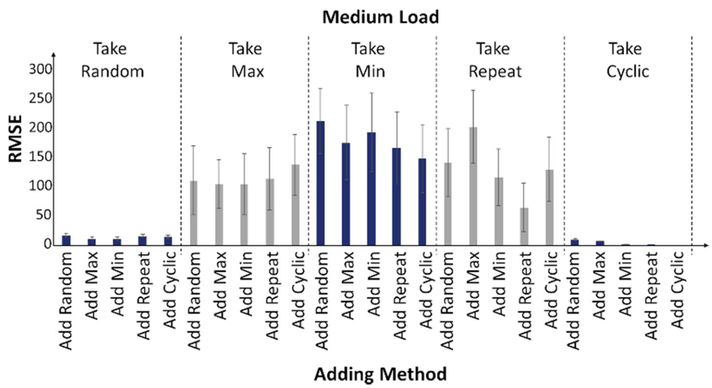


**Fig. 5.** RMSE and confidence intervals of all 25 combinations for medium load

The differences between the removing methods indicates that the removal method has a significant effect on the sequence quality. Removing items using the *Take Min* approach results in the worst sequencing quality, having an average RMSE across all five adding strategies of 180. The *Take Repeat* and *Take Max* approaches are only marginally better with an average RMSE of 131 and 115. Removing items randomly using *Take Random* is actually a pretty good strategy with an average RMSE of 13. However, the best sequence quality was achieved by using *Take Cyclic*, with an average RMSE of only 5.6 across all five adding strategies. Comparable results were achieved with the low- and high-load conditions. A strict FIFO can be maintained by the combination of *Add Cyclic–Take Cyclic* strategy with a RMSE of 0. This combination brought overall the highest quality FIFO sequence. If a weak FIFO is sufficient, a *Take Cyclic* approach gives the smallest RSME regardless of the adding sequence, saving the additional effort of *Add Cyclic*.

## 7 Summary

Overall, a strict FIFO maintaining the correct sequence is of course the best approach. However, for parallel FIFO lanes that are not managed digitally, the effort of maintaining strict FIFO may exceed the benefit. In these cases, a weak FIFO can be achieved simply by using the *Take Cyclic* approach, where every item is taken from the next FIFO lane. This approach maintains an adequate FIFO sequence with acceptable additional effort, regardless of the logic used for adding items into the FIFO. It is also a robust approach. While this does not maintain a strict FIFO sequence, it is often the appropriate solution for practical applications. Overall this gives a good trade-off between effort and FIFO quality if a strict FIFO sequence with parallel FIFO lanes would lead to high effort or additional investment costs.

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# Sketching the Landscape for Lean Digital Transformation

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**Abstract.** Lean management remains the most popular approach to operational excellence within industry. The next wave of industrial improvement is widely considered to be driven by the application of digital technologies. Organizations are seeking to understand how the two approaches can be utilized synergistically. This paper aims to sketch the landscape for current theories and managerial challenges facing Lean and digital transformation based on Lean principles with respect to organizational design, supply chain planning, decision systems and supplier relationships. We raise fundamental questions that should be addressed by future research in the field of digital lean manufacturing and lean digital transformations.

**Keywords:** Lean management · Digital transformation · Organization design · Supply chain planning · Decision systems · Supplier relationships

## 1 Introduction

For several decades, improvement efforts in organizations have built on the concept of "Lean Thinking" and related ideas of process standardization and continuous improvement [25]. The next wave of industrial improvement is widely considered – within industry and academia alike – to be driven by the application of digital technologies [18, 26]. Hence, there is growing appreciation among managers of the need to understand how these new digital technologies can be put to good use in order to improve efficiency and competitiveness.

Digital Lean manufacturing refers to the application of digital technology in order to enhance the Lean and learning transformation in manufacturing organizations. E-kanbans, digital problem solving, or kaizen in digital collaborative environments are some examples. In a recent article, Romero et al. [27] discussed the emergence of Digital Lean Manufacturing and the significance of digital waste that may that may come into existence in the cyber world due to the non-use (e.g. lost digital opportunities) and/or over-use (e.g. abused digital capabilities) of new digital/smart manufacturing technologies.


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On the other hand, industrial experience suggests that too often technology adoption happens according to a "technology push" model: some technological component is developed or bought, and work processes are adapted to fit the technology. Technology pushes often contradict the key Lean principle that technology should serve the people and the processes [21]. Lean digital transformation, therefore, refers to the application of Lean principles to digitalization processes in order to achieve a digital transformation that creates less waste.

Management research on Lean and digitalization is still in its infancy [4, 30], as it remains poorly understood which organization models and principles make possible the best utilization of the new digital technologies [2]. This paper aims to sketch the landscape for Lean and digitalization joint transformation. We propose that novel theoretical insights can be developed by framing the relationship between the two.

## 2 Frontiers of Knowledge and Technology

### 2.1 Lean Management

Lean management, as popularized by Womack et al. [33], was ultimately a description of the philosophy and production system of the Japanese car manufacturer Toyota. Lean was subsequently presented as the global solution to improve efficiency and quality [13]. Lean has evolved over time and been embraced by other industries and in other cultures than that of its origin [25]. Five fundamental principles have been claimed to be universally applicable [34]: specification of value, identification of value streams, continuous flow, customer pull and striving for perfection. Netland & Powell [25] recently proposed a further abstraction in that Lean, cut to the core, is about continuous improvement and three essential Ls: Learning, Leadership, and Long-term perspective. In their recent book, Ballé et al. [1] challenged organizations' traditional understanding and practicing of Lean by putting forward the Find-Face-Frame-Form strategy as a fresh new approach to understand the "true" Lean vs. the "false" one, i.e., Lean without learning. Yet, the practical application of Lean usually involves using a set of techniques such as just-in-time logistics, standardized work procedures, supplier feedback, reduction of set-up times, total quality management and statistical process controls [31].

### 2.2 Digital Manufacturing Technologies

As a result, from a future-oriented project, the German government coined "Industry 4.0" at the Hannover trade fair in 2011. New concepts, like Cyber-Physical System, Internet of Things, Big Data, Digital Twin, Block Chain and collaborative robot were introduced. Some of these concepts are old technologies recombined in new ways, and often incorporated with new technologies [12]. The overreaching goal of Industry 4.0 is to create highly flexible, yet high volume production lines, making processes more efficient and robust as well as reducing costs and improving the quality [20].

All of these technologies are powerful by themselves and create new opportunities, however, the core value of digitalization remains in true value creation for the customers, and at its core, to enhance "connectivity". This connectivity can be divided into two dimensions, internal and external. Internal connectivity deals with how to connect seamlessly different technologies and work processes inside the organization [26, 30]. The external connectivity relates to data flows, system integration, etc. between companies. Important and essential quality information can be shared using the Internet of Things technology [3].

## 3 The Landscape

The topic of Lean and digital transformation is fairly new and complex and it requires insight from several disciplines. In order to bring further clarity into challenges associated with Lean and digitalization interactions, a fairly extensive literature review was performed during the course of this study. As a result, four categories for further research are proposed. These categories correspond to four theoretical domains that are: organization theory, operations management, operations research and inter-organizational business relationships. In this section, each of these categories are briefly explained and some outstanding questions that ought to be addressed by further research are put forward.

### 3.1 Organizational Design

The Lean work organization is characterized by both functional integration and integration of performance and control [5, 15]. Extensive involvement of operators is premised on this organization design, as it empowers the shop floor vis-à-vis specialist functions. Digital technologies can support such an organization design, by providing faster and more reliable information for operational decision-making and continuous improvement activities [30]. If the technology is designed with this purpose, the relationship between Lean and digitalization may be synergistic. However, these synergies are not realized if the digitalization drives an organization-wide redistribution of decision-making power in favor of ICT-specialists organized in staff functions. For several reasons, such a redistribution of power is a likely development. Firstly, knowledge about how to design, configure and maintain the technologies will be a scarce resource, making the shop floor more dependent on outside expertise. Secondly, the big investments associated with digital technologies call for organization-wide standardization of technology, limiting the shop floor's discretion on the choice of technology and how to operate it. Thirdly, when continuous improvement becomes more analytical and data-driven, it relies more heavily on theoretical knowledge and require a deeper understanding of statistics. Hence, it may likely become the domain of experts, rather than shop floor workers [14]. These tendencies clearly contradict the Lean principles of creating functional integration at the shop floor.

To address these challenges, the following questions can be put forward:

- How are the collaboration between the shop floor and ICT-specialists reconfigured considering digitalization?
- How can digital technology be designed to support functional integration at the shop floor?

- How may shop-floor workers and managers be trained to master the digital technologies, so that they retain participation in continuous improvement activities?

### 3.2 Supply Chain Planning

Supply chain planning aims to improve performance in operations by mitigating uncertainty through managing operations and customer demand, and coordinate supply chain activities with business strategy. With principles leading to elimination of waste, improving quality, cost reduction and increasing flexibility, the Lean concept has strongly influenced existing planning models and made planning highly sensitive to disturbance and variability [7, 9]. However, driven by technology combined with shifting supply and market complexity such as globalization, customization and serving individual needs instead of market categories [3], variability and uncertainty increases. While planning is becoming more demand and event driven (real-time, increased frequency, shorter planning horizon and cross functional), and turned into a process within the supply chain rather than in individual companies, the complexity and uncertainty increases [16].

Information technology strongly facilitates planning models by efficiently allowing access to information, advanced analytics and integrating operations between supply chain partners and across functions, which is crucial in most Lean programs [23]. However, technology may also come into conflict with Lean or in short of unlocking the potential by a standardized functionality and design, hindering the support of complex planning environment and interaction between the partners in the supply chain [28].

To address these challenges, these questions can be raised:

- Why and how are digital technologies influencing supply chain planning?
- How do digital technologies affect roles and responsibilities in supply chain integration?
- How can digital technologies be designed to support supply chain planning?

### 3.3 Decision Systems

Quantitative models and methods have been used for decades to provide decision support within operational production and logistics planning (see e.g., [11]). Many of these models have been made available to companies through commercially available Advanced Planning Systems [19]. Traditionally, most models for operational production, inventory, and distribution planning assume centralized decision making [6, 32]. Lean principles, however, advocate decentralized planning at the lowest possible planning level [5].

Digitalization and advances in information technology will make more data faster available to a decision maker, for example, through the extensive use of sensors monitoring state and surroundings of a production system (or product), or the Internet of Things (see Sect. 2.2). This will lead to more and more data-driven decisions, taking into account a much more comprehensive view of the production system [24].

To evaluate the impact these developments have on Lean principles, the following questions should be addressed:

- Will digitalization lead to more centralized decisions? It has long been recognized that systems need to be optimized as an entity, rather than optimizing subsystems [10]. Using large amounts of data in order to provide decisions for the entire system may push towards more centralized decisions.
- How can local decisions be coordinated in order to optimize the entire production system? Local decision makers may not only need access to vast amounts of data, but also help in understanding the consequences of their decisions. This applies especially in situations where e.g. local maximization of capacity utilization is counterproductive with respect to total cost within the production system.

### 3.4 Supplier Relationships

While most research on Lean management has focused on intra-organizational applications of Lean principles [17], some attention had been paid to inter-organizational applications, e.g. to develop Lean suppliers and supply networks [8, 22]. Digital communication and decision making with the need for and advantages of personal communication and participative decision making at both the suppliers and buying firm are, therefore, very important.

Furthermore, while some efforts have aimed at offering assistance to suppliers in order to improve their performance in the short run, strategic supplier development efforts have aimed at encouraging and enabling suppliers to develop their Lean capabilities by means of which the suppliers can continuously improve their Lean practices and performance [29]. Suppliers have been encouraged to find their "own Lean way" [25], thus preserving the autonomy of the suppliers. Finally, the development of Lean supplier networks has considered challenges of competitive rivalry, and for example, Toyota has taken care to create separate arenas for interaction with suppliers who are in direct competition [29], whereas Honda has had joint arenas.

The potential of digital technologies to transform performance is now widely recognized, and a few contributions connect efforts at digital transformation with Lean supply principles [26], however, how digitalization can facilitate as well as hamper the manner in which manufacturing firms encourage, enable and enforce the development of Lean practices in their supplier relationships and networks is still challenging.

To address these challenges, the following questions can be raised:

- How can the key characteristics of Lean supplier relationships and networks be reconfigured considering digitalization, with the aim to improve the cost efficiency and the effectiveness of such efforts?
- How can digital technology be used for enabling and enforcing interaction, mutual trust, and knowledge-sharing routines between the suppliers and a buying customer, and between suppliers who may cooperate and compete?
- How can the integrity and autonomy of suppliers be preserved when they become connected in supplier networks by means of digital technologies with requirements for standardization?

## 4 Conclusion

In this paper, we have sketched the landscape for Lean and digital transformations. Interactions between the two improvement strategies and associated challenges are poorly understood in the current literature. This contribution sheds light on the landscape by classifying various challenges in four areas and proposing key questions for future research. The four areas are organizational design, supply-chain planning, decision systems, and supplier relationship. Although these areas correspond to established management disciplines, Lean- and digital transformations are multidisciplinary in their nature. Therefore, in addition to doing in-depth research within each area, researcher might work together in multidisciplinary team to create workable knowledge addressing practical challenges more holistically.

We hope our framework and research questions will trigger further discussions and research that aims to help organizations obtaining a correct strategy in their pathway towards Lean, learning and digital organization. For practitioners such a framework might be instrumental in clarifying the different aspects of a complex problem.

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# Cyber-Physical Waste Identification and Elimination Strategies in the Digital Lean Manufacturing World

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**Abstract.** Lean Manufacturing and Industry 4.0 are at times portrait as conflicting paradigms. However, we take the stance that they are two sides of the same coin, and should be considered as mutually beneficial. Based on this understanding, this paper is part of a series where we discuss established Lean practices in the emerging Digital Lean Manufacturing World. In this paper, we specifically focus on the issue of "buffer waste", and what that implies within a cyber-physical production system. We discuss the vicious cycle of Mura, Muri, and Muda, and provide observed examples in industry for "buffer waste" from four different, yet interdependent perspectives: (i) physical to physical, (ii) physical to digital, (iii) digital to physical, and (iv) digital to digital. The results of this study confirm that "buffer waste" is indeed an issue that deserves our attention as academics and practitioners in the emerging Digital Lean Manufacturing environment.

**Keywords:** Digital manufacturing · Smart manufacturing · Lean Manufacturing · Digital Lean Manufacturing · Digital lean enterprise · Cyber-physical production systems · Industry 4.0 · Muda · Mura · Muri · Waste · Digital waste · Obvious waste · Buffer waste

## 1 Introduction

The systematic identification and elimination of *waste* is one of the main principles of *Lean Manufacturing* [1, 2] in order to create and deliver value more "efficiently" to the customer. In the *Lean lexicon*, *Muda* is the Japanese word for "waste". According to the Toyota principles, three *MUs* – *Muda* together with *Mura* (unevenness) and *Muri* (overburden) – represent the three biggest enemies of *lean production efficiency* [2].


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While there exists a broad literature on the three *MUs* in the physical world, research lacks in understanding how *Muda, Muri,* and *Mura* influence each other in the context of the evolution of *traditional Lean Manufacturing systems,* in the Industry 4.0 era [3], towards *Digital Lean Manufacturing (DLM) systems.* The latter, defined by [4] as a "Lean Manufacturing System that builds on data acquisition, data integration, data processing and data visualization capabilities [5] to create different descriptive, predictive and prescriptive analytics applications [6] to detect, fix, predict and prevent unstable process parameters and/or avoid quality issues inside defined tolerance ranges that may lead to any type of waste within the cyber- and physical- worlds". A *DLM System* involves the generations of two types of *Muda* (waste) according to its physical or digital plane of manifestation, thus calling for a more holistic and systemic planning of *physical* and *digital waste* management [4].

On these premises, this paper discusses the new *cyber-physical* scope of *Muda, Muri,* and *Mura* in the emerging *DLM systems*, and provide general recommendations for *physical* and *digital waste* identification and elimination strategies under a holistic and systemic approach. The proposed recommendations are supported by a conceptual framework built upon a scientific literature review on "waste" meaning and its different types and typologies and are derived from discussion-based interviews with *Lean Researchers* and *Managers*, as well as the authors' experiences as *Lean Pracademics*.

## 2 Literature Review

Traditionally, *Muda* covers seven distinct types of waste: (i) defects, (ii) overproduction, (iii) waiting, (iv) transportation, (v) inventory, (vi) motion, and (vii) overprocessing [2]. Recently, an eighth *waste-type* emerged: not-utilizing talent [7].

Several extensions of the classical concept of *Muda* have been presented in the literature. A first relevant distinction about *waste-types* is provided by [8], from a strategic waste identification and elimination perspective, dividing waste in (i) *obvious waste* – as any waste that can be reduced or eliminated without creating another form of waste, and (ii) *buffer waste* – as any waste that cannot be reduced or eliminated without creating another waste. This division helps *Lean Managers* to strategically plan their *waste* management actions in order to best achieve (lean) performance targets [8]. Nevertheless, not all *obvious wastes* can be eliminated. According to [2], there are wastes that are related to non-value-added activities for the customer, but are necessary for the current operational activities; like special controls requested by an independent body in order to issue a certification that a product, process or system meets specific requirements (e.g. ISO standards), therefore, these *obvious wastes* can only be reduced not eliminated.

*Muri* is defined as the unreasonable burden of operators or equipment. It refers to any action that relates a tangible-physical or intangible-psychological stress condition. Examples of *Muri* involving operators are bending to work, lifting heavy weights, or repeating tiring mental and physical actions, while given deadlines that are constantly too short for the workers' individual skill level [9]. Hence, the interconnected nature of most production processes can cause *Muri,* especially when too many/much *Mudas* are removed from a specific point in a process (i.e. over-optimization). As a result, *Muri* can cause *Muda,* as in the case of a breakdown or defects generated due to the over-utilization of machines and/or people, or due to the over-optimization of a process since *lean efficiency* means a balanced, stable, and standardized process [2, 10]. For instance, the introduction of rigorous standards for the execution of work activities forces the workforce to operate in limiting and alienating conditions that create stress and resistance [11].

Finally, *Mura* identifies the irregular use of a person or a machine. It can be found in any process (or operation) fluctuation, which should be reduced or eliminated in order to avoid the possibility of *Muri* in any value-adding production resource (e.g. an operator, a machine tool, a robot, a computer, etc.), and therefore, *Muda* [2]. Indeed, *Mura* is strongly connected with both *Muri* and *Muda.* Consequently, processes' fluctuations are related to their instability, and in turn, create conditions which generate waits and queues. Together with the over-utilization of one or more of the production resources involved at specific times and phases in a process lead to *Muda* and *Muri* emerging, and call for the creation of stocks and buffers to overcome such variability in the processes, thus, more *Mudas* appear.

## 3 Muda, Muri and Mura in a Digital Lean Manufacturing System

As described before, the three *MUs* have been traditionally interrelated in the physical world. Moreover, the traditional *vicious cycle,* where the creation of *Mura* involves the generation of *Muri* which, in turn, produces *Muda* thus creating new *Mura,* can be replaced by other potential combinations. For example, as depicted in Fig. 1, "inventory" is *Muda*. The reason for this inventory is variability or *Mura* [12]. The reason for *Mura* is typically "overburden" somewhere in the system, i.e. *Muri*. But the high inventory itself puts even more burden on the systems. This further strains the system and leads to more *Mura* and, consequently, even more *Muda*. Breaking this *vicious cycle* is the main objective of *Lean Managers.*

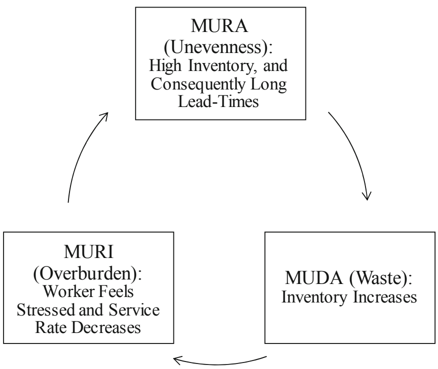


**Fig. 1.** Mura, Muri, and Muda vicious cycle

While breaking this cycle is a challenging task, with the novel *cyber-physical nature* of production systems [13], *Muda, Muri,* and *Mura* have gained a second *digital plane* of manifestation with also interrelations between their *physical* and *digital nature.* This results in at least IV different domains in which waste is created as illustrated in Fig. 2. Note that the *vicious cycle* depicted in Fig. 1 also exists in the *digital plane.* Unevenness between information processing requirements and information processing capability, i.e. *Mura*, leads to large amounts of unused data, i.e. *Muda*. This, in turn, puts more strain on the system (i.e. *Muri*) since it negatively effects decision-making [14], which leads to even more *Mura* and, consequently, *Muda*.

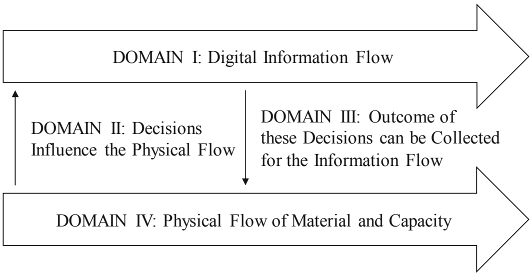


**Fig. 2.** Cyber-physical domains of Muda

As a result, these emerging *DLM systems* call for a more holistic and systemic planning of *physical* and *digital waste* identification and elimination strategies by *Digital Lean Managers,* always avoiding the creation of another form (type) of waste in one or both of the cyber- and physical- production system worlds. Moreover, *Muri* and *Mura* in any of the production resources may result in one or more of the classical seven cases of *Muda* [2]. Additionally, the eight *waste-type* of "non-utilizing talent" [7], in the form of non-properly trained operators, in *Muri* and *Mura* for such operators due to high-stress levels when aiming to perform standard operations without the proper knowledge and skills, leads in particular in many occasions to one or more of the already mentioned classical seven *Mudas* in the production line when it comes to aiming for a continuous flow and zero-defects manufacturing system. In general, the interrelation between *Mura, Muri,* and *Muda* can be understood as a "vicious cycle" (see Fig. 1).

In the next sub-sections, we discuss the new *cyber-physical* scope of the three *MUs* in the emerging *DLM systems* through a set of non-extensive real examples and provide general recommendations for *physical* and *digital waste* identification and elimination strategies under a holistic and systemic approach. In particular, we focus on *buffer waste.* This is waste that is created by *Mura* or *Muri* and can consequently not be reduced without creating another waste.

### 3.1 From the Physical World to the Physical World

According to [15], *Muda, Muri,* and *Mura* are connected with each other through a chain of causes and effects in the physical world, where *Mura* creates *Muri* and the two of them together create *Muda.* For example, variations in production volumes force a company to alternate between overloading and underutilizing its production resources, consequently resulting in *Muri* and *Muda* (overproduction). This, in turn, leads to downtimes, mistakes, backflows, and waiting times causing other types of *Muda.* Therefore, *Mura* and *Muri* are the root-causes of *Muda,* creating more non-valued added activities and undercutting previous efforts to eliminate waste [15] (see Fig. 3).

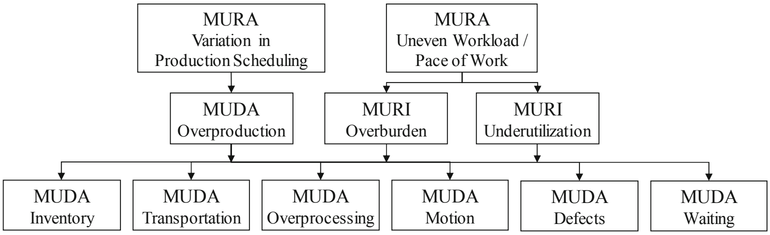


**Fig. 3.** Interdependencies of Mura, Muri, and Muda [15]

Hence, *Digital Lean Managers* should always remember that any waste reduction and/or elimination strategy must be based on a "holistic" approach, considering the importance of the whole production system and the interdependencies of its operations and resources in order to not create more waste when trying to remove it.

### 3.2 From the Physical World to the Digital World… to the Physical World

The Internet of Industrial Things (IIoT) offers tremendous new opportunities for capturing data from the physical world in order to create digital records to support a smart production planning and control. Through "smart" interventions, by applying advanced modelling, simulation, and (big) data analytics techniques [16–18], it is now possible for *Digital Lean Managers* to analyse data from multiple sources and visualize it in real-time and interactive-matter in digital dashboards in order to make better decisions supported by hard-data and various scenarios-testing. These aims lead to *Kaizen* (improvement) actions with higher levels of success. Nevertheless, in the previous scenario described *poor data quality*, acquired through damaged or tampered sensors may lead to *digital waste,* in case it is not detected on-time and at the level of the enterprise information systems, and even worse to *physical waste,* in case decisions were made and actions were taken based on incomplete, no longer valid, inconsistent, and/or not accurate data. Furthermore, *digital obvious waste* identification in the form of *poor data quality* represents one of today's biggest challenges in *DLM systems,* urging *Digital Lean Managers* to implement: *Total Data Quality Management (TDQM) practices* [19–21].

### 3.3 From the Digital World to the Physical World

There is no question that advanced modelling, simulation, and (big) data analytics tools [16–18] may offer great optimization capabilities at the production line. Nevertheless, such analytical efforts should not create *waiting times* and *queues* for the production resources due to what can be described as "paralysis by analysis". The use of *digital/ smart manufacturing technologies* [22, 23] supports operators in simple and repetitive tasks (i.e. routines), and helps them to reduce quality defects as the technology is not exposed to the risk of "human error". Thus, contributing to "predictable" and "stable" processes outputs. For instance, the adoption of *digital poke-yokes* avoids the generation of errors during production. It allows to record the actions taken by each operator and produce real-time tutorials to guide users in the optimized use of their tools (e.g. augmented reality assistance systems), speeding-up their operations, and minimizing future errors and reworks [23]. This implies a potential reduction of fluctuations that are generated when different production practices are adopted by workers characterized by distinctive learning approaches. Another example is the use of *exoskeletons,* which allow reducing the physical overloads in the case of heavy and repetitive tasks, thus avoiding loss of productivity and quality [23].

Introducing *digital/smart manufacturing technologies* [22, 23] in a production system where processes are not under control, it amplifies the risk for additional physical *Muri* and *Muda*. For example, the use of robots/co-bots supports operators in repetitive tasks and helps them to reduce quality defects. However, if each production phase is not well balanced, the speed improvement achieved in robotized areas can involve the creation of bottlenecks both downstream and upstream of the production system that in turn cause generation of stocks and waits.

Finally, high-levels of *automation* can cause stress at the organizational level, and push operators to reduce their effort, interest, and commitment towards their work with a consequent risk of creating new forms of *Muda* in the production operations.

In these cases, the ability of the management to plan and communicate properly the introduction of *automation* will be very important in order to avoid unnecessary stress into the organization. Moreover, *Digital Lean Managers* should avoid over-engineering their cyber-physical production systems, and adding unneeded "complexity" to their operations, which may increase the potential of catastrophic, but also incremental, failure of the system [4]. Some recommendations to avoid this situation have been provided by [24] and [25] based on various design principles for Industry 4.0 solutions, which advocate for decentralised structures and for small and simple-to-integrate modules (i.e. plug-and-play) in order to better manage their complexity as well as the complexity of the overall system when being adopted.

### 3.4 From the Digital World to the Digital World

The *digitalization* of paper-based information flows as well as capturing data from the physical world thanks to the IIoT, offer new opportunities to envision the paperless and proactive sensing factory [26]. This vision aims to provide availability and access of everything online, readily available for advanced data analytics and information "push" technologies (e.g. real-time and interactive digital dashboards, artificial intelligence-based reporting tools, wearable *Andon* systems). Thus, *digital information flows, digital visual controls* and *human-machine interfaces* in these new data-rich manufacturing environments called: “smart factories”, should be now more than ever designed in a way that they avoid cognitive *Muri* [27] for the operators due to information saturation. Some cognitive *Muri* cases that should be avoided in DLM environments are: (i) not properly designed augmented reality (digital) assistance systems that are overwhelming operators with information in their direct view, (ii) over-engineered human-machine interfaces (i.e. control panels) making it hard for the operators to control a machine tool, a robot, or a computer system, (iii) complex dashboards (i.e. data visualizations) making it difficult for the operators to interpret the information provided, (iv) abuse of *Andon* systems to the point that operators may decide to ignore the alarms (i.e. alarm fatigue), and (v) irrelevant reports for supporting decision-making. Hence, *Digital Lean Managers* should promote and adopt “cognitive ergonomics” best practices [28] to avoid *Muri*.

## 4 Conclusions

In the emerging *Digital Lean Manufacturing World,* we have to rethink the established concept of the seven (or eight) wastes. We have to recognize, that both *physical* and *digital waste* exist and have to be addressed individually while keeping a holistic perspective. While *digital waste* currently appears to be less of a problem, seen computer power is typically less costly, there are two issues that need to be considered. First, computer power is, in fact, limited and many optimisation problems cannot be solved. There are also problems with storage and retrieval of large unnecessary data, something already recognized by [2]. Second, managers are unlikely to give control to a machine. The human will remain a central aspect of any management system. As a consequence, the main task in “digital management” is the reduction of data to the essential information to allow a human user to make an informed decision. But this is itself just *Muda* elimination, being any data that does not contribute to the informed decision is *Muda*. In this paper, we specifically focussed on the “buffer waste”. *Buffer waste* in a *DLM system* is created by *Mura* or *Muri,* and can consequently not be reduced or eliminated without creating another *waste.*

Moreover, we have discussed the issue of *buffer waste* and its impact on *DLM systems* taking four different, interdependent perspectives: (i) from the physical world to the physical world; (ii) from the physical world to the digital world, and back to the physical world; (iii) from the digital world to the physical world; as well as (iv) from the digital world to the digital world. In doing so, we recognize that there is a wide range of *Muda* that emerges when *digital/smart technologies* [21, 22] are introduced in a manufacturing system. For example, introducing (co-)robots in a manufacturing system to support operators at the assembly line does address *Muda* and *Muri,* however, can negatively impact process fluctuations: *Mura.* This dilemma has been termed: *Mura, Muri, and Muda vicious cycle.*

This paper is a first attempt to discuss the issue of *buffer waste* in a *DLM system* from a holistic perspective. The results confirm that this is indeed a problem deserving of our attention as researchers with a strong impact on manufacturing practice. Future work needs to focus on defining the interdependencies between the different *Mudas,* ideally in detailed case studies as a basis for instruments and methods addressing the effective and efficient design of *DLM practices.*

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# Using Prescriptive Analytics to Support the Continuous Improvement Process

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**Abstract.** The continuous improvement process (CIP) enables companies to increase productivity constantly by sourcing ideas from their employees on the shop floor. However, shorter production cycles require manufacturing companies to also adapt their production processes in a faster manner and reduce resources for CIP activities. Traditional CIP approaches fall short in such a fast-paced environment characterized by uncertainty. This study proposes a novel approach for increasing the efficiency and speed of the CIP by using data of previous improvements and predict current potentials. This results in a prescriptive model supporting the employees how to improve their processes.

**Keywords:** Continuous improvement process · Data-driven production management · Knowledge management

## 1 Introduction

Manufacturing companies are required to constantly improve their capabilities to increase their productivity in the future. A main driver for increasing the productivity on a day-to-day basis is the continuous improvement process (CIP), which is at the heart of any manufacturing organization [1]. In the popular illustration of the Toyota Production System (TPS), for instance, the CIP stands in the center of the illustrated house and receives special focus [2]. The CIP helps to access and use the knowledge and suggestions of the employees to constantly question the current processes.

However, not only the required capabilities itself change - also the rate at which this change is happening increased within the last years. Customers are asking for more individualized products for the same costs as mass-produced products. Digital technologies allow for needed productivity gains outside current limits. The usage of these technologies will significantly change the way manufacturing companies produce products. Such significant changes of the process, so called process innovations, will induce highly cyclical changes until new stable production conditions are achieved.

In order to ensure increasing productivity under such conditions, the CIP needs to be enhanced to overcome its time consuming latencies. Therefore, digitalization offers


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new opportunities for collecting and analyzing huge amount of data in a short time that a human could not handle. Hence, this paper proposes a model to enhance the CIP with digital capabilities to leverage its potential for future productivity gains.

## 2 Definition and Challenges of the Continuous Improvement Process

The CIP is rooted in the literature on lean management and total quality management (TQM) [3]. It is a method of constantly developing processes further towards an overarching goal [4]. This goal serves as a direction and guides the improvement actions. The employees perform these actions continuously along the way.

The CIP is often taken as a synonym for Japanese term *kaizen*. This term is first introduced by Imai [5] who further differentiates between three levels of kaizen: *management*, *group*, and *individual*. The focus of kaizen is the incremental, iterative, and continuous improvements of a system [6]. In contrast, the literature defines the term *kaikaku* as step-wise improvements [7]. These happen for instance with the introduction of a new manufacturing technology.

Whereas in earlier years companies tried to operationalize the CIP through tools and rigor meetings, companies recently acknowledge the importance of the softer aspects; For achieving sustainable results the CIP needs to be anchored in the company's culture [1]. Therefore, the key resource of the CIP are the employees [2]. Not only do they shape and influence the culture, but they also possess the specific knowledge about the process and are the problem solvers. This is critically as the CIP is not a top-down approach but lives throughout the organization.

With an increasing complexity of the processes due to quicker cycles of different products, traditional continuous improvement falls short on quickly identifying the root causes. Digitalization allows for the collection and analysis of a huge amount of data to manage such complex processes. However, incorporating information technology into the manufacturing process can detach the employee from the problem solving process: they might lack the expertise for analyzing the data needed to understand the process. Thus, data that can help in improving the processes remains far too often unexplored.

The performance and financial benefit of the improvement activities are not always clear. In a case study of two plants for instance the annual costs for the continuous improvement investment exceeded the annual cost savings from it for one plant [8]. The financial pressure increases when island solutions are developed. If a similar problem has already been solved in another line or another plant, the company could take advantage of scaling the solution throughout the organization. However, if the knowledge about the presence of these improvements is not shared, the company will develop redundant improvements that create a non-standardized infrastructure [9].

Following the literature, the ability to minimize the latency times regarding acquiring and analyzing data, as well as decision making towards the final implementation is key to efficient continuous improvement in a frequently changing production environment. To reach that goal, an approach is required that meets the requirements for the future continuous improvement developed above, namely:

- Low individual effort during the process chain of analyzing data until decision making in a fast pace to preempt frequent changes of the production environment.
- Real improvement of processes instead of simple failure prediction and handling.
- Making use of the organization-wide knowledge.

## 3 State of the Art

Most of the different approaches for continuous improvement follow two different streams, namely management- or data-driven. The management- (or experience-driven) CIP is the most researched one. The data-driven approach is growing fast due to new opportunities that come along with Industry 4.0. In the following, existing continuous improvement approaches for both streams are reviewed and evaluated.

### 3.1 Discussion of Existing Approach

Regarding management and experience driven CIP, Rother [4] describes the "Toyota Kata" as the currently most prominent approach. Newer explanations of this approach like "Toyota Kata Culture" or "Leading improvements successfully" share the same concept, that, based on a vision, the current state has to be improved towards a target condition. Working one´s way up on that path will reveal many obstacles, which have to be addressed step by step in the problem solving cycle (respectively the PDCA-cycle). This approach is executed by the employees, driven to learn how to improve their processes daily. In an addition to that, those problem solvers embody the first link of a hierarchy of coachees and coaches, way up to the plant manager. Rother [4] recommends this "Coaching Kata" to further enhance the problem solving ability of the coachees as well as providing a quick escalation and plant overarching goal setting. Hence, those two aspects make this approach very time and resource intensive when applied thoroughly [4, 10, 11].

In the field of data driven improvement, Gröger et al. [12] develop prescriptive analytics for recommendation-based business process optimization at process runtime. Using data mining, the quality output of a product can be predicted via a decision tree for specific processes. The discovered rules of the decision tree are then translated into recommended actions. If during an executed process a metric deviation is predicted, these actions should be taken. This approach focuses on quality issues and how to avoid them, but does not address the challenge of how to improve a process regarding time nor cost. Kassner and Mitschang incorporate unstructured information like pictures or text descriptions into a decision support to handle exceptions on the shop floor. Their described architecture "MaXCept" does this in 5 steps: exception recognition, exception classification, exception escalation, solution recommendation and task-expert matching [13]. Although being intended to be automated and in real-time, their approach is still depending on experts and focuses on solving operational problems on the shop floor rather than addressing process improvement. Ringsquandl et al. [14] introduce a graph-based analytics framework derived from a comprehensive requirement analysis in order to reduce the customization efforts which come along with most advanced manufacturing analytics. Being developed on an architectural level, this approach still requires adjustments to consider extensive domain knowledge like constraints or relations of a specific process into the algorithm [14]. Wuest [15] provides a method applying Supervised Machine Learning to the "product state concept" by incorporating product and process inter- and intra-relations rather than only focusing on individual processes. Using product states consisting of a set of state characteristics enables a product oriented view of the physical value stream. Those characteristics can be altered by process inter- and intra-relations, the so called state drivers. Wuest incorporated this element into the analysis through applying support vector machine-based feature ranking. The results of this method can be used for e.g. quality monitoring and advanced process control. However, this concept is still depending on expert knowledge when it comes to incorporating implicit process inter- and inter-relations.

### 3.2 Deficits of Existing Approaches and Summary

Management and experience driven approaches on the one hand take up too much resources of employees and time regarding the described challenges in the previous section. Data driven approaches on the other hand lag behind when the production environment is changing too quickly. The effort to design and implement a new improvement system or application exclusively for the changed process is surpassing the benefits of the achievable improvements, given the limited time until the same process changes once more [15]. Moreover, the existing approaches focus on predicting quality instead of recommending real process improvement. To overcome the challenges of both streams, a new approach for an efficient continuous improvement process in an unstable and therefore frequently changing production environment is proposed in the following.

## 4 Approach for a Data-Driven Continuous Improvement Process

The novel approach presented in this section combines the advantages of the previously described two directions to meet the requirements stated in the theoretical background. Figure 1 illustrates the three phases of the approach. The aim is to provide tailored solution suggestions to a responsible employee who has chosen a specific process to focus on. Artificial intelligence is used to choose suggestions from the database of previous suggestions. The required input besides already conducted improvements are the organization-wide targets, respectively the broken down ones for the chosen process and its parameters. The following describes the approach of each of the three phases.

### 4.1 Description Model for the Determination and Preparation of Data

The aim of this first phase is to determine the required data and format to prepare this information as an input for the subsequent phases. Therefore, the digital maturity is evaluated based on the index developed by Schuh et al. [16]. To detect the required

| I: Description phase | II: Modelling phase | III: Suggesting phase |
| --- | --- | --- |
| Aim:<br>• Structured and implemented data base | Aim:<br>• Trained predicting model | Aim:<br>• Derivation and suggestion of improvement activities |
| Procedure:<br>• Evaluation of digital maturity<br>• Determination and preparation of data | Procedure:<br>• Retrospective determination of cause-effect relationships<br>• Training and testing | Procedure:<br>• Implement pattern recognition of user stories<br>• Integrate data base and predicting model |

**Fig. 1.** Three phases for identifying suggested improvement action

changes on the quality and availability of the company's process data. Only when the company is ranked on level three or higher the procedure can deliver robust improvements. This level requires an already digitized production while collecting and visualizing data in a manufacturing execution system (MES) [16].

As illustrated in Fig. 2, this phase connects the available process data of the current state with situational data of the respective process environment (e.g., room temperature, humidity, etc.). This information has to be stored together as an event log to be accessible by the system for later comparison with other event logs or choosing the next process to be improved. A complete event log consists of a process use-case, describing the current condition with parameters, KPI's and the respective targets for a specific process, data of the environment, improvement idea and the corresponding results. These often separately stored information can be linked via timestamps and identification numbers. Whenever an improvement idea is performed, it will be saved as a new event log to be available in the constantly growing organization-wide database. Ideas of the past will also be imported likewise.

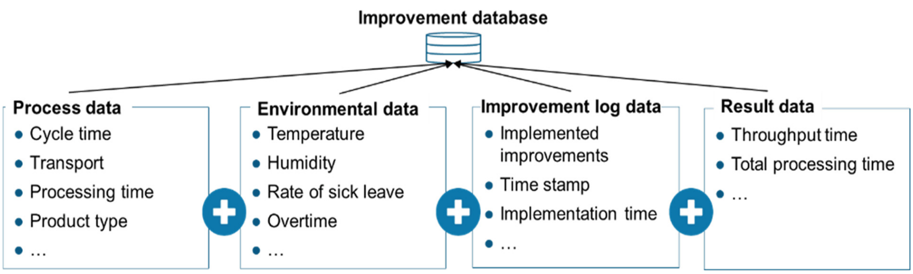


**Fig. 2.** Logic of the merged database of improvement data

### 4.2 Extended Effect Model for Retrospective Determination of Cause-Effect Relationships

One of the objectives of the model in the second phase is to discover unknown or implicit cause-and-effect relations of the production processes. To find these relations and thereby foster better improvement ideas, the second phase integrates the knowledge discovery in databases (KDD) process as described by Fayyad et al. [17] to feed the model. Thereby, unknown relationships between different processes or parameters are added to a library of already known manufacturing-relevant cause-and-effect relationships, for instance provided by Hopp and Spearman [18]. With these discovered relationships new improvement ideas can already be developed at this stage. The results of past improvements will also be added in the suggested format described in Sect. 4.1 to the collection of formulas. The formulas in the library are incorporated into a multi-variant model to work as a digital shadow, which can also be used to forecast situations that have never existed before. Instead of simply feeding and training the multi-variant model with process data, this approach suggests to explicitly train it with the extracted formulas of the library and past improvements in an artificial generated data-set upfront. Later on, the preconditioned model will continue learning currently unknown relations on its own, especially by taking environmental data into account. This way a neural network for instance can focus on new relations in the real data-set instead of having to learn already known relations or formulas from the start.

Figure 3 shows the basic structure of the multi-variant model. The previously introduced model provides process and environmental data as information on the input layer as well as result data on the output layer.

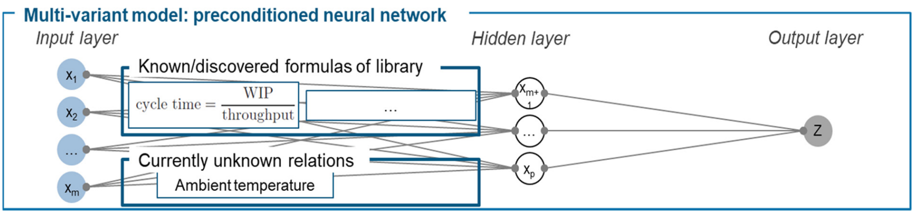


**Fig. 3.** Structure of the preconditioned multi-variant model

### 4.3 Explanation Model for Pattern Recognition of User Stories and Derivation of Improvement Activities

The model of the third phase serves as an indirect interface to the person in charge to improve a specific process. The aim is to suggest the most suitable improvement and its effects, which can be visualized via an individually designable app on a portable devise as the direct interface. The suggestion is based on a similarity analysis between the process to be improved and the event logs in the organization-wide database of already implemented improvements. This phase begins with the description of the actual problem of the production process. The KPIs and parameters of the current state in contrast to the targets reveal a delta and are consolidated in a set of numbers similar to an event log as shown in Fig. 4 on the right side of the input vectors.

This vector is then compared with the vectors of all event logs in the database. This comparison is performed by calculating the distance based on the Jaccard Metric, followed by applying hierarchical clustering to identify clusters of similarities. These will select the most similar event log by comparing the vector of the selected process and the ones of all event logs. Thereby, similar processes with the smallest vector-variations

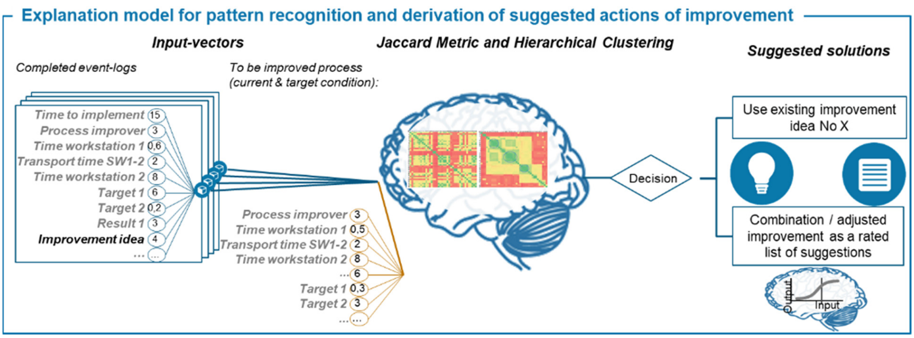


**Fig. 4.** Logic of the model to suggest improvement actions

(e.g., parameters, KPIs, targets or environment data) are suggested. The effect of those variations on the future result are then predicted by making use of the second model. The final model might also suggest applying two different improvement ideas at the same time if the delta between the current and the target state is too big for only one existing improvement solution. The hierarchical clustering allows the person in charge to choose from a set of different options suggested by the model. After implementing one of the suggested improvement ideas, the idea and its outcome are integrated into the database and constitute to a new event log.

## 5 Conclusion

Given the opportunities of Industry 4.0, the continuous improvement process can hugely benefit by incorporating the right algorithms and an advancement of the methodology. Besides improving required efforts this approach also enables an easy way to harvest historical data for recommendations and to turn implicit or even unknown process knowledge systematically into explicit organizational knowledge. If not yet documented, this approach helps to start filling up the organizations database with first improvement ideas in a structured format, which of course will take some time to reach a beneficial quantity. Further research should focus on the industrial application of this approach, which initially requires a detailed design of how to realize the three phases, and identify contingencies for different environments and industries.

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# Lean Leadership in Production Ramp-Up

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**Abstract.** Today's production systems are complex sociotechnical systems. Especially during the production system ramp-up phase, which is of particular importance in terms of ensuring a timely, qualitatively and cost efficient market entry, both technical challenges, as well as the integration of human employees with their diverse abilities, wants, and needs, must be considered. Due to a growing number of product variants, shorter lead times, and global supply chains, planning and launching production systems can be seen as a competitive advantage. Consequently, managing the period of production system ramp-up, which is characterized by high production demand but low production control, becomes increasingly important. To handle the increasing complexity and uncertainty in this special phase, human decision makers must be adequately supported by an appropriate leadership style. In this paper, the Lean Leadership approach will be identified to best meet the special requirements of the socio-technical production system ramp-up phase. The results of a mixed-methods data collection, which has been conducted in commercial vehicle industry, help to better manage complex product launches in the future.

**Keywords:** Production system · Ramp-up · Leadership

## 1 Introduction

In times of rising customer requirements and increasing globalization, products as well as the associated production systems need to be adjusted or redesigned in increasingly shorter time periods. This is necessary in order to ensure the timely market rollout of the new products. Consequently, the cost-efficient, high-quality and timely management of production system ramp-ups becomes a competitive advantage for organizations in the future. A production system can be described as a complex socio-technical system in which human, organizational as well as technical aspects need to be coordinated in order to create value [1]. A production system ramp-up, in turn, can be seen as the phase in which the complex socio-technical system needs to be transferred from an uncertain and instable state into a stable series production state [2, 3].

Taking into consideration that each production ramp-up phase is unique, has a defined beginning as well as a defined end point and is measured by its degree of fulfillment of certain objectives, such as quality, time or costs, it can be regarded as a project. The following definition in the DIN 69900-5:2009 says that a project is an "initiative that is characterized by the uniqueness of its conditions as a whole" [4]. Given that a production ramp-up can be described as a project, ramp-up management,


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in turn, can be compared with project management. Regarding DIN norm 69901-5:2009 project management is defined as “all leadership tasks, -organization, -techniques, and -means that are necessary for the initiation, definition, planning, steering and completion of projects” [5]. Consequently, it can be derived that the role of leadership is of special importance for managing unstable and uncertain production system ramp-up phase.

## 2 Production System Ramp-Up – A Socio-technical Perspective

In general, production ramp-up can be described as the link between product development phase and the series fabrication process. It represents an important integral function when it comes to the physical implementation of a products’ value-added processes in the overall product development process [6]. As shown in Fig. 1, the ramp-up phase builds upon the development phase, which includes the product development as well as the development of the processes and the production system.

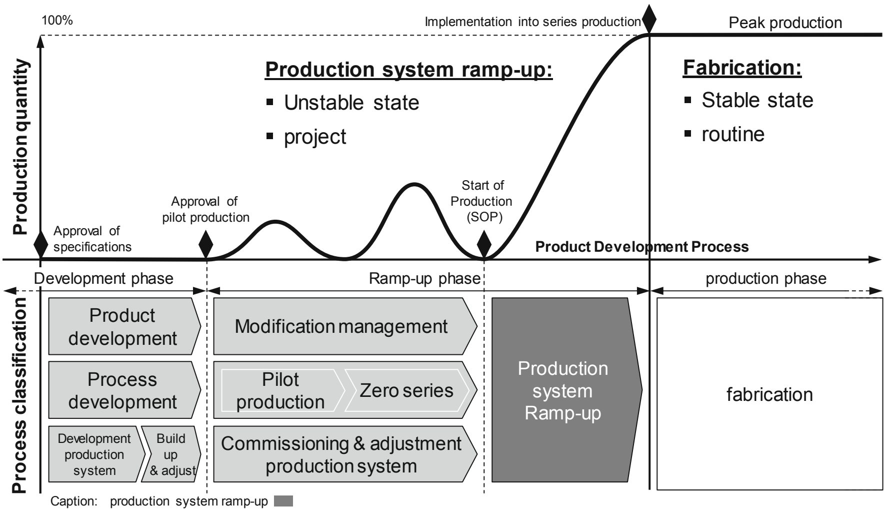


**Fig. 1.** Process organization of production ramp-up, based on [6–9]

Within the ramp-up phase focus is on the coordination of objects and functions in order to successfully complete the pilot production phase, the zero series production phase, the phase of commissioning and adjustment of the production system as well as the modification management phase. After fitting and setting up all product-, process- and organization-specific requirements, start of production (SOP) follows [10]. In the subsequent production system ramp-up phase, production quantity is raised. Two conflicting factors are characteristic of this period: low production capacity, and high demand. High demand arises because the product is still relatively new and might even be the first of its type. Thus, customers are ready to pay a premium price. However, output is low due to low production rates and unforeseen disturbances. The production process is still instable and socio-technical systems interactions are poorly understood [11]. Machine break downs are unexplainable, humans do not have practical knowledge, special operations are needed to correct product and process oversights, and other factors impede output. Over a certain time, the organization has to learn about the production processes and equipment so that yields and capacity utilization increase [12]. In case that the required production quantity is reached the production system ramp-up phase is finished and series production phase begins (compare “peak production” in Fig. 1).

The aforementioned explanations show that the production system ramp-up phase is of special importance for the whole product development process since it is the first time that the complex socio-technical production system needs to perform under pressure [13]. All possible failures from previous process steps, such as the product and process development phase, that could not be anticipated or identified in the planning process will come to light and result in costly delays of the time-to-market span (compare Fig. 1) [9].

According to Wiendahl [6], the production system ramp-up phase can be defined as follows: “In production system ramp-up phase, all system elements in the production system will be brought to full capacity under consideration of nominal, personnel, organizational and technical conditions. Therefore, optimization and stabilization of operational performance in terms of human oriented, organizational and technical inadequacies necessarily need be done in this special phase. “It becomes clear that, once implemented, the technical subsystem is rather rigid and inflexible. Therefore, in terms of joint optimization and appropriate reaction in case of unforeseen disturbances, the social subsystem with its human elements plays a vital role in production ramp-up management [15]. All ramp-up involved personnel must be guided appropriately in order to be resilient towards disturbances by developing abilities that enable to anticipate, monitor, react and learn from failures within the production system (Fig. 2).

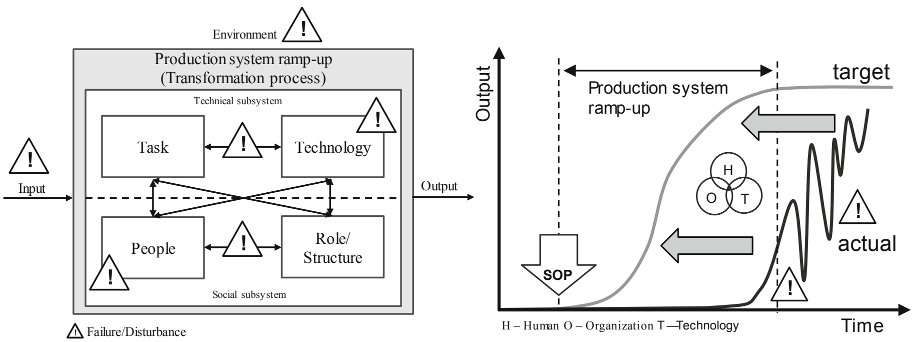


**Fig. 2.** Instability in socio-technical production system ramp-up, based on [14]

## 3 Lean Leadership – Principles and Its Application

Whereas technical elements, such as machines or processes, can be reconfigured and reorganized easily, the reorganization of people and the creation of value-adding mindsets is nontrivial. Therefore, in context of series production in lean production systems, a people-oriented leadership style has evolved to state of the art. Several authors acknowledge that the Lean Leadership (LL) style is the important aspect in implementing and supporting a culture that focuses on value-adding, customer orientation and continuous self-development [16]. According to VDI guideline 2871, LL is defined as a *"company specific, methodically set of rules and methods for goal-oriented leadership in order to sustainably implement and continuously improve a lean production system"* [17]. The basic design principles of lean leadership as well as their application are listed in Fig. 3.

| Lean Leadership principles and its application | | |
|---|---|---|
| 1 | Culture of improvement | ▪ Striving for perfection<br>▪ Thinking in target states<br>▪ Problems and failure as source for improvement |
| 2 | Gemba | ▪ Leaders showing their presence on shopfloor (Go&See)<br>▪ Appreciation and respect for employees<br>▪ Fact based decision making |
| 3 | Coaching/ Qualification | ▪ Employees' competence development on the job<br>▪ Empower people for independent problem-solving<br>▪ Continuous learning through practical routines |
| 4 | Participation | ▪ Involvement of employees in problem-solving processes<br>▪ Use of tacit, implicite knowledge<br>▪ Raise acceptance for change initiatives |
| 5 | Self-development | ▪ Continous re-learning of leadership skills<br>▪ Development of situational leadership skills<br>▪ Leadership behaviour serves as a role-model |

**Fig. 3.** Lean Leadership: Principles and its application (acc. to [17])

Similar to the general structure of lean production systems, LL orientates towards goals, processes, design principles, methods and tools [17]. As an example, LL can help to improve the KPI *"product quality"* by focusing on the principle *"coaching"*. Special guidelines help Lean leaders encourage people to build competences on the job or empower employees to solve problems independently (compare [17]). As a result, LL helps to set up a culture of continuous improvement and enables people in complex socio-technical systems to become problem solvers and decision makers in order to improve processes decentralized, independently and on a daily basis. Since implementing Lean and LL is time-consuming, the initiatives often only start up subsequently to the ramp-up project when fire-fighting is over and stable state of production has been reached. However, as Dombrowski [7] has shown with the "Lean Ramp-up" approach, the application of certain Lean tools and methods can be also very beneficial in the instable production system ramp-up phase. Regarding the Lean Leadership principles and its application areas in the context of special characteristics of the production system ramp-up phase, it becomes obvious that a similar leadership approach might also be beneficial in terms of reducing the time-to-market span by jointly optimizing social and technical subsystem.

## 4 Lean Leadership in Production System Ramp-Up

### 4.1 Research Design

To answer the research question, whether the application of Lean Leadership might have potential for the production system ramp-up phase, a mixed-method data collection approach was conducted in a components facility of a big German commercial vehicle manufacturer [18]. First, a short self-administered questionnaire was designed including the question whether the five Lean Leadership principles, all 15 associated sub-elements as well as the ten guidelines presented in VDI guideline 2871 have *5 – much more, 4 – more, 3 – as much as, 2 – less, 1 – much less* potential in production ramp-up phase compared to series production phase (compare 5-point Likert-type scale in Fig. 4). Since Lean Leadership has shown it applicability in series production in various industries and is equally important throughout the whole production system lifecycle, the questionnaire did not aim at investigating whether the principles are more or less *important* in any of the phases. Instead, the investigations shall rather give notice that some of the principles have even higher *potential* to cope with special characteristics of the phases, such as higher uncertainty in the instable production ramp-up phase. To control the bias in the quantitative data collection, the participants were chosen from a broad range of disciplines and professional background. Thus, the results shown in Sect. 4.2 represent the opinion of representatives of operational and other ramp-up involved business segments, such as blue collar workers, managers of operational segments, higher managers being decision-makers in ramp-up projects, other personnel involved in ramp-up projects and people that are currently not involved in ramp-up projects. While selecting the participants it was ensured that he/she is able to draw on experience in working in production ramp-up phase as well as series production phase, in order to get an experience-based answer from the participants. The total sample size that completed the survey is n = 58 whereby all groups of participants were approximately evenly distributed. Additionally, in order to explain the purpose of the study and to gain further in-depth understandings, a qualitative semi-structured interview was conducted with each participant before and after filling out the questionnaire. The purpose was to deepen the participants' understanding on the different characteristics of the series production phase and the production ramp-up phase as well as the LL principles and guidelines in order to ensure that they can objectively assess the potential on the Likert-type scale. At the end of the mixed-method data collection approach the participants were asked to assess the suitability of the existing LL approach for the production system ramp-up phase. On another 5-point Likert-type scale they had to estimate whether the LL approach needs to be adapted to the special characteristics of the production system ramp-up phase (5 – fully agree, 4 – agree, 3 – do not know, 2 – disagree, 1– fully disagree).

### 4.2 Results

The survey results are illustrated in Fig. 4. The bar chart on the left hand side shows the potential of Lean Leadership principles and guidelines in production system ramp-up phase relatively to series production phase. For each of the five principles the arithmetic means have been calculated from the estimates of n = 58 participants. In general, from the data analysis it can be derived that there is clear evidence that the application of the principles has high potential for production system ramp-up phase (all mean values $\bar{x}_{1-5} > 3{,}8$). In particular, *Coaching/Qualification* and *Participation* with a mean value $\bar{x} > 4.0$ were identified to be very beneficial for the production system ramp-up phase. Especially the sub-elements *"Employees' competence development on the job"* ($\bar{x} = 4.50$), *"Striving for perfection"* ($\bar{x} = 4.28$) as well as *"Involvement of employees in problem-solving processes"* ($\bar{x} = 4.22$) were considered to have very high potential in production system ramp-up phase. The results of the other 13 sub-elements of the principles are not part of this publication.

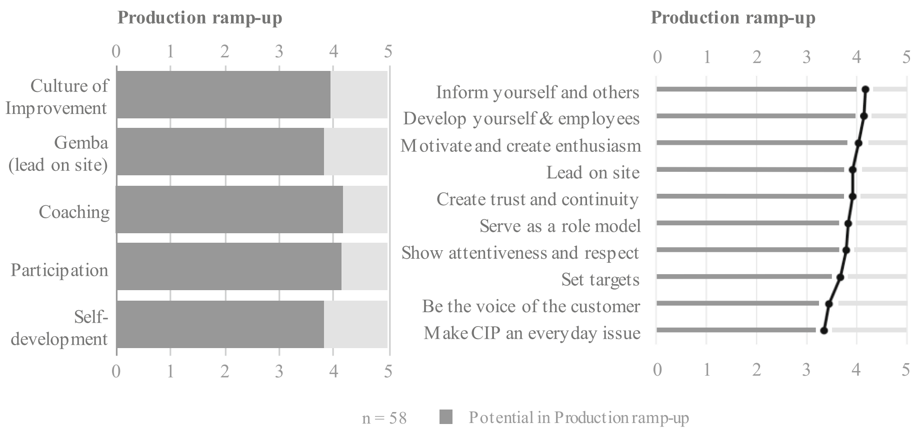


**Fig. 4.** Potential of Lean Leadership principles & guidelines in production ramp-up phase

In order to identify applicable recommendations that can be helpful for better managing sociotechnical system ramp-up, the survey participants were also asked to assess the potential of applying the Lean Leadership guidelines in production system ramp-up relatively to series production on the 5-point Likert-type scale. The results can be seen on the right hand side in Fig. 4. Especially the leadership tasks *"Inform yourself and others"* ($\bar{x} = 4.17$) and *"Develop yourself and your employees"* ($\bar{x} = 4.14$) were identified to have high potential in the production ramp-up phase. With an average mean value of $\bar{x}_{1-10} = 3{,}83$ all recommendations should be especially focused in ramp-up projects in order to optimize the instable sociotechnical system. Therefore, in their descending order the presented guidelines should serve as a basis for the development of a ramp-up specific LL orientation that focuses on transparency, employee development, problem-solving and participative value creation. The need for adapting the existing LL approach by prioritizing certain principles and guidelines was also emphasized by the survey participants. With a mean value $\bar{x} = 4.07$ the 58 respondents agree that the LL approach needs to be adapted to the special requirements of the production system ramp-up phase.

## 5 Conclusion

Since it is the first-time interaction of the planned technical subsystem and the social subsystem, the production system ramp-up phase can be characterized by its high complexity and uncertainty. In order to ensure a timely, qualitatively and cost efficient market entry, both technical challenges, as well as the integration of human employees with their diverse abilities, wants, and needs, must be considered in a ramp-up project. Consequently, decision makers in production ramp-up phase must be adequately supported by an appropriate leadership style. In this paper the results of mixed-method data collection approach at a components facility of a German commercial vehicle manufacturer indicate that the Lean Leadership approach, which has proven to be very supportive in series production, can be also beneficial to meet the special requirements of the socio-technical production system ramp-up phase. Strong focus on *Coaching/Qualification* and/or *Participation* as well as the consideration of leadership guidelines, such as *"Inform yourself and others"*, have been identified to be very helpful. Based on the findings in this paper, future research work in the field of production system ramp-up should not only concentrate on technical aspects, but on the joint optimization of socio-technical production ramp-up systems. Therefore, the application of human-oriented concepts, tools and methods, such as an appropriate leadership style, is just as important as the application of organizational aspects or technologies in order to increase resilient behavior of production system ramp-up phase. The development of an approach that allows to purposively adopt existing LL principles and guidelines (that focus on series production so far) as well as the prioritization of principles that are of special importance in different phases of the production system lifecycle (e.g. in the production ramp-up phase) can be a valuable contribution to better manage production ramp-up projects in the future.

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# No Lean Without Learning: Rethinking Lean Production as a Learning System

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**Abstract.** It's one of the most popular and most misunderstood business concepts of our time. Since the term Lean Production was first popularized in 1990, lean has come to mean very different things to different people. In this paper, we go back to the origins of Lean Production - an alternative business approach pioneered by Toyota Motor Corporation - and present insights into how Toyota actually developed a learning system to gain competitive advantage through the continuous development of people, rather than simply designing and optimizing an efficient production system. We draw on our observations from Toyota plants around the world and our discussions with various Toyota sensei, and present a framework for understanding lean as a learning system, *not* a production system.

**Keywords:** Lean Production · Toyota Production System · Total Quality Management

## 1 Introduction

Lean Production has a research history spanning over 30 years. Yet, it is still a puzzle why some companies and CEOs who adopt Lean Productions tools and principles experience extraordinary business results, while others experience little or no improvement, at best exhibiting only marginal gains in operational performance.

In *the Machine that changed the World* [1] the authors present Lean Production as a complete business system, consisting of five parts: Dealing with the customer, Designing the car, Running the factory, Coordinating the supply chain, and Managing the (lean) enterprise. Yet, Lean Production is still mostly associated with efficient production and operational excellence. Because the systematic learning practices of Toyota consist of tools and principles, it becomes easy for companies and CEOs who operate in the business paradigm of design-execute-optimize to turn these tools and principles into one-time improvements to their production system by interpreting Lean Production simply as a set of best practices that can be implemented to achieve operational excellence.

There are many different paths to new value creation, to realize products and services that will create value for both the customer and the producer. For example, one


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can introduce a product or service that is radically different to what has ever been offered before, and then optimize the delivery process for that particular product or service until defunct. On the other hand, it is possible to incrementally change an existing product to deliver more functionality at lower cost. Often, Lean is thought of as simply a method for optimizing flow in the design, manufacturing and delivery process, and has even been critiqued as a hinderance of innovation [2].

In this paper we present Lean as a different paradigm, based on the assumption that Toyota asked themselves a different question from the outset. Instead of asking; "*how do we optimize the design, manufacture and delivery of our products?*", they asked themselves; "*how can we create, manufacture and deliver ever better products by learning and evolving from one change to another, always looking for the next step?*" [3] This paper identifies four separate learning systems that each serve a different purpose. The basic questions underpinning these systems are: How to create a constantly evolving product line? What to keep and what to change when developing new products? How to constantly and consistently look for the next step? And how to make the managerial organization change its response as the company evolves?

## 2 Literature Review

After over 40 years of research into the operational and managerial practice of Toyota and 30 years of research on Lean Production there is an abundance of literature that presents these practices [cf. 3], the adoption of such practices into different companies or different industries [5, 6], how to implement these practices [7–9], what to expect from adopting them [10, 11], and how these practices influence worker conditions [12, 13].

The research that has studied Lean Production and learning simultaneously has usually focused on the evolving understanding of Lean Production. For example, [14] describes the evolution of the understanding of Lean Production, concluding that a separation of the strategic and operational aspects of lean is needed. Another example is [15] which discusses the history of the International Motor Vehicle Program (IMVP) that gave rise to the term Lean Production, highlighting the key events of the development of car production and the major publications that chronicled them.

There is also a body of research on organisational learning in general [cf. 16]. Some of this research was based on case studies of Japanese companies in the quality management tradition [17]. However, this body of research has not explicitly looked at the practices of Toyota as a system of organisational learning per se.

Fujimoto, one of the first researchers who studied lean as a learning system [18] described the evolutionary learning capabilities of the Toyota Production System, and how they built on the practices of American automakers and from their experiences with producing automatic looms. Toyota further developed a system that enhanced the learning capabilities of its people through smaller lot sizes, and the experimentation needed to develop in-house design and production capabilities [19].

By looking at Lean as a *learning* paradigm, the tools and techniques can be seen as accelerators for learning rather than as a means for achieving operational excellence, showing where and what we need to improve [20]. The improvements are realized by the people working in the system, not by the tools themselves. In fact, Some Toyota veterans refer to TPS as the *Thinking People System* - a system for continuously developing people through problem solving [21] placing greater emphasis on the suggestion that *"Toyota makes people before they make products"* [22].

Toyota's practices are both "hard", allowing the company to constantly develop its technical know-how in design and manufacturing, and "soft"; an organisation open for criticism, where there is enthusiasm for improvements and a focus on developing employees [23]. These practices create a learning environment for self-testing and adoption [24] where the emphasis is not on process efficiency, but instead on developing the technical and creative skillsets of the company's workers and managers – skillsets that are critical for sustained innovation [25]. The emphasis on learning is what drives innovation in both design, engineering and manufacturing, and what allows Toyota to align the organisation by engaging *"all the people, all the time, everywhere*" [26].

## 3 Research Design

This is a conceptual paper based on an exploratory investigation of Toyota Motor Corporation (TMC), drawing new insights from the observations of the authors during site visits, from the available literature that describes Toyota's business practices, and from semi-structured interviews with current and former company employees from various functions in the organization – including product planning, product development, production and quality management. In addition, we draw on our practical experience with lean implementations in various industries and companies worldwide.

## 4 Lean as a Learning System with Four Distinct Sub-systems

Through our research (as a process of discovery), we have gradually come to recognize lean as a learning system. In this process of discovery, four distinct sub-systems emerged, each serving a different purpose:

- Product Planning (PP) system – how can we learn what products to improve or introduce next to make each customer a life-time customer?
- Toyota Product Development System (TPDS) – how do we keep in touch with customers evolving needs and better understand what to keep and what to develop or discard in each product?
- Toyota Production System (TPS) – How can we continuously look for the next step?
- Total Quality Management (TQM) – How do we develop the management and back-office practices that are needed to support the other three learning systems?

The Lean Product Planning system has more recently been exemplified by Apple, a company that, as if by clockwork, introduces new products each year in September. Some products will go through a full update of specifications and features, while others will have smaller, sometimes cosmetic changes made to them. Ever since Toyota and the other Japanese car companies decided to compete in all segments, as opposed to dividing the different market segments between them, Toyota has constantly sought to learn how to make a *first-time customer* a *life-time customer;* whereas other companies have sought to be efficient in their use of capital and assets by constantly looking to shed older products and/or move away from unprofitable market segments. Toyota has constantly evolved its range of products, while efficiency of capital and assets are driven by Value Analysis and Value Engineering (VAVE), a fundamental part of the Target Cost planning system [27]. **The core learning challenge for the Product Planning system is how to constantly evolve the product line-up such as to never lose a customer.**

When Toyota set out to design and develop its own automobiles, they did not start by licensing American or European models. Instead, they set out to learn how to design automobiles from scratch. Exemplified by the 12 generations of Corollas designed and manufactured for almost 60 years, the Toyota Product Development System (TPDS) builds on generations of acquired engineering know-how that is recorded and kept in the form of A3 reports and concrete technological learning curves [26]. **The core learning challenge for this system is to discover what to keep and what to change** (Approx. 70% of an existing product remains untouched in the next version [27]).

Instead of creating a production system from scratch, Toyota set out to create a revolutionary learning production system that built on the industrial engineering breakthroughs of Ford, GM [18], and German aircraft manufacturers [15]. However, instead of just adopting best practices, we believe that Toyota developed its production system practices by continuously looking for the next step. First, by mechanically connecting each process with its direct customer through Just-in-time and the Kanban system in order to foster continuous improvement through respect for people and full worker participation [28]. Second, by reducing changeover time in order to reduce batch sizes and reduce the lead-time between order and delivery on each internal Kanban; and third, by creating a system of visual control (Andon) to stop and fix defects at the point of discovery [29]. Indeed, from our discussions with current and previous Toyota employees, we understand **the core learning challenge of this system is satisfying the conditions of basic stability, just-in-time, jidoka, and employee satisfaction by encouraging the constant search for the next step of lead-time reduction, flexibility-enhancement, cost-reduction and quality-improvement, made possible by the continuous development of all employees, at all levels. This will lead to higher customer satisfaction.**

Finally, after discovering that the rate of quality improvement did not keep up with the rate of productivity improvements, Toyota accepted the challenge from Ishikawa and Deming to build quality into the product at the design stage, by creating a system of quality assurance, rather than inspecting poor quality out of the system after production [30]. This Total Quality Management (TQM) system evolved from the early 1960s into "The Toyota Way" [3] and represents the fourth learning system. **The core learning challenge of this system is how to support the development of *zero defect thinking* amongst managers and back office staff – in addition to front line associates**.

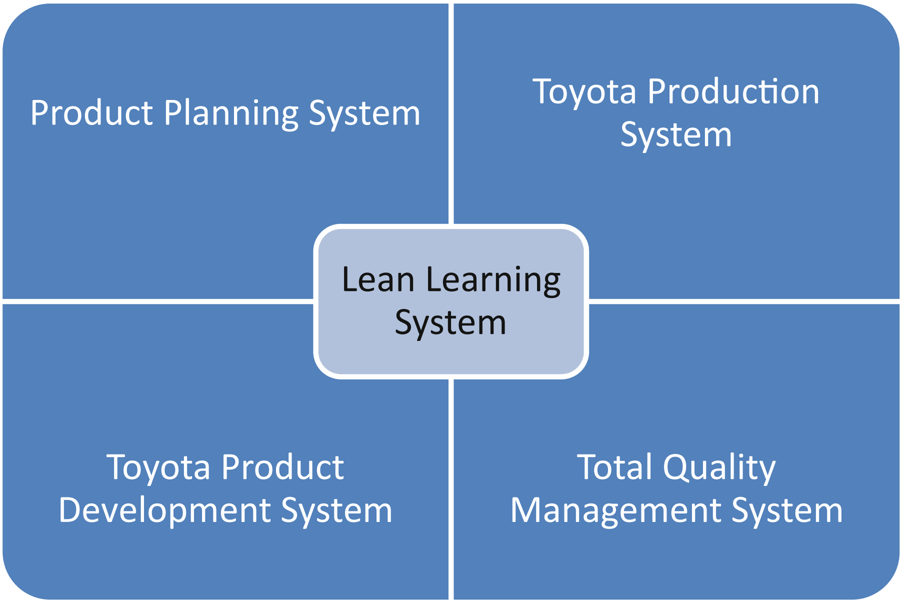


**Fig. 1.** Lean learning system: four distinct sub-systems

## 5 Conclusions

Based on the findings, we are able to reframe Lean Production as a learning system, consisting of four distinct sub-systems (see Fig. 1). The sub-systems are by no means discrete but are profoundly integrated and intertwined throughout the organization as an organic entity. The learning sub-systems described herein consist of both principles and tools that aim to deepen thinking and experimentation. Understanding and adopting both is critical to the success of the *lean enterprise*. Ignoring the principles and simply copying the tools and adopting them as best practices often leads to unsatisfactory results and discontinued lean implementations, yielding little learning and at best offering only point optimization. The learning system as presented in this paper represents the findings from looking at Toyota's principles and practices together from the lens of a learning paradigm. With the continuous development of people at its core, such a learning system promises to build improved organizational capabilities through a resolute process of continuous experimentation and learning.

We suggest that this article has implications for both theory and practice. Firstly, with regard to theory, we reframe Lean Production as a learning system, by drawing on insights from Toyota Motor Co. as the de facto exemplar of the *Lean Learning System*. This promises to help academic researchers to understand the real reasons for the success of Toyota - a company that exhibits the sales volumes of Volkswagen combined with the 'boutique' profitability of BMW.

Secondly, for practice, we suggest that by rethinking Lean Production as a learning system to continuously develop people (throughout the entire enterprise not just factory floor operations) through promoting structured problem solving and improvement using deep thinking, reflection and experimentation, organizations may be better prepared to realize the true potential of a successful lean transformation, reducing the otherwise high rate of failure reported for so-called “lean implementations”. This is achieved in practice by actively discovering what one needs to learn to solve the next problem, rather than simply planning to implement the next *best practice* from the lean *toolbox*.

Understanding that lean is *not* a production system but rather a system for continuous improvement and learning is essential for business success in the future. After all, improvement without learning is not lean thinking [31].

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# The Effect of Team Size on the Performance of Continuous Improvement Teams: Is Seven Really the Magic Number?

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**Abstract.** Continuous improvement teams play an essential role when implementing a corporate improvement programme, the success of which is significantly dependent on the organization of such teams. This paper specifically addresses the effect of team size on the performance of continuous improvement teams. We take insight into a Norwegian case study during the first two years of a lean transformation to explore if there are any indications of an optimum size for continuous improvement teams. The results suggest that there may not be a perfect size for a CI team, rather the performance outcome of different sized teams may depend on the maturity level of the lean programme. Whereas in the establishment phase teams of up to twelve employees seem to perform well, this number appears to reduce when the programme matures. This study may therefore assist practitioners in establishing the right team size dependent on the status of transformation.

**Keywords:** Lean production · Team size · Team performance · Continuous improvement

## 1 Introduction

Since the term "Lean production" was popularized in The Machine That Changed the World [1], lean thinking has arguably become the most successful approach to business improvement of our generation. What is generally agreed to have begun in the automotive industry based on the management philosophy and working practices demonstrated by the Toyota Production System, lean thinking has now been adopted in most manufacturing environments, as well as construction, healthcare, government agencies, and higher education establishments to name just a few examples.

In order to adopt the lean management philosophy successfully, many companies have developed their own "company-specific production systems" or "corporate lean programmes" [2]. The successful deployment of such programmes is dependent upon a number of critical success factors, including management support and commitment [3], becoming a learning organization via constant reflection and continuous improvement [4], and the holistic adoption of lean as the new management "way" [5]. The latter is


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considered to be largely reliant upon a resolute process of continuous improvement, where a team-based organizational design has been promoted as an effective means for a successful continuous improvement process [6]. The collaboration of this team-based improvement process is operationalized through regular (e.g., weekly) meetings, directly on the shop floor. However, little is known regarding the ideal size of a continuous improvement team. This begs the question amongst researchers and lean program coordinators alike: How big should a continuous improvement team really be? To shed light on this topic, we pose the following research questions (RQs):

**RQ1:** ***How does the size of a continuous improvement team affect team performance?***
**RQ2:** ***Is there an optimum team size for continuous improvement teams?***

While the limited research on optimal team size is not conclusive, it does tend to suggest that a team size in the range of five to 12 team members is optimal. Nieva et al. go so far as to suggest that a team of seven is the best [7]. Many consultants also advocate that seven is the optimum size for a continuous improvement team, particularly in the field of agile (e.g. [8]), but is this really the case? Is seven really the magic number?

There are of course seven days of the week, seven colours of the rainbow, seven notes on a musical scale, seven seas and seven continents. Snow White ran off to live with seven dwarves, and there were seven brides for seven brothers. Whilst seven appears to be a very popular number in society, this paper explores if seven really is the optimum size for a continuous improvement team.

## 2 Literature Review

### 2.1 Lean Production and the Importance of Teams

Lean production stems from the management philosophy and working practices of the Toyota Production System, which has been defined in terms of three fundamental constructs: Just-in-Time, Jidoka, and the Respect-for-Human System [9]. The respect-for-human system is essential for the success of any lean programme, and requires management support and engagement as well as the subsequent empowerment of all employees.

Given that an organization's top- and middle management have pledged their full support and commitment to its corporate lean programme, the success of the lean deployment then becomes firmly rooted with the front line managers in the continuous improvement teams, at the lowest hierarchical level of the firm [10]. This is because continuous process improvement is difficult to achieve without the cooperation of front line workers, in particular the generation of their improvement ideas and improvement implementation efforts [11]. As such, a continuous improvement team can be defined as (a) a group of two or more individuals, (b) who cooperate to deliver one or more core product(s) and/or service(s), (c) with the shared goal of eliminating waste and increasing customer value (adapted from [12]).

### 2.2 Effective Team Organization

Several authors present a detailed review of the performance and effectiveness of teams in work organizations, and consider several key factors for team effectiveness, including team cohesiveness, team composition (e.g. homogeneity/heterogeneity of the group), quality of team leadership, motivation, and clarity of group (team) goals. For example, Magjuka and Baldwin identified factors thought to contribute to the effectiveness with which employee involvement teams are designed and implemented [13]. They found that larger team size and greater access to information were positively associated with team effectiveness. This brings into play questions regarding the effect of team size on team performance. If Campion et al. [14] also found team size to be positively related to effectiveness, why should we believe that the optimum team size is seven?

### 2.3 Team Size

In sports, teams have a specific number of team players: football teams have 11 players, rugby teams have 15, and basketball teams have five. In the case of work teams, however, it is a little more complex. There is no hard-and-fast rule to determine the optimum size of a team. At Toyota, production employees are typically assigned to groups of 20–30, each with a group leader. These groups are then further subdivided into teams of 5–7, including a team leader [15]. Alternatively, in Agile Software Development, Rising & Janoff state that Scrum advocates the use of small teams, preferably 7 team members ($\pm 2$) and certainly no more than 10 [16]. Ironically, in the game of Rugby Union, a scrum is a formalised and heavily structured (i.e. non-creative) set piece that consists of eight forwards per team.

Though several researchers have analysed the effect of team size on the performance of teams across different organizational settings, it remains unclear as to the significance team size has on the performance of the team. This is due to an array of inconsistent and inconclusive results as illustrated in Table 1. For example, Katzenbach and Smith suggested that work teams should contain a dozen or so members [17], whereas Scharf suggested that seven was the best size [18]. A variety of other such recommendations are easily found in the extant literature, often with opposing views. Some research suggests that size has a curvilinear relationship with effectiveness such that too few or too many members reduces performance [7], whilst others suggest that increasing team size actually improves performance without limit [14]. Haleblian and Finkelstein also found that firms' performance was better when [top- management] team size was greater [19], whilst Behrens asserts that small teams tend to be more productive [20]. Useem even goes so far as to state that a small team size of precisely 4.6 team members is in fact the optimum [21]. Other studies have simply found team size to be unrelated to performance [22, 23].

Kozlowski and Bell conclude that overall, the question of the "optimal" group size is a complex one and future empirical research is needed to determine the impact of team size given specific team contingencies, such as the nature of the team's task [12]. This research therefore sets out to contribute to the field by examining the impact of

**Table 1.** Suggested team size by different studies

| Reference | Context | Suggested team size |
|---|---|---|
| Useem (2006) | Business teams | 4.6 |
| Liker and Meier (2005) | Lean teams | 5–7 |
| Scharf (1989) | Work teams | 7 |
| Rising and Janoff (2000) | Scrum teams | 7 (±2) |
| Katzenbach and Smith (1993) | Work teams | 12 |
| Magjuka and Baldwin (1991) | Work groups | The larger the better |
| Campion et al. (1993) | Work groups | The larger the better |

team size on the performance of continuous improvement teams during the deployment of a corporate lean programme.

## 3 Research Method

This empirical study examines the impact of team size on the performance of continuous improvement teams during the initial stages of the deployment of a corporate lean programme. The research method for collecting and analysing data is the case study method [24, 25]. Data was collected at the case company by way of participant observation – allowing the researcher unlimited use of open-interviews and open-access for the analysis of company documentation. By taking such a role, the quality of the data collected as well as the results of the analysis was increased due to the inherent inside knowledge of the company.

The case company in question is a Norwegian producer of hydro-acoustic sensor systems. Due to increasing competition from low-cost suppliers, in 2014 the case company began its lean journey through the deployment of a corporate lean programme, which itself is based on five fundamental lean principles, one of which is Continuous Improvement. In order to operationalize this principle, continuous improvement teams have been formed throughout the organization.

The continuous improvement teams meet weekly in front of team-specific Kaizen boards to discuss identified problems and improvement suggestions. The teams are encouraged to focus on small, simple improvements rather than larger project-type improvements, and as such are measured on the number of completed improvements, per employee per month (pepm). Larger project-type improvements are subsequently broken down into smaller individual tasks, making the data more comparable from team to team. The number of employees in each team varies across the teams. It is therefore interesting to examine the performance of teams in relation to team size. This study addresses six different continuous improvement teams of varying team size over a two year period (2015–2016).

## 4 Results

The following results are derived from six different continuous improvement teams and during the first two years of a lean deployment. The analysis is limited to six teams, as these teams are all organized under the same middle manager (the production manager), and all team members carry out manual assembly and test type work (Table 2):

**Table 2.** Number of completed improvements (PEPM) per team, 2015 & 2016

| Team | 2015 | | 2016 | |
|---|---|---|---|---|
| | Size | PEPM | Size | PEPM |
| A | 7 | 1,3 | 6 | 2,5 |
| B | 12 | 2,1 | 10 | 2,9 |
| C | 17 | 1,4 | 15 | 1,4 |
| D | 4 | 0,5 | 5 | 1,6 |
| E | 13 | 1,5 | 12 | 2,0 |
| F | 17 | 0,7 | 13 | 1,1 |

The results are interesting from several perspectives. Firstly, with the exception of team C, all teams reported more improvements in the second year. Secondly, all teams (with the exception of team D) encountered a reduction in team size during the investigation period. This was a consequence of a strategic downsizing process due to the increasingly difficult market conditions experienced by the case company. In spite of this, however, there was still a marked improvement in the number of implemented improvements in the second year. Thirdly, and perhaps essential for this investigation, is the result shown in Fig. 1. It appears that there is in fact an optimum team size for effective continuous improvement process, though the result indicates that this may in fact lessen with an increase in lean maturity.

In line with the conclusions of [7], Fig. 1 suggests that team size has a curvilinear relationship with team effectiveness, such that too few or too many members reduces performance. It shows an overall trend for greater team performance with a team size between (approx.) seven and 12. Interestingly, the "sweet spot" appears to become more prominent with a higher level of lean maturity (i.e. in year two of the investigation). In this case, it would appear that nine is the "magic" number. Furthermore, and regardless of the maturity level of the teams evaluated, there does appear to be an accelerated decline in team performance as team size increases beyond 12 members.

From the results of this research, we can make several propositions:

**P1.** Team size seems to have a curvilinear relationship with team performance such that too few or too many members may reduce performance (as also suggested by [7]).

**P2.** A team size greater than 12 may result in a significantly reduced level of team performance. (Contrary to the findings of [13] and [14])

**P3.** For organizations in the early phases of a lean implementation, larger continuous improvement teams may provide the basis for greater team performance.

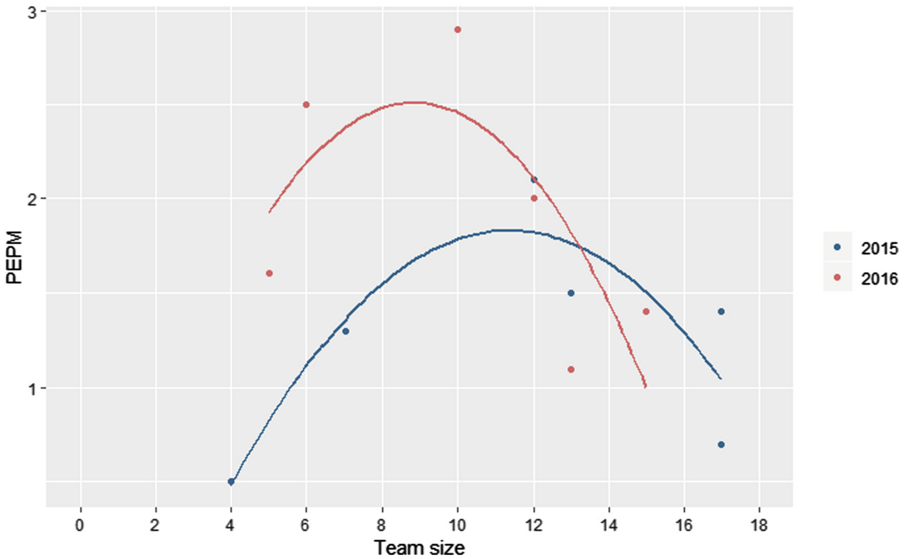


**Fig. 1.** PEPM in relation of team size

**P4.** As the lean programme develops and matures, a slight reduction in team size may allow for more effective team performance.

## 5 Conclusions

Though the results presented here cover only a sample of six continuous improvement teams during the first two years of a lean implementation, the results do seem to indicate that seven is not the magic number when it comes to peak performance of continuous improvement teams. Neither is 12. Nor in fact 4.6. Revisiting the RQs that guided this investigation, the results tend to suggest that there is not an optimum team size for continuous improvement teams. However, the results do allow us to present a set of propositions that may guide managers and practitioners in harnessing the greatest level of performance from continuous improvement teams during the initial stage of lean transformation.

We suggest that further work should evaluate if this is still true as the company continues to progress with the lean implementation, taking into consideration the maturity levels of the various teams, and including a greater sample of continuous improvement teams at the case company. Further work should also investigate the level of education and training of various continuous improvement teams contra their achieved performance. One would expect greater performance from teams with more skills from the continuous improvement toolbox, for example. Other factors that were identified in the literature review should also be evaluated in terms of their effect on team performance, in particular team composition (e.g. homogeneity versus heterogeneity), quality of leadership, level of motivation, and clarity of team goals.

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# Lean and Digitalization—Contradictions or Complements?

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**Abstract.** Lean has been the dominant production paradigm for the past few decades. With its focus on reducing complexity, lean suggests to limit the use of digital technologies on the shop floor. Recent advancements in digital technologies, however, promise significant improvements through its ability to manage complexity. This apparent conflict raises the question as to whether these two paradigms—lean and digitalization—contradict or complement each other. Furthermore, there is ambiguity about whether or not firms should excel in lean before investing in digitalization. This paper contributes to this discussion through an empirical investigation of this relationship. It draws on survey data from Swiss manufacturers as well as consecutive interviews with selected firms. The analyses indicate a positive correlation between the digital maturity and the lean maturity of firms. This relationship is discussed from two perspectives: first, how digitalization can support lean and, second, how lean can support digitalization. Furthermore, the different characteristics of companies of different maturities in lean and digitalization are examined. It is concluded that a favorable organizational culture and some specific continuous improvement practices help the mature implementers of lean and digitalization to achieve superior operational performance.

**Keywords:** Lean management · Digitalization · Smart manufacturing

## 1 Introduction

In manufacturing, state-of-the-art process innovation is built on many ideas from the rich literature on lean management—or its derivatives and relatives (e.g., agile, world-class manufacturing, six sigma, and total quality management) [1]. Historically, lean manufacturers have been intentionally slow to introduce new technology and IT systems [2, 3]. Instead, the lean philosophy focuses on human learning, with the purpose of "developing every employee into a scientist" who can continuously improve the work processes that have been tested and proven in the past [4].

Although digitalizing manufacturing processes allow for much better and accurate data collection—in near real time—it risks alienating the human being from the problem-solving process and, thereby, reduces the ability to innovate. Lean management emphasizes the reduction of complexity, leveled flow, visual control, and


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standardization as enablers for process innovation [5]. Digitalization, in contrast, enables the handling of high complexity in manufacturing processes [6].

Scholars and practitioners still struggle to understand how the two paradigms of lean and digitalization influence each other. It is still a question of how digitalization and lean will coexist in the future. Do they complement each other or will digitalization replace lean? To contribute to this discussion, this paper addresses the following two research questions with a focus on the Swiss manufacturing industry.

**RQ 1:** Is there a correlation between firms' lean maturity and digitalization maturity?
**RQ 2:** What characterizes companies with different lean- and digital maturities regarding performance and enabling structures?

## 2 Theoretical Background

This chapter briefly introduces the paradigms of lean and digitalization. Thereafter, it summarizes the current state of the discussion on the relationship between the two.

### 2.1 Lean

The term *lean* was introduced by Krafcik in 1988, following a study of the International Motor Vehicle Program [7]. Lean aims to align value creation with customer demand and to continuously eliminate waste in processes. Both these principles are necessary to be competitive and require continuous improvement within the existing processes [8]. The Japanese term *Kaizen,* which means change for the better, requires all employees to continuously challenge the status quo and to think about how they can improve the production system [4, 9]. To reduce wasteful activities and increase value for the customer, five lean principles have been defined by Womack and Jones: *specify customer value, identify the value stream, flow, pull,* and *strive for perfection* [10].

### 2.2 Digitalization in Manufacturing

The digitalization of manufacturing currently receives much attention from academia [11] and governmental agencies [12]. Although digitalization in manufacturing is discussed frequently in the literature, no universally accepted definition exists [13]. However, almost all definitions include the application of modern information and communication technologies (ICT), as well as data analytics, as enablers for increased efficiency and flexibility of manufacturing operations [14].

Even though scholars associate potential benefits with the digitalization of manufacturing [15], the actual implementation rate is slow [16]. Given the lack of personnel with the needed skills, as well as restrained financial resources, especially small and medium enterprises (SME) face the following question: does investment in digital technologies pay off? Digitalization needs to prove its contribution to operational and financial performance in order to convince managers to support its further implementation.

### 2.3 The Relationship Between Lean and Digitalization

The literature reveals a discourse about the relationship between lean and digitalization. The superior competitiveness of lean production systems does not originate from the extensive use of cutting edge technology [9]. Traditionally, the lean literature sees a conflict between lean and modern technology, such as IT systems. Whereas lean advocates simplicity, IT systems usually introduce high complexity [6]. For instance, Toyota is usually not among the first companies that introduce new technology. Instead, Toyota spends much time to test new equipment extensively and only introduces it if it does not interfere with the lean principles of the Toyota Production System. New technology needs to either reduce existing waste or contribute to higher customer value before it is introduced in lean production systems [9].

However, the literature also indicates that lean is the foundation for digitalization. Lean processes are transparent, robust, and standardized, and this foundation is, according to some research, crucial for the successful introduction of digital technologies [17]. The argument is that lean thinking, which reduces process and product complexity, facilitates the efficiency of digitalization. Companies with a high level of lean implementation are more likely to also implement "Industry 4.0" digital technologies [18]. Kolberg and Zühlke have identified use cases of the combined application of lean and "Industry 4.0" and conclude that "the integration of innovative automation technology in lean production is an up-to-date and promising topic [19]."

Furthermore, scholars argue that digital technologies likely to benefit from a high lean maturity that they also have the potential to raise lean maturity to an even higher level. Lean is not particularly good at handling increasing flexibility requirements (e.g., manufacturing highly customized products). Digitalization, in the context of "Industry 4.0" has the potential to enhance the flexibility of lean in order to successfully address the challenge of increasing product customization [20]. Moreover, digital technologies can contribute to further increasing the stability of lean processes [21]. Digital technologies can support lean in addressing some of its inherent limitations, such as increasing product customization [17].

The parallel implementation of lean and digitalization is estimated to yield a 40% improvement potential, compared to a 15% saving potential for the standalone implementation of lean or digitalization [22]. Scientific literature on the interplay of the two, however, is rare. Although the research suggests a positive link between both paradigms, it currently lacks rigorous empirical studies to test the relationship [18]. To contribute to the ongoing discussion, this paper empirically analyzes the interrelation of lean and digitalization with a focus on the Swiss manufacturing industry.

## 3 Method

To study the relationship between the paradigms, we used a mixed-method approach as described by Creswell [23]. First, a questionnaire was developed and tested together with academic and industrial experts in the field of operations management. The authors then conducted the survey throughout 2017 and distributed it to 500 manufacturing companies. When the survey closed, 74 usable responses had been returned.

*Digital maturity* is set as the dependent variable. In line with previous work (cf. [18]), digital maturity is defined by the implementation level of related digital technologies. Each technology is measured on a scale from (1) "no utilization" to (4) "company-wide roll-out." The mean from the maturities of the different technologies forms the overall digital maturity (Cronbach's alpha = 0.78).

*Lean maturity* is set as the independent variable. It is defined similarly by measuring the maturity of the company in lean within different areas of the firm. The investigated areas are production, quality, R&D, administration, procurement, logistics, marketing, sales, and services. Each area is measured on a scale from (1) "no application of lean" to (4) "history of lean success." The simple mean of the different areas represents the overall lean maturity (Cronbach's alpha = 0.85).

Multiple regression analysis is used to analyze the correlation between lean maturity and digital maturity. The companies are then clustered into four segments. We investigate the clusters regarding four different areas—namely, operational performance, financial performance, organizational culture, and continuous improvement (CI). *Operational performance* is measured by the relative performance in the areas of cost, quality, and delivery compared to the industry. *Financial performance* is measured by the change of revenue, EBIT, and market share within the last three years. The *organizational culture* is measured by questions about open communication, alignment to overall goals, understanding of value stream, and access to business intelligence. The measure CI is built from four questions about the continuous improvement process—namely, striving towards waste reduction, feedback evaluation, joint improvement program, and market screening for new technologies.

Two controls are included: *lean experience* and *size of the company*. The lean experience is divided into five levels: "no experience," "more than 3 years," "3–5 years," "5–10 years," and "more than 10 years." Finally, we control for the size of the investigated company; the binary measure SME gets one for companies smaller than 250 employees. Following the quantitative analysis, qualitative interviews were conducted with companies of the clusters. Six companies were interviewed and analyzed.

## 4 Results

Figure 1 illustrates the companies based on their lean and digital maturity. The resulting clusters are colored, and the size of the bubble indicates the size of the company. Most of the companies are in the first cluster with a lean maturity below 2.16 and a digital maturity below 2.17. Few companies fall in the high-lean and low-digital cluster (Cluster 2) and in the low-lean and high-digital cluster (Cluster 3). The impression of a correlation between the two maturities is supported by the regression results shown in Table 1. Thereby, a one-unit increase in the lean maturity is related with an increase of the digital maturity of 0.33 in the second model. The first model includes only the independent variable digital maturity as predictor, whereas the second model also includes the lean experience and the size as predictors for the digital maturity. The impact of the control variable SME is also significant, reducing the digital maturity by 0.29. The control variable lean experience returns insignificant effects.


**Fig. 1.** Matching firm's digital and lean maturity (bubble sizes indicate company size) (Color figure online)

The analysis of the characteristics of the different clusters reveals significant differences within the clusters (Table 2). Companies with higher lean and digital maturity (Cluster 4) tend to perform better, have a better organizational culture, and have a better CI process in place. There was insignificant evidence that Cluster 4 companies have a better financial performance than the other clusters.

**Table 1.** Regression results on digital maturity

| | Digital maturity | |
|---|---|---|
| | (1) | (2) |
| Constant | 1.384*** | 1.241*** |
| Lean maturity | 0.364** | 0.333** |
| Lean experience | | 0.084 |
| SME | | −0.289* |
| R-squared/Adjusted R-squared | 0.197/0.186 | 0.319/0.289 |

*Note:* $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$

**Table 2.** Mean value of characteristics of the different clusters

| Characteristic | | Cluster 1 | | Cluster 2 | | Cluster 3 | | Cluster 4 | |
|---|---|---|---|---|---|---|---|---|---|
| | | Avg | SD | Avg | SD | Avg | SD | Avg | SD |
| Performance | Operational* | 3.59 | 0.68 | 3.72 | 0.65 | 3.14 | 1.06 | 3.89 | 0.61 |
| | Financial | 2.24 | 1.67 | 3.13 | 1.57 | 2.81 | 1.47 | 2.68 | 1.63 |
| Enablers | Culture** | 3.31 | 0.91 | 3.95 | 0.77 | 3.14 | 0.85 | 4.13 | 0.77 |
| | CI** | 3.33 | 0.62 | 3.75 | 0.68 | 2.95 | 1.17 | 3.98 | 0.83 |

*Note:* $^{*}p < 0.05$; $^{**}p < 0.01$

## 5 Discussion

The results add insights to the discourse about the relationship between lean and digital by suggesting they do not contradict each other. In contrast, the results support a positive correlation between the two paradigms. This relationship thereby shows that firms implement lean and digital at the same time: Fig. 1 shows that most companies are situated along a diagonal of lean and digitalization and thereby supports the previous research [18]. The following paragraphs discuss the findings of the quantitative research in light of the insights from the qualitative interviews.

Digitalization can support the implementation of lean. Digitalization offers opportunities to manage and mitigate complexity for the operator on the shop floor. An example is digital shop floor management; complex processes are reduced to a few important influencing factors, which are discussed in a morning meeting. Digitization can further help in achieving lean principles [10]. For instance, flow and lot-size-one can be enhanced by improved production planning techniques through the manufacturing execution system or digital work instructions via augmented reality. Transparency about the value stream can be increased by process mining [24, 25], and prescriptive analytics helps to strive for perfection (i.e., quality) in the processes. The interviews with company representatives supported the finding that digitalization can enhance lean principles for two main reasons. First, the availability of up-to-date, high-quality data increases transparency and facilitates the identification of waste. Second, digitalization allows a higher degree of flexibility regarding to customer requirement (e.g., by enabling product customization or last-minute order changes).

In reverse, lean can also support digitalization. Efforts can be guided to not push technology into the production plant but to satisfy the relevant requirements of the operators. Lean principles simplify the data collection required for digital projects by having streamlined processes, which can reduce the time to integrate digital solutions. The interviewed company representatives described the risk of implementing digital technologies for the sake of applying state-of-the-art technology while neglecting the core purpose of new technology—to support and improve existing value creation processes. Lean thinking ensures a permanent focus on customer value and waste elimination, which facilitates the identification of technologies that support these objectives. One company manager expressed it concisely: “if we do not apply lean principles, we digitalize waste.”

The different characteristics suggest differences in the level of operational performance between the clusters. A higher level of operational performance is related with a high level of lean maturity (e.g., Cluster 2 and Cluster 4). Companies following a digitalization strategy while neglecting lean are represented in Cluster 3. These companies reveal the lowest average performance in the sample, supporting the argument that lean is needed as a foundation for successful digitalization. The results suggest that although the lean principles of customer orientation and elimination of waste remain the basis of efficient production, the combination of lean thinking and digital technologies enables superior performance compared to a standalone implementation of lean or digital technologies. For the financial performance, however, the results are not significant, which is likely due to other factors outside of manufacturing.

There is also a difference within the enablers. Companies achieving high values for the enabler category "organizational culture" consistently report an open communication culture, which includes appreciating contributions of all employees regardless of their hierarchical position as well as encouraging an open feedback and failure culture. This allows solution-oriented instead of blaming-oriented discussions about failure. CI may be supported by a structured process to contribute to CI suggestions. However, such processes are also in place in companies with lower CI levels, thus suggesting that it is more the design than the bare existence of a proposition system. Companies with high CI levels stress the importance of user friendliness and timely as well as qualified feedback on suggestions, whereas no pattern was found regarding financial incentives. Companies should further focus on culture and the continuous improvement process. Both enablers have shown differences within the clusters, hence providing a best practice for companies. Having an effective CI process in place differentiates the best-performing companies from the lower-performing ones.

## 6 Conclusion

Lean and digitalization are complementary, not contradictory. This paper adds empirical findings to support a symbiotic relationship between the two paradigms. Digitalization can support lean, but lean can also support digitalization. The paper reveals differences in the characteristic of companies with different lean- and digital maturities. It suggests companies to focus on continuous improvement and open organizational culture to achieve highest operational performance. Further research can focus on the paths that lead companies to higher maturity in both lean and digitalization.

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# Production Management in Food Supply Chains

# Neuro-Fuzzy System for the Evaluation of Soya Production and Demand in Brazilian Ports

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**Abstract.** Brazil and the United States account for approximately two thirds of the world soybean production. In 2018, the Brazilian soybean crop was approximately 117 million tons, more than half of which was exported. The Port of Santos is the largest shipper of soybeans, followed by the Port of Paranaguá. The supply chain involves factors that are difficult to measure, resulting in chaotic and nonlinear activities. Thus, we propose to analyze the relationship between supply (production) and demand (export) using artificial intelligence techniques in a hybrid model called neuro-fuzzy. Data from 20 years of soybean production and exportation were used in the Matlab©R2017b software. The results indicate that the supply tends to be low when the demands of the ports are overloaded, that is, the ports act in a synergistic and balanced manner.

**Keywords:** Neuro-fuzzy · Soybeans · Brazilian ports

## 1 Introduction

Food supply chains worldwide are directly affected by soybean production. This commodity is important not just for food but for meat production (animal feeding), frying oil production, and different industrial products. Currently, Brazil and the United States are the largest growers of soybean; together, they produce approximately two thirds of the world's production of this commodity [6].

Despite this scenario, obtaining a balance between supply and demand is not an easy task because it depends on many factors, such as market, logistics and economy.

In 2018, the Brazilian soybean crop was approximately 117 million tons [4], and more than half of this production was exported, that is, approximately 68 million tons (US$ 25.7 billion); the main markets were China and the European Union [5].

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In Brazil approximately 95% of international trade passes through ports. According to statistical data from the National Waterway Transportation Agency (ANTAQ), in 2018 Brazilian ports moved 1.11 billion tons, and in relation to the flow of agricultural commodities, the Port of Santos is the largest shipper of soybeans, followed by the Port of Paranagua [1].

The Port of Santos is located in São Paulo state (southeast region), and the Port of Paranaguá is located in Paraná state (south region). These regions are near and provide widely available maritime routes, as well as access to the main roads in the country [1] and [2].

With soybean being one of the most important products for the Brazilian economy and the ports of Santos and Paranaguá being the main shippers of this commodity, the main aim of this study is to analyze the relationship between supply (production) and demand (export operation in these ports).

The supply chain involves factors that are difficult to measure, such as consumer behavior, changes in demand, price fluctuations, shortages, and expectations. These factors result in chaotic and nonlinear activities [11].

In [7], the authors corroborate the affirmation that, in the case of demand, obtaining an accurate estimation is a difficult, but vital task for reducing costs and improving service levels, that is, achieving competitive advantages.

Thus, we propose the use of a neuro-fuzzy hybrid model that employs artificial intelligence (AI) techniques in dealing with complex problems and conducting simulations that help decision makers in terms of production and export [8].

In [10], different techniques have been used to solve problems that occur in supply chain management, among them fuzzy logic, artificial neural networks (ANNs), genetic algorithms, and hybrid technologies, such as neuro-fuzzy proposed in this work.

## 2 AI for Diagnostics

Currently, AI has been proven effective in several areas, with applications in automation and robotics, as well as in support of decision making, through expert systems. The use of this technology to the detriment of classical methods of analysis does not aim to suppress, classical methods but only to offer more accurate responses to complex problems [15] and [13]. Comparison studies between these technologies should be encouraged.

### 2.1 Fuzzy Logic

Fuzzy logic amplifies the potential of classical logic used in computational systems because it enables the grading of values through membership functions. Thus, qualitative terms, such as low, medium, and high, can be used for the functions of the variables, and intersections between the functions can be obtained, giving more precise inferences. Fuzzy logic is a mature and robust technology with applications in thousands of patents [10,13,15,16], and [14].

### 2.2 ANNs

Analogously to biological neural networks, ANNs are able to extract patterns from noisy real data, that is, to learn by means of the complex behavior of variables. An artificial neuron is a computational model that receives the input data and obtains the weighted sum. The result may or may not activate the neuron by propagating the signal to other neurons in a network. Learning takes place through iterations, with the backpropagation algorithm being the most used. This algorithm adjusts the weights and activation variable of the neuron to minimize the learning error. Follow-up can be done through correlation and linear regression [9,10,13,15], and [8].

### 2.3 Neuro-Fuzzy Hybrid System

Fuzzy systems are expert systems. Hence, to obtain information, such as membership functions and rule base, professionals with tacit knowledge should be consulted [15] through surveys or interviews. This work requires the technical, subjective opinion of different people and demands a significant and consistent sample to increase objectivity.

However, when the combination of fuzzy system and ANN is trained with a real dataset, it is able to quickly and efficiently provide the membership functions and rule base [11,15], and [17].

In addition, each technology has its advantages and disadvantages. Table 1 shows the main differences between fuzzy logic and ANN.

**Table 1.** Differences between fuzzy logic and ANN. Adapted from [15]

| Definition | Fuzzy | ANN |
|---|---|---|
| Parameters | Specialists | Numerical data |
| Analysis | Qualitative/quantitative | Quantitative |
| Training | Interactive/inductive | Weight adjustment |
| Robustness | Very high | Very high |
| Fault Tolerance | Not evident | Very high |

The use of hybrid systems has been shown to be promising because one technology can compensate for deficiency of another technology and vice versa. Thus, the Adaptive neuro-fuzzy inference system (ANFIS) is an interesting solution that supports important decision making [10,17], and [11].

## 3 Methodology

Data from the national movement (export) of soybean through the ports of Santos and Paranaguá in the past 20 years (1999–2018) in thousand tons were used. Data were extracted from the Ministry of Industry, Foreign Trade and Federal Government Services (COMEX STAT) [3].

For the national production of soybeans in the past 20 years (1999–2018), data were taken from the National Supply Company (CONAB) [4], which is also related to the Brazilian federal government.

The neuro-fuzzy system was built using the Matlab©R2017Rb software with fuzzy logic toolbox and ANN toolbox as complements. For the initial configuration, the Sugeno inference engine was used [11] with two input variables, that is, **input1** (Port of Santos) and **input2** (Port of Paranaguá), and one output variable, that is, **output1** (soybean production) (see Fig. 1).

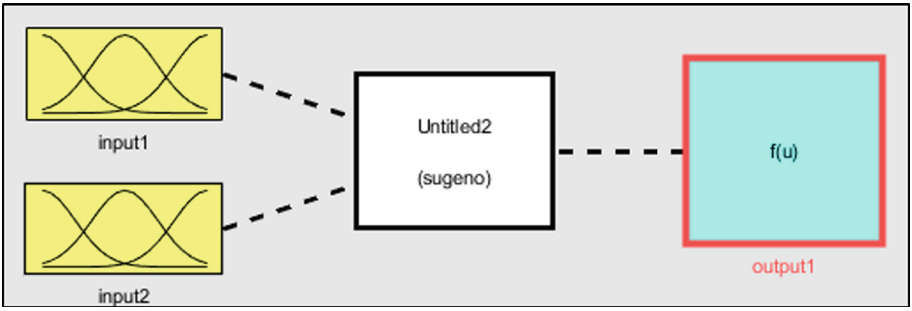


**Fig. 1.** Inference engine. Performed on Matlab©R2017b

After the initial setup, ANFIS was created. Then, data for the training and final configuration of the hybrid system were loaded. We opted to use five membership functions (Gaussian model) for the input variables and the linear type for the output variable, aiming to achieve high accuracy and smoothness in the transition between inferences. Two input variables with five membership functions generated 25 fuzzy rules (Fig. 2).

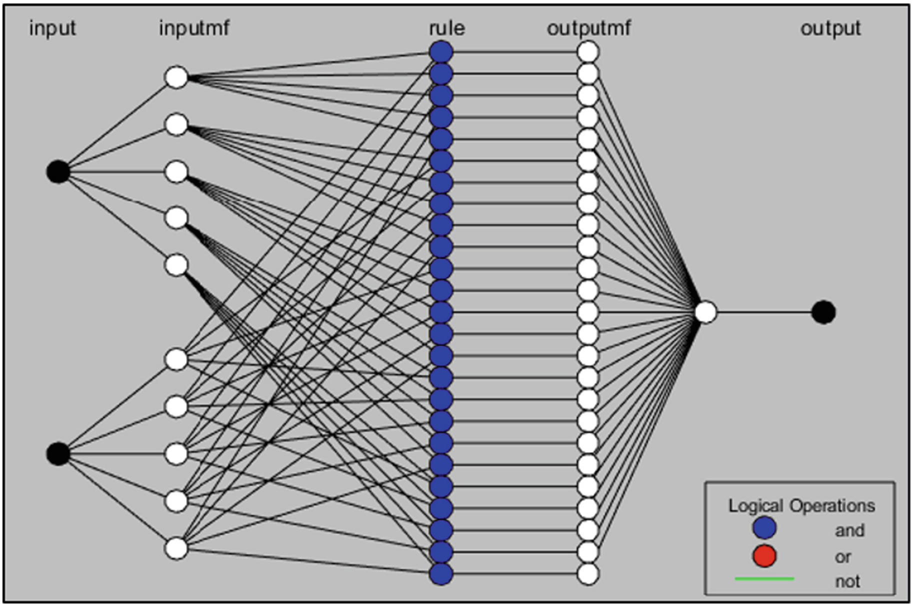


**Fig. 2.** ANFIS. Performed on Matlab©R2017b

A total of 3,000 iterations were used through the backpropagation algorithm to train the neuro-fuzzy system. From approximately 1,500 iterations, the error diminished drastically. Afterward, it was possible to draw up the trend and simulation graphs.

## 4 Results and Discussions

The trend graphs (Fig. 3) illustrate the possible relationships between input and output variables, with the dark blue areas representing the smallest output values and the yellow areas representing the largest output values. The effects of transition (i.e., gradation of values) are evident; this characteristic is favored by fuzzy technology.

The results point to an interesting relationship between the demands (exports) of the ports of Santos and Paranaguá and the supply (soybean production). It is feasible that the supply tends to be low when the demands in the ports are overloaded, that is, when there is much interest in the Port of Paranaguá and low interest in the Port of Santos, and vice versa. When interest in both ports is low, the production tends to be reasonable. Indeed, when the demands of both ports are high, the production is high. The simulations presented in the subsequent paragraphs help elucidate this relationship better.

Afterwards, five simulations were performed (Simulation 1 shown in Fig. 4 and the others demonstrated in Table 2).

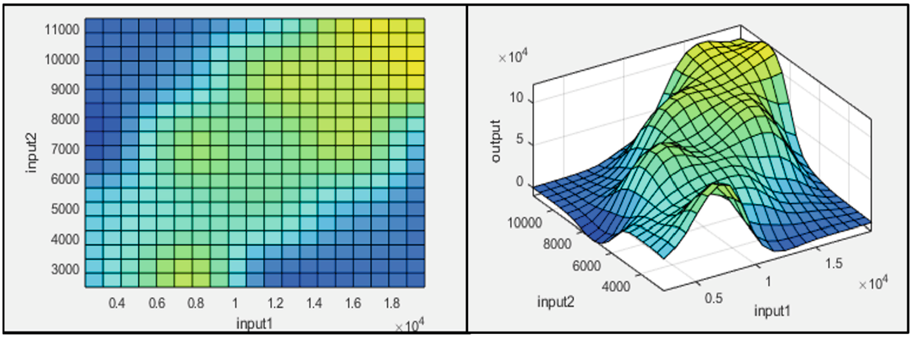


**Fig. 3.** Trend graphic (in thousand tons). Performed on Matlab©R2017b (Color figure online)

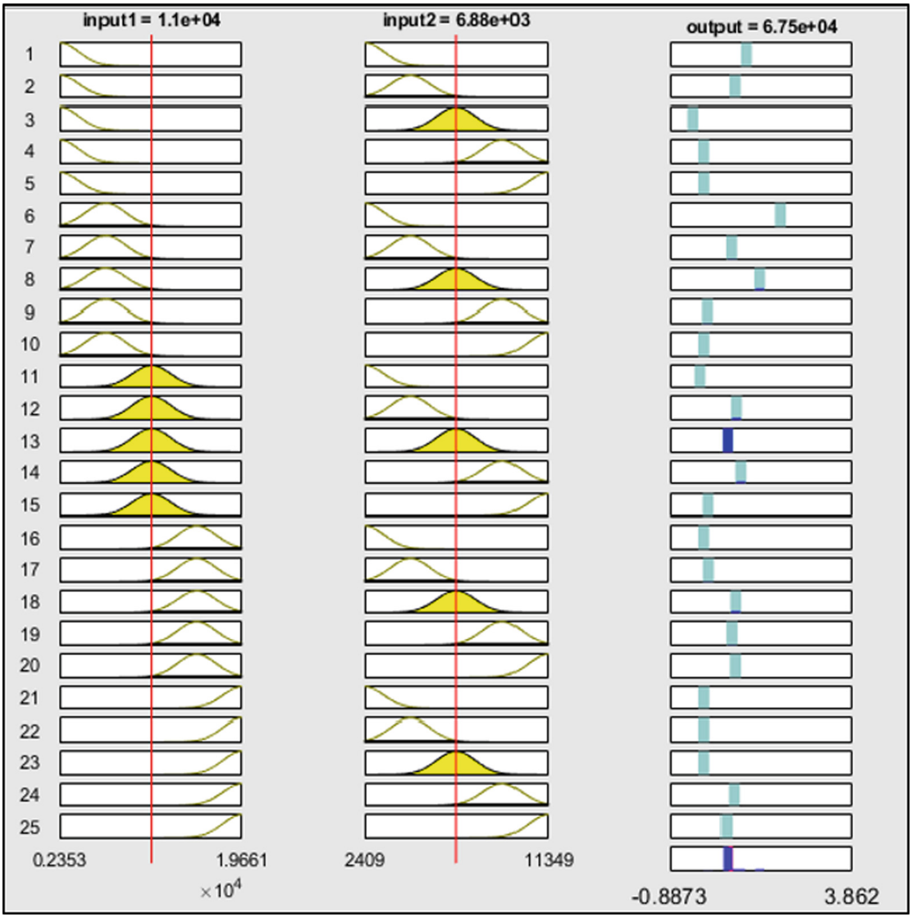


**Fig. 4.** Simulation 1 (in thousand tons). Performed on Matlab©R2017b

The values of other simulations are listed in Table 2.

**Table 2.** Other simulations (in thousand tons)

| Simulation | Input 1 | Input 2 | Output |
|---|---|---|---|
| 2 | 4.50e + 03 (low) | 3.67e + 03 (low) | 4.75e + 0.4 |
| 3 | 4.50e + 03 (low) | 1.04e + 04 (high) | 1.54e + 03 |
| 4 | 1.80e + 04 (high) | 3.26e + 03 (low) | 1.89e + 03 |
| 5 | 1.78e + 04 (high) | 1.04e + 04 (high) | 1.10e + 05 |

When comparing simulations 1 and 2, it is evident that, when the demands of the ports are similar, that is, medium or low for both ports, the production does not oscillate, thereby maintaining four decimal places. Notably, when there are significant differences in demand (Simulations 3 and 4), the supply tends to be low, thereby maintaining three decimal places for both cases. Finally, the last simulation performed (Simulation 5) illustrates the high production trend when the demands of the two analyzed ports are high.

It is important to emphasize that the movements of these ports are beyond what are now exported. Moreover, it is possible that both ports absorb the total soybean load for export. In 2018, 53 million tons of solid bulk were shipped in the Port of Santos, that is, 19.6 million tons of soybeans, whereas 25 million tons of solid bulk were shipped in the Port of Paranagua, that is, approximately 10 million tons of soybeans [1] and [3].

Despite this reality, the main result points to a natural tendency to share the work by dividing the export cargo. This fact is interesting because, according to the projections of the Organization for Economic Co-operation and Development (OECD) and the Food and Agricultural Organization of the United Nations (FAO), the Brazilian harvest of 2026/27 will be approximately 129 million tons, an increase of 19% over the 2016/17 production [12].

## 5 Conclusions and Outlook

This work proposed a differentiated analysis of the relationship between supply and demand that enabled the simulation of the trend or encouraged the supply of soybeans through variations in the demands of the main ports of the country. It is evident that, despite the fact that the movement of solid bulk in the ports analyzed is beyond what is exported from soybeans, these ports are prepared to meet the increasing demands in a balanced and synergistic manner. The main limitation of this study refers to the analysis of only two ports. For further work, it is intended to perform more complex simulations with a larger number of ports, which will require the creation of more variables and the conduct of more in-depth discussions.

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# Port Logistic Support Areas (PLSA) for Exporting Grains: An Exploratory Case-Study in the Largest Port in Latin America

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**Abstract.** The Port Logistic Support Areas (PLSA) receive and carry out the sorting of trucks that have the aim to reach the maritime terminals of the Port of Santos. Such areas are vital for the logistics of grains exporting as they regulate the flow of these vehicles, avoiding logistic bottlenecks and maintaining an appropriate balance within the city. This research aims at analyzing the prospects of PLSA in the face of new credentials carried out by the different Port Authorities in several parts of Brazil since there is a fall down in the trade of these companies. An exploratory method was used to analyze the truck movement data during the years of 2015, 2016, and 2017. It was considered the in-flow of grain carrying trucks facing the out-going from São Paulo city to the port of Santos. A reduction of more than 30% in vehicle movement was verified, from Jan 2015 to Dec 2017, where some determining factors were responsible for this reduction, as the use of other ports to the outflow of harvesters and the use of the rail modal, which leads to the questioning of the real need for the accreditation of new PLSAs.

**Keywords:** Grain transportation · Logistics

## 1 Introduction

The Port of Santos is the largest port complex in Latin America and accounts for almost a third of Brazilian trade [1]. Much of this movement is directly related to agribusiness, where Brazil stands out on the world stage as one of the great exporters of solid vegetable bulks. The PLSA receive and carry out trucks with access to the grain terminals, and play an essential role for port logistics since the accesses on the left, and


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right banks of the Port of Santos and their respective areas do not favor heavy traffic due to lack of space.

The new accreditation of regulatory support areas carried out by Brazilian port authorities seems to be against the movement of trucks, since according to the objective of this research, there is a deficit of more of 30% in the occupation of these places, caused by several reasons, such as the spraying of these vehicles among the other PLSA. Therefore, it is noticed that the trend is for a decrease in the movement of trucks in the PLSA, with an ample supply of vacancies that will not be occupied. Some factors such as the growth and modernization of the ports of Arco Norte, which are widely used in the export of soybeans and corn, attract demand to the north of the country, thus causing damages to the companies that exploit these areas, and in many cases activities. In such a way, the port authorities should evaluate the form the accreditation of new parking places is made based on the demand and existing spots warrantying the PLSA sustainability.

The present study aimed to analyze the perspectives of the companies that carry out such support areas, facing the new accreditations. Data on the movement of a company that has parking areas in a neighbor city of Santos (Cubatão), in the years 2015 to 2017 were analyzed.

## 2 Literature Review

Over the past decade, companies involved in grain production and logistics have become highly competitive and technologically advanced, with many opportunities and risks arising in this operation. Difficulties in managing national and international grain logistics are uncertainties faced by logistic companies of solid plant bulk, as they depend on the seasonality of production and environmental factors such as climate, disease, and pests [2].

According to [3], Brazil is one of the world's largest exporters of soy and corn. Therefore, much of the harvest is negotiated with other countries and mainly drained by the Brazilian ports. Since the plantation areas are mostly located in the Center-West of the country, logistical transport of these bulk cargoes has become a challenge, since Brazil is a continental extension country with only a few railroad options. A series of factors, ranging from the research of new varieties of plants, agricultural defenses, machinery, management and efficiency of the producers, led to a growing increase in the production of Brazilian grains [4].

The use of parking areas for trucks staying prior to shipment of grains [5] is pointed out by the Brazilian ports' authority (SEP in Portuguese) as an outlet to minimize the impacts of the export of the grain production by the Port of Santos in the cities of the coastal line (Baixada Santista). The idea is to contain the massive flow of trucks that are heading towards the bulk terminals before the vehicles go down to the Sierra (that separates the metropolitan area of São Paulo to the coast), to avoid causing heavy traffic on the roads that attend the municipalities of the region. Only trucks transporting grain to export are required to make use of the PLSA before going to the terminals [5]. According to [6], the parking areas are those where the vehicles with cargo stop, while they wait for the release of the terminal that will receive their loads. However, it also serves to relieve traffic near the Port of Santos, chaired by trucks parked on highways accessing Santos, since there is not an appropriate place to wait for final positioning.

From the perspective of transporting cargo from the point of departure to the Santos dock, the route planning must be useful, since in this way the trucks are received at the destination terminal only when there are space and service area available. Nevertheless, this practice exists in some situations; since the large portion of the terminals uses these cargo vehicles as a moving warehouse [6]. The parking pockets are like places of obligatory stop for the truck drivers towards the Baixada Santista. These spaces have intelligent devices that make a direct connection to the terminals and the Port of Santos. Such initiative allows the checking of the duration of the vehicle's movement and the precise period to check the documentation and unloading. Afterward, the truck moves to the port terminal [6].

In the PLSA this monitoring is carried out by the Operational Control Center (OCC), where information on the occupancy rate of the area, vehicle release, hourly movement, and other relevant management information is controlled and released to the supervisory institution [5]. The PSLA is like an organized warehouse, with its release through free areas and the terminal's ability to operate. These warehouses allow a constant and organized flow in the shipment of cargoes at the Santos quay [7]. According to [6], a large portion of the terminal users do not feel comfortable leaving the vehicles away from the port area (in highway areas) due to reasons such as:

(a) The deteriorated roads, causing unforeseen events on the way to the destination of the cargo;
(b) The expenses as a consequence of unpaired movement and the security of what is being transported.

Bulk ships do not have to schedule their arrival at the terminals, that is, this interferes with the organization for the reception of the vehicles since the terminals must be predisposed to attend to the ships that dock. According to the port operators, when the terminal is not loaded, it will have to bear a high cost for the delay in operating the ships [6]. The best thing would be to channel the information system into a single parking area, which would substantially reduce the cost of the operation. However, there is no technical restriction to use a defined area system, since it is of the utmost importance that the patios are connected. For some authors, the per-stroke times from the parking to the Santos pier of each truck vary according to where it is parked since the trans-carriers might use more than one pocket for the unloading activity.

Another way of transporting these bulk grains for export, without compromising the Port-city relationship, is by the rail mode. Rail transport accounts for about 27% of the cargo handled at the Port of Santos, which has an internal railway network with 100 km of extension [1]. One of the most benefited cargoes is agribusiness since 53% are transported through the railways located in the port of Santos.

## 3 Methods

The company chosen for this study is the pioneer in the state of São Paulo in the operation of truck sorting and parking areas in access to the port of Santos. Also, it has the largest area, with $443 \times 10^3$ $m^2$, with the most significant number of available spaces, with 1250 areas (Fig. 1). It is, therefore, an essential reference for the operation of PLSA in Brazil.

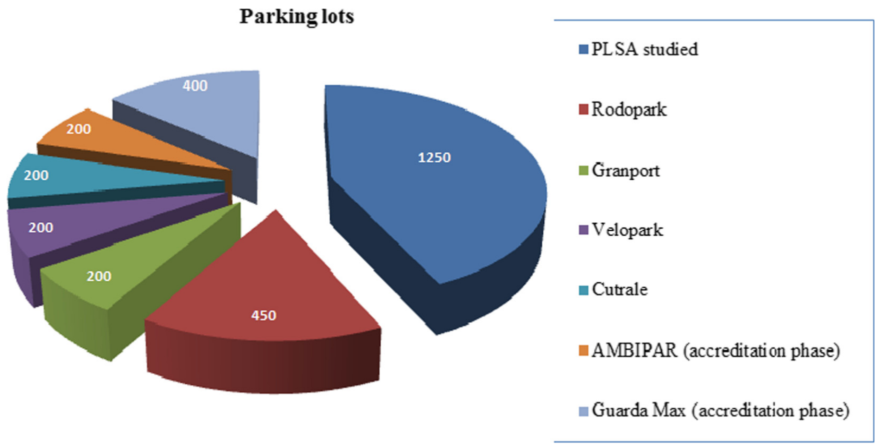


**Fig. 1.** The unoccupied capacity of logistic parking lots (PLSA, area) of the São Paulo State in 2018. Source: [5]

Figure 1 shows a comparison of the number of parking spots available amongst the studied company and other of the same segment. Such information indicates the representativity of each company in the Porto d Santos.

The present research is an exploratory case-study in a PLSA located in the county of Cubatão – SP, in the metropolitan area of Santos. An analysis of the procedure of the PLSA was carried out for 36 months, from January 2015 to December 2017. The dataset was organized using the number of trucks accessing the company every month. Such information is stored by Syslog (the software used by the studied company) which receives the data in an automated way by the Optical Character Recognition (OCR), made available monthly in the form of a report.

A case-study was adequate in the present study since the research requires a situational explanation and some detailing [8–10].

The output of the vehicles in the studied PLSA system should be performed for all trucks entering the company. To be operationalized such exit in the system, the driver presents/displays a ticket and find the departure of the truck in the system using a bar code. Thus, by controlling the entrances and exits of the trucks in the PLSA in an automated way, OCR forwards such information to the company's software, there is an accuracy of the information of satisfactory movement for the gathering and study of this data. The movement of the vehicles is directly linked to the grain harvest companies, mainly coming from the western area of the country, where the port of Santos has a significant portion for the flow to the main world markets.

## 4 Result and Discussion

The company object of the study established a system in its work instructions for the entrance of the trucks in the PLSA, and in this way to account the flow and movement of the vehicles in its patio. The driver of the truck is directed to the automated entrance gates (01 to 10), where after stopping in front of the gate, the OCR system reads the vehicle's license plate. The OCR performs the reading of the board and searches the operation of the patio regulator studied, the link/scheduling using the captured number.

After verifying the previously performed scheduling, a message is generated by the system releasing the vehicle. Figure 2 shows the timeline of vehicles in the current study PLSA, from January 2015 to December 2017. Vehicle volume decreased by 31%.

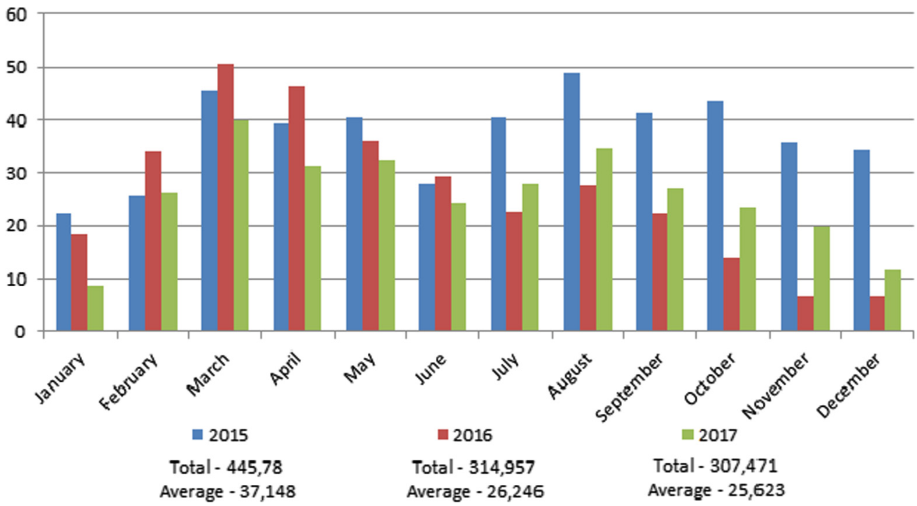


**Fig. 2.** Number of vehicles in movement (2015–2017)

The decrease evidenced during these years occurs from the second semester of 2016, where it refers to a low movement related to the sugar harvest. However, according to CODESP, sugar exports in bulk in the year 2016 obtained an increase of 11.8%, indicating that the sugar terminals have used, as an alternative, the use of own regulatory yards, such as COSAN, which has a logistics division that includes an exclusive truck sorting yard to meet the company's demand.

Another decrease was observed in the first half of 2017, where it refers to a low movement of soybean and corn crops. The Brazilian export of bulk soybeans and corn in the accumulated 2017 obtained 13.6% and 80.5% increase respectively, signaling that some of the vehicles occupied the new regulatory yards opened and accredited by CODESP recently, as the municipalities of Santos and Guarujá [1]. The trend for the next years is to continue falling, since until March 2018 the average movement reached 23,413 vehicles, representing a reduction of 8.62% compared to 2017.

The importance of PLSA is undeniable and necessary in the region that permeates the port of Santos. The Port Authorities, observing the positive operational results both on the highways and in the urban mobility of the port cities, increased the accreditation of new PLSA increasingly the offer of vacancies for trucks in these companies. A fact to be considered is that, according to the Brazilian Ministry of Agriculture, Livestock and Supply (MAPA), part of the exports is being destined to the ports of the Northern Arch (Itaquatiara, Itaqui, Santarém, Barbacena and Salvador), accounting today for 24% of all volume exported by Brazil, with a focus mainly on soybean and corn harvests.

Another point to consider is the increase in exports by the ports of Paranaguá and Antonina (located in the Southern region of the country). According to the Port Administration of Paranaguá and Antonina (APPA), in 2017, there was an increase in traffic in 14.2% compared to the previous year, reaching a historic result in the region. In 2013, the company Rumo in the city of Rondonópolis (Brazilian Center-West region) its new intermodal terminal, which brought a new reality for the storage availability of the agricultural harvest. It is from such intermodal terminal that the most substantial part of the flow of soybean harvest from the Mato Grosso area departs to the port of Santos. Today the terminal carries, on average, seven trains with eighty wagons per day and moves about 15 $10^6$ tons of soybeans/year. The structure with seven dump trucks and a warehouse with a capacity of 45 $10^3$ tons can receive up to 1,200 trucks/day.

Finally, this research presents the current stage in the PLSA operation studied, indicating that there is still much to do to improve and optimize requirements in this business model. The volume of trucks is undoubtedly important data to be considered in a survey of this relevance in PLSA since there is a significant difference in the flow of vehicles using the system. In this way, this study can serve as a reference to other PLSA, and especially for new companies that intend to be accredited with the Port Authorities.

## 5 Conclusion

The present study indicates that the port authority should have stricter criteria before accrediting a company to operate a PLSA, limiting the number of vacancies of the trucks by region, once all the requirements imposed by legislation are met. In this way, with the supervision of the competent governmental bodies, the prospects of the PLSA in the face of new accreditations will continue to be an essential tool to control the access of trucks with bulk solids to the Port of Santos. Also, the terminal has a PLSA that allows the static parking of 700 trucks, in addition to another 350 internal spaces. Currently, more than 800 jobs are generated in such an enterprise.

The country's largest railroad operator, the company says it has been carrying out a revitalization and logistical expansion work of significant impact on its network, which totals more than $12 \times 10^3$ km of the railroad. This process comes from the merger with Latin America Logistics (ALL), completed in April 2015. In this way, even the railroad model does not present an expectation of considerable improvement to reduce the movement in the PLSA. The destination of the harvests to other ports and mainly the opening and accreditation of new yards of sorting of trucks by the port authorities become a factor decisive for the functioning of these companies because each year the demand decreases, where it does not become financially and operationally sustainable.

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# Sustainability of Meat Chain: The Carbon Footprint of Brazilian Consumers

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**Abstract.** The term "carbon footprint" of products refers to the mass of greenhouse gases (GHG) emitted due to the production, use, and disposal of a product. The option of buying food is a complex behavior influenced by different factors that play an essential role in consumer perceptions. The present study aimed to analyze the carbon footprint profile of Brazilian consumers of beef, broiler meat, and vegetarian. A questionnaire was sent by e-mail, and 222 answers were obtained. Three consumer profiles were defined based on the similarities (C0, C1, and C2). The carbon footprint of C0 was 18 ± 3 tons/year; the C1 17 ± 2 tons/year; and the group C2 had 18 ± 3 tons/year. No difference in the carbon footprint of the meat eaters and vegetarians was found in the clusters studied. The meat consumers and the vegetarians have the same impact on the environment when the WWF calculator is applied.

**Keywords:** Meat production · Environmental impact · Meat supply chain

## 1 Introduction

The term "carbon footprint" for products refers to the mass of greenhouse gases (GHG) emitted due to the production, use, and disposal of a product. Thus, studies on product carbon footprint account for emissions from a set of processes related to the life cycle of a product. The proliferation of a wide variety of products, to satisfy the heterogeneity of the tastes of each consumer, do the decision-making process increasingly difficult, which leads to the consumer using mental shortcuts, as is the case of labels and brands, to facilitate decision making [1]. Understanding more clearly, the behavior of the consumer as well as what influences their choices is essential to achieve a way to motivate sustainable consumption.

The choice of buying food is a complex behavior [2] influenced by different factors that play an essential role in consumer expectations and perceptions [3, 4]. Some consumers become more cautious when they seek safety, high quality [5], authenticity, health, and tradition in their food than others [6]. Therefore, there is an attempt to meet this demand; an in-depth knowledge of consumer behavior is required [7]. Previous studies concluded with the provision of information alone is not enough to encourage a


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more sustainable purchasing decision because the information is available, but rarely does the consumer seek to read or digest all the information available [1].

Consumers are goods contribute to anthropogenic climate change throughout their product lifecycles through the carbon emissions resulting from the extraction, processing, logistics, and storage of raw materials until their use and disposal [8]. Growing demand for food is a global trend for the coming decades, highlighting the difficulty in supplying food to the global population [9]. The food industry, therefore, assumed a unique situation, driven by unprecedented changes in economic, technological, and social structures. Given these changes, a new pattern of consumption in the population must be recognized to pinpoint the factors that influence behavior.

Meat is one of the essential items of the Brazilian diet, and the domestic market is responsible for the consumption of more than 70% of the national production [10]. Despite their importance, research aimed at understanding the particularities and determining the consumption pattern of the population is still incipient. How can manufacturers of consumer goods make step-by-step reductions in their product lifecycle carbon emissions by engaging and influencing their key stakeholders?

The Brazilian government has been encouraging the adoption of measures to reduce GHG emissions in all productive sectors, especially agriculture. At the end of 2009, the National Policy on Climate Change was established [11], which instigated the various sectors of the economy to research, develop, and adopt low carbon technologies [12]. According to the Interministerial Committee on Climate Change [12, 13], low-carbon agriculture is related to the adoption of processes aimed at pasture recovery, crop-livestock integration, no-tillage, biological nitrogen fixation, and planted forests. This same committee set emission reduction targets of between 5% and 6% for the agricultural sector, considering the emission forecast for 2020.

The present study aimed to analyze the carbon footprint profile of Brazilian consumers of beef, broiler meat, and vegetarian and to evaluate the sustainability of these consumers.

## 2 Materials and Methods

A total of 222 subjects from different regions of the countries responded to an online questionnaire containing some issues related to consumption habits, including daily consumption of broiler meat, beef, and non-meat. The consumer profile included questions related to age, education, sex, marital status, number of children, type of household, salary, kind of model car, and appropriate actions towards sustainability, such as recycling.

The responses were organized in a database, and the software WEKA® version 3.6.13 [14] was used to divide the data into three groups. The algorithm applied was the Simple K-means using the Euclidean distance to select the categories considering cross-validation samples with 10% of data (10-fold cross-validation), e.g., the initial data were randomly partitioned into ten mutually exclusive subsets, each of approximately equal size. Training and testing were performed ten times. For classification, the accuracy of estimation is the overall number of correct classifications from the ten iterations, divided by the total number of instances in the initial data, as suggested [15].

An online questionnaire containing questions related to the topics described below was used in the following categories: age, schooling; sex, marital status, family size, and salary range of the interviewees. Concerning issues related to animal welfare emphasized to the point of knowledge about recycling, savings on purchases, such as pets, clothes, internet, use of lighting and heating at home, and daily use of cars.

The 222 responses of consumers from all Brazilian regions, the database was prepared. It used the data mining technique to discover the variables that will determine consumption patterns, as recommended by [16]. The most extensive group interviewed was characterized between 36–45 years, with higher education. Most were married and childless. The most representative salary range was R$ 5,000.00 (five thousand reals).

The responses were organized into three profiles pre-defined by the clustering task, and data were analyzed.

## 3 Results and Discussion

Three clusters were selected (cluster 0 - C0, cluster 1 - C1 and cluster 2 - C2) based on the similarities, such as 69 (31%), 61 (27%) and 92 (41%) for C0, C1, and C2, respectively. The sum of the square errors was 461.30 in five interactions. Five individuals from each group were randomly selected, and the baseline data were used as input to WWF's online footprint calculator. Table 1 summarizes the results found. The C0 profile was individuals ranging from 26 to 35 years of age, university education, mostly female, single, and she had no children. The carbon footprint of C0 was 18 ± 3 tons/year. The C1 profile had individuals over 45 years old, with a university degree, mainly female, married, and with two or more children.

**Table 1.** Carbon footprint results of consumer's broiler, beef, and vegetarians

| Carbon footprint ($CO_2$-e tons/year) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Broiler consumer | | | Beef consumer | | | Vegetarians consumer | | |
| Cluster 0 | Cluster 1 | Cluster 2 | Cluster 0 | Cluster 1 | Cluster 2 | Cluster 0 | Cluster 1 | Cluster 2 |
| 15.20 | 16.20 | 20.60 | 18.50 | 21.80 | 21.10 | 18.10 | 23.30 | 15.40 |
| 16.70 | 14.80 | 21.00 | 20.10 | 26.30 | 19.40 | 11.50 | 20.60 | 19.90 |
| 19.40 | 19.70 | 20.00 | 21.10 | 21.10 | 15.40 | 13.30 | 20.95 | 23.50 |
| 23.40 | 18.40 | 16.50 | 22.60 | 19.50 | 20.40 | – | – | – |
| 18.70 | 16.70 | 14.20 | 19.40 | 25.70 | 20.80 | 14.30 | 21.62 | 19.60 |
| *Mean ± standard deviation* | | | | | | | | |
| 18.7 ± 3.1 | 17.2 ± 1.9 | 18.5 ± 3.0 | 20.3 ± 1.6 | 22.9 ± 3.0 | 19.4 ± 2.3 | 14.3 ± 3.4 | 21.6 ± 1.5 | 19.6 ± 4.0 |

The data indicate that the carbon footprint is a function of the option of consuming beef, poultry or neither (either most of the meals with beef or chicken or without the consumption of them), as well as the life and the profile of people grouped in cluster 0, cluster 1 and cluster 2 (Fig. 1). The choice of consumers is coherent with the findings of [2, 3]. Results may serve as a basis to reduce the carbon footprint of consumers, as proposed by [8].

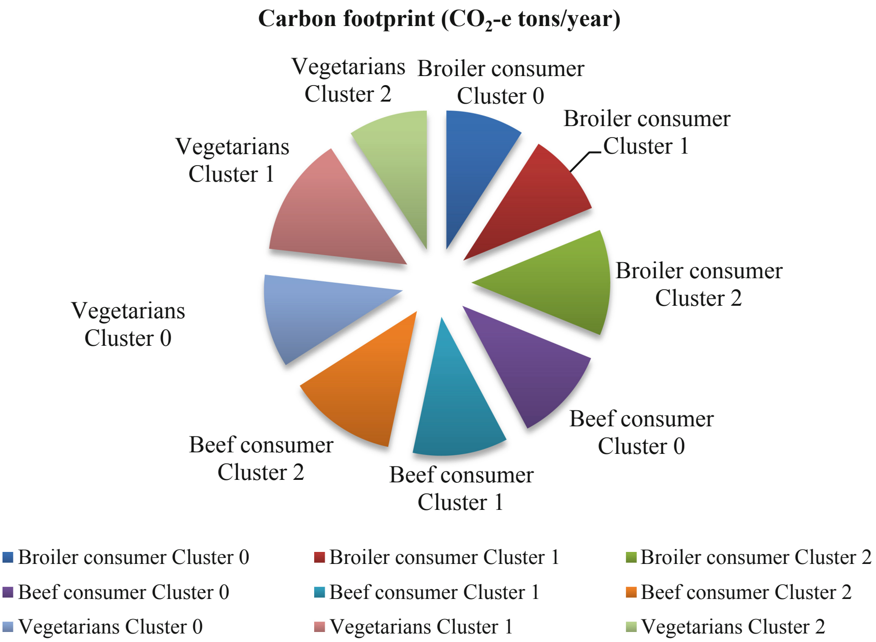


**Fig. 1.** The scenery of the meat eaters and vegetarians clusters in carbon-equivalent emission.

Carbon footprint results of chicken, beef, and vegetarian meat consumers show a standard behavior in the $CO_2$-e emission ratios. The three groups selected (cluster 0 - C0, cluster 1 - C1 and cluster 2 - C2) had the same number of similarities, such as 69 (31%), 61 (27%) and 92 (41%) for C0, C1, and C2, respectively.

The sum of the square errors was 461.30 in five interactions. Five individuals from each group were randomly selected, and baseline data were used as input to WWF's online footprint calculator. In this case, the sum of the quadratic error was 557.91 for the division of the database of the individuals interviewed in three different profiles.

Beef consumers showed a high carbon footprint, mainly the Cluster 1 (Fig. 2), followed from the mean value of broiler meat eaters, and the vegetarians. Similar profiles were suggested by [7].

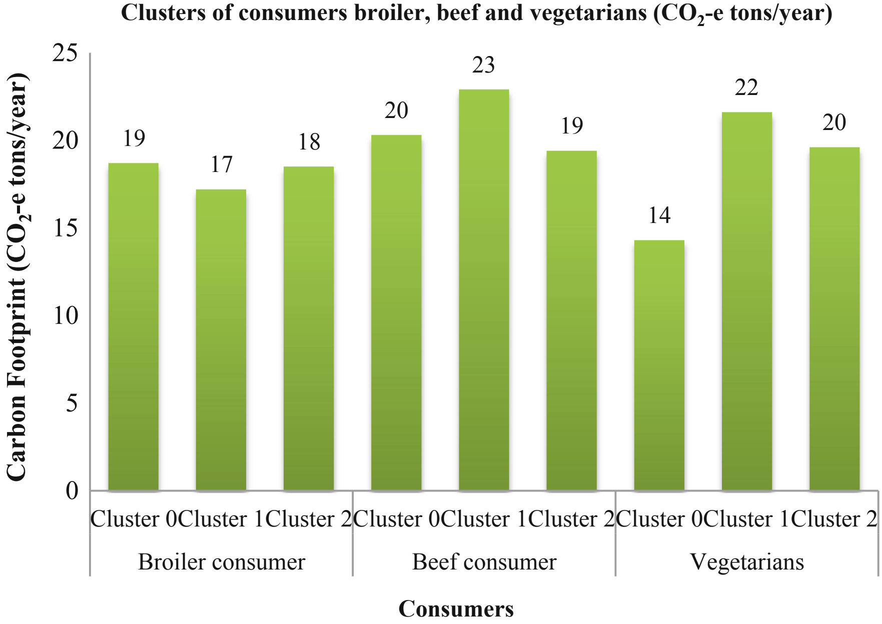


**Fig. 2.** The carbon footprint of the clusters studied from broiler meat and beef eaters, and vegetarians.

## 4 Final Remarks

Note the importance of consumer influence in the market. Award to a survey by [17], about 8% of Brazilians declared vegetarians, representing around 15 million consumers. Amongst the reasons for the exemption of meat in the diet, there is the poor condition of the production systems in which animals are reared. That may concern about the environment and health issues, but even the profile of the consumer being vegetarian their lifestyle in Brazil is still the same concerning sustainability and carbon footprint. There are still no consumer concerns with decreased green energy consumption, with reduced car pollution or savings on shopping with clothes, internet, pets, among others.

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# Global Warming Impact in a Food Distribution System: A Case-Study in an Elementary School in Piaui

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**Abstract.** The present study aims to evaluate the environmental impact of the food supply system in the State of Piaui, Brazil, through the transport of the provision of school meals from the farm to a public elementary school located in Piracuruca-Piaui. The concepts of 'local food' chains, carbon reduction policies, and global environmental sustainability were applied. The research has an exploratory emphasis and used a survey for analyzing the data. The food used in the school meals was divided into two groups: perishable and non-perishable. The environmental impact study on greenhouse gases emissions focused on perishable food, separating them into two groups: those from family farming and local production, and others from abroad. It was found that it is necessary to improve the logistics of transportation of family farming production, avoiding that each farmer makes the transport of its production individually. Such an initiative might have a significant impact on the reduction of greenhouse gas emissions.

**Keywords:** Local food · Transportation · Logistics · Environmental impact

## 1 Introduction

The development of the so-called 'local-food' chains intends to allow the renewal of the relations between the city and farms [1]. Within the 'local food' global discussion, environmental impacts considered are not restricted to GHG (greenhouse gases) emissions. However, carbon reduction policies may deliver potential trade-offs in overall environmental sustainability until other impacts are entirely considered [2]. The GHG emissions from truck transportation cause a severe burden on climate change since the transport within the supply chains is an essential player in the global carbon dioxide emissions [3]. The road freight segment is a sole contributor to $CO_2$ emissions in large countries such as Brazil [4]. Diesel on-road trucks travel vast distances from


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the farms to the food distribution centers in the country. The Global Warming Potential (GWP) was developed to permit comparisons of the global warming impacts of different gases. It is a measure of how much energy the emissions of 1 t of gas will absorb over a given period, relative to the emissions of 1t of $CO_2$ [5].

The current case-study aimed to evaluate the partial environmental impact of a perishable food supply system (familiar farming) in Piaui State, Brazil.

## 2 Literature Review

The 'local food' concept is based on certain boundaries [6]. (1) Geographic distance: calculated in units of distance, usually with a defined maximum distance; (2) Temporal distance: calculated in units of time, e.g. the food can be trucked to the point of consumption in 24 h or less; and (3) Political and administrative boundaries: based on municipal, regional, or national borders [1].

***Family Farming***

The expression of family farming has been studied in academic, political, and social scopes. In order to stimulate social participation and encourage local economies, the federal government established proper legislation [7] that establishes the guidelines for the formulation of the National Policy on Family Agriculture. A family farmer entrepreneur is one who practices agricultural activities, and uses the family's workforce in the activities, and have a family' income derived from that economic activity [7].

In relation to school meals, [8] determines that at least 30% of the value transferred from the National School Feeding Program (PNAE) by the National Education Development Fund (FNDE) to states, municipalities and the Federal District, should be used for the purchase of food products produced by the family farming. Such an initiative is an important public policy for small farmers to assess the market, allowing them to sell the products more efficiently while benefiting schools that can offer the student's food free of pesticides. Farmers who supply their agricultural products to the county elementary schools in Piracuruca live in a small settlement on the road BR 343, 10 km from the municipality's headquarters. Produce fruits and vegetables and sell in their own residence or provide for dealers of the Municipal Public Market. Their average income is around 1 (one) minimum wage. However, family farmers do not have production all year around compatible with the needs of the schools [8] at the county of Piracuruca.

***Strategies of School-Meal Distribution Logistic***

School meals in the present county have a warehouse in which the food received from the producers is stored (Fig. 1). The city council then takes responsibility for distributing food from the storage (deposit lunch) to schools. In this distribution process, a schedule prepared by the school nutritionist is considered, which contains all the necessary weekly information, such as the number of products, menu, and other recommendations regarding food preparation. The separation of these foods immediately is made by the demand of each school. The transportation is carried out once a week on the morning shift on each Monday.

The distribution logistics of family farming products is still one of the main restrictions experienced by farmers [9]. School meals in the present county have a

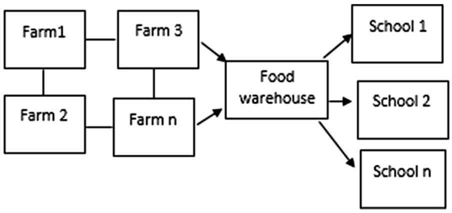


**Fig. 1.** Logistics flowchart for school meal distribution

warehouse in which the food received from the producers is stored. The county council distributes the food to schools. The vehicle used to perform this transport is a pickup truck. The possible contribution of local sales chains to the reduction of energy consumption has been debated in recent years. Results of comparing the fuel consumption from different modes of distribution of fruits and vegetables in a region of France was discussed by [10].

## 3 Methods

For the investigation of the subject, a survey was carried out in an elementary school with 350 students enrolled in the county of Piracuruca that is in the State of Piauí. According to data of the [11] has income HDI (Human Development Index) is 0.575, and is located in the geographic microregion of the Piaui coast, comprising a territorial area of 2,134 km$^2$, with an estimated population of 27,553 inhabitants and the GDP of the county in relation to agricultural activity is US$ 2,398.82, the industry sector is US $ 3,504.95, and service is equivalent to US$ 23,461.64.

The economy of the county develops around the Agri-industry with emphasis on the production of cashew nuts, honey production, fish farming, and family farming that is cultivated in small farms along the banks of the Piracuruca dam, which accumulates 250 million cubic meters of water where hundreds of families produce vegetables throughout the year.

***Selected Boundaries for the Analysis***

The research focused on the volume of food transported and the distance from farms to the warehouse distribution center for the elementary school. Transportation was done using pickup truck and motorcycles. Meat, chicken and fruit pulp are transported in a truck adding up to 204 kg/month, and the bread totaling 1,600 units/month. On motorcycles 290 kg/month of products, such as tomatoes, onions, peppers, green scents, sweet potatoes, orange, mandioc, pumpkin).

The products were grouped into two categories: perishable (vegetable and fruit) and non-perishable (processed rice, beans, garlic, chocolate, powdered milk, biscuit, sugar, noodles, tomato extract, soybean oil, seasoning, refined salt, ‘coloral’ (local seasoning), canned corn, flour, and coffee). The cluster of perishable food products represents 60% of the total food consumed monthly.

The farmers do transportation using pick-up trucks and motorcycles. The cluster of perishable food products represents 60% of the total food consumed monthly.

***Description of the School-Meal Logistics in Piracuruca, Brazil***

School meals in the studied county of have the following logistics: all suppliers deliver their products in a central (School Lunch Distribution Center), where the school makes the separation, and then all delivery is done by the responsible for this sector. Perishable foods are delivered once a week, and non-perishable foods are delivered biweekly.

Thus, the food route for school meals in the "Hermínio Conde" elementary school can be described as follows: the fruit pulp is transported from 9.2 km, packed in a refrigerated vehicle. The other perishable foods are delivered to the warehouse, using transport such as a bicycle and a motorcycle, and travel up to 10 km. Non-perishable foods come from long distances. The leftovers from the previous delivery are collected by the delivery vehicle and taken to a reserved area for redistribution. In this way, waste is always avoided. The school manager is advised to check, at the time of receiving the products, the expiration date as well as the aspect of each food, such as color, and consistency. Such special care is aimed at avoiding foods that have expired or that expire before the day they are served to the students.

The survey focused on the amount of food transported and the distance from farms to the school. The perishable foods are vegetables and fruits, and non-perishables are processed rice, beans, and others. Calculations were made, considering the reference values of one month of school meals in a public elementary school. A projection of these values was made for a school year, which, in this case, corresponds to ten months, given the need to subtract the 45 days of school vacations. After the calculations were completed, the total kilograms were converted into tons. Concerning the sample criterion, the present research is limited to non-perishable products produced in the region used in school meals. Figure 2 indicates the scheme of delimitation in the current study.

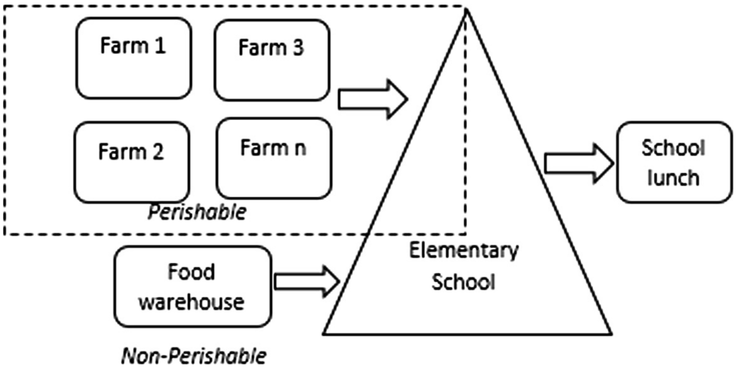


**Fig. 2.** Scheme of the geographic limits of the study of the environmental impact of the school-meal logistics of perishable food.

***Global Warming Impact Assessment***

The information was collected through analysis of tables used for the menu of meals composed of food products of March 2019. The values of the $CO_2$ equivalent ($CO_2$-eq) emissions were estimated adopting the 100-yr Global Warming Potential (GWP) values used by the Fourth Assessment Report (AR4) of the IPCC [12] and using the online calculator [13]. The online calculator uses as input the distance traveled and the average fuel consumption, and the result is the amount of $CO_2$-eq/year, referred to the GWP in 100 years [14].

## 4 Result and Discussion

After analyzing the data, it was observed that the use of local sales chains in school meals brings benefits from the social point of view. The incentive of such a production generates income and boosts the economy of the municipality, besides including small farmers in the local market. Such a benefit goes beyond the social analysis since through the current study it was found that energy consumption and GHG emissions in the environment decreased significantly when the foods travel short distances to their destination, contributing to environmental preservation.

The results of the energy consumption of different modes of fruit and vegetable distribution were presented (Table 1), as suggested by [10], and it was verified that the food produced near the county's headquarters has a lower impact than that produced in another county located 95.4 km from Piracuruca, as seen in the results of the fruit pulp. These policies to reduce carbon emissions, according to [2] are potential trade-offs in global environmental sustainability. The lower the distance in transport, the less GHG emission.

**Table 1.** Perishable products analyzed for one year, the quantity (t), the corresponding traveled distance (km) from the farm to the elementary school case-study, and the global warming impact.

| Product | Quantity (t) | Distance (km) | Fuel type | GWP ($CO_2$-eq t × $10^{-4}$ in 100yrs) |
|---|---|---|---|---|
| Fruit pulp | 0.64 | 7,616 | Diesel | 288 |
| Fresh bread | 0.08 | 80 | Diesel | 30 |
| Ground beef | 0.44 | 80 | Diesel | 30 |
| Broiler breast | 0.96 | 80 | Diesel | 30 |
| Tomato | 0.18 | 800 | Gasoline | 50 |
| Onion | 0.18 | 800 | Gasoline | 50 |
| Green pepper | 0.06 | 800 | Gasoline | 50 |
| Cilantro | 0.96 | 800 | Gasoline | 50 |
| Sweet potato | 0.16 | 800 | Gasoline | 50 |
| Orange | 1.04 | 800 | Gasoline | 50 |
| Manioc | 0.16 | 800 | Gasoline | 50 |
| Pumpkin | 0.16 | 800 | Gasoline | 50 |

Note: The school year corresponds to 10 consequent months, with 5-days/week

Table 1 shows that, although it is verified that the perishable food is transported in less than 24 h (one of the characteristics of the 'local food'), it consumes less energy in its transport. The production is made by family farmers, which each produces and delivery a product individually, using their transport (motorcycle). Thus, the sum of GHG emissions in the transport of the products (tomatoes, onions, peppers, green odor, sweet potatoes, orange, cassava, and pumpkin) corresponds to 400 GWP. While the sum of the GHG emission values of the others shown in Table 1 (fruit pulp, ground meat, cold broiler chest, and bread) corresponds to a lower value (378 GWP; even considering that one of these products, the fruit pulp, traveled a total distance of 7,616 km) and all other products take up only 6,640 km. Such results lead to the conclusion that it is not enough to search for local sales chains, it is necessary to improve the logistics of transport, causing this production to be transported together, avoiding that each farmer transports the agricultural production individually, which will significantly impact emissions from greenhouse gases.

Figure 3 shows the relationship between the GWP and the distance of food distribution, and the fuel used to transport the food-products.

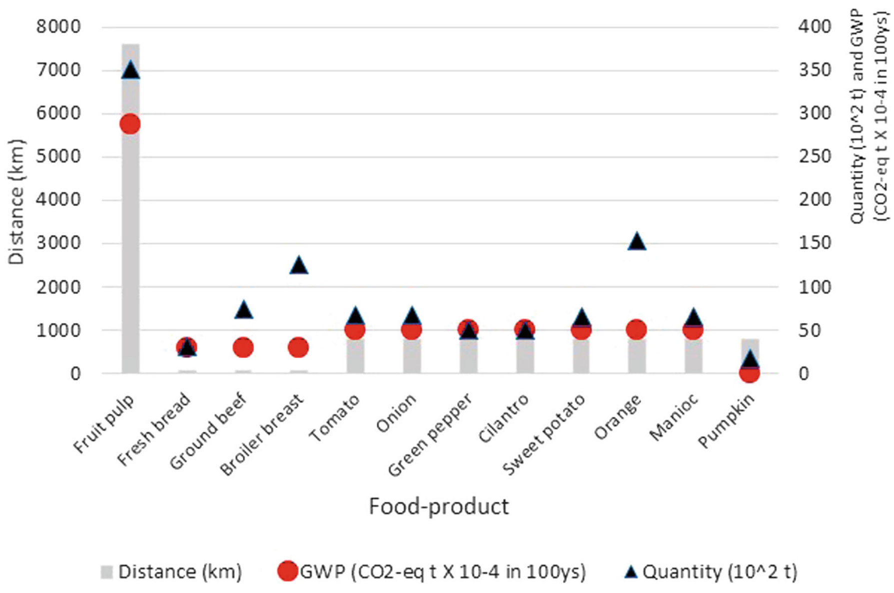


**Fig. 3.** Results of the GWP based on the amount of fuel used in the transportation of perishable food.

One intrinsic part of a globalized food order has to do with market segmentation and with the corresponding consumer reaction [15]. It is also related to a growing understanding that the properties of food are 'natural' properties and that the heterogeneity of farm environments improves the aspects of the various foods. Therefore, there is a potential for logistical optimization in 'local food' chains. Such chains are newer than long and already established chains, and the logistics experience is being built-up lately. Those local-food chains have room for improvement, which could significantly improve the performance in terms of distribution and reaching their consumers [10].

Based on data analysis, 'local food' is a sustainable way of buying food since it implies social sustainability and it places small farmers in the market and boosts the municipality's economy and incorporates environmental sustainability. Transportation in trucks, energy consumption, and GHG emissions are also reduced. However, if the logistics of such transport are not well planned, this energy consumption can increase and threaten the carbon reduction policy in the environment. Regarding those aspects, such a form of acquisition is still the most socially and environmentally sustainable.

## 5 Final Remarks

Based on the present data analysis, 'local food' seems a sustainable way of acquiring food since it implies social sustainability since it places small farmers in the market and boosts the municipality's economy and in environmental sustainability. Reduce the transportation of trucks, energy consumption, and GHG emissions are also reduced. However, if the logistics of such transport are not well planned, this energy consumption can increase and threaten the carbon reduction policy in the environment. Such a form of acquisition is still the most socially and environmentally sustainable.

Potential strategies to develop a 'local food' system include promotional programs focused on local consumers, institutional purchasing programs that create direct links between local growers and local institutions, low-interest small loan programs for small or family farmers. Establishing a cost-share program may also help farmers transition to 'local food' production. Other important step includes increased food processing capacity in areas close to the consumption center that would amplify the local and regional market access.

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# Broiler Meat Production in Piaui State: A Case Study

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**Abstract.** The state of Piaui is inserted in the broiler production chain in a significant way as a feed-ration supplier in a vast new agricultural frontier. The present case study analyzes the evolution of a local company, as the Northeast presents itself as a promising market when comparing regional and national per capita consumption. For the present study, production costs were classified in the items of feed, labor, cost of capital, depreciation. Prices of the finished product (broiler meat) were investigated. Data included the production costs of broiler production from a commercial broiler farm. It was verified that the farm represents 63% of the regional production. Piaui state has emerged as a producer of soybeans and corn, and the slaughtered broiler of the largest producer pole is the southern region of Brazil. The transport is the main factor for raising the production costs of the meat supply chain.

**Keywords:** Brazilian meat production · Broiler meat supply chain · Meat market · Logistics

## 1 Introduction

Poultry meat is the 2$^{nd}$ world most consumed meat representing around 30 kg/capita/year [1], and the increase in consumption by 2027 is forecasted to be near 35 kg/capita/year. Such an increase in consumption comes from the less developed countries in Africa, Asia, and Latin America [2]. Globally 10% of meat output in the next 15 years span will increase coming from poultry meat production sector. Import demand will be weak during the first years of the outlook period, mainly due to the slower growth in China, but will probably strengthen in the second half of the projection period, due to import growth in the developing world (Asian potential emerging countries such as Viet Nam) [3]. The growth of broiler meat consumption represents expansion and the development of other derived chains.

Brazil is a broiler production country with 1.4 million tons produced on average in the last years (2015–2018) [3]. The Brazilian exports added up to 625 million tons in 2018, and the forecast to 2028 might reach 5,178 million tons [4]. The forecast of annual growth projected for the Brazilian consumption of broiler meat is 2.6% in the


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period 2017/18 to 2027/28, meaning an increase of nearly 30% increase in consumption over the next ten years. The consumption of broiler meat projected for 2027/28 is a probable consumption of 56.7 kg/capita/year [4].

The Brazilian Northeast region is undergoing a process of growth with little national representativeness, where only the State of Bahia stands out as the ninth position in the national production. Today the production profile of the region is focused almost entirely on domestic market. The state of Piauiis inserted in the productive broiler chain in two aspects, the first one as producer and consumer, with a consumption of 8.2 kg/capita in 2017. According to [5] the state is ranked second place as a supplier of feed-ration, within a vastnew agricultural frontier in Northeastern Brazil, currently in the 12th position in the national ranking according to the report on the Brazilian grain harvest [6].

The current study compares the information on the production costs of broiler amongst Brazilian regions. The present study analyzes the evolution of a local commercial broiler company, as the Northeast region has been evolving as a promising broiler meat market within the regional and national scenarios.

## 2 Literature Review

***Brazilian Broiler Meat Production Scenario***

Brazilian chain of broiler meat has been studied in several aspects [7] from the climate conditions of the country that favor the production, to the technological difficulties of investments in infrastructure and the dependencies of variations of the foreign exchange and commodities.

The economic crisis experienced in Brazil [8] in recent years has had a negative impact on gross meat consumption. The rise in unemployment and consequent reduction in the purchasing power of the population slowed down the domestic market. In parallel, there was a strengthening of exports, due to the Brazilian broiler health status, the professionalism of the productive chain, the exchange rate variation, and the product supply. In the year 2017, 33% of Brazilian poultry production was exported. Brazil expanded its sales to countries that were not amongst the leading national importers, such as Chile.

According to the Brazilian Animal Protein Association [3], in 2017 the Brazilian production of broiler meat was 13.5 million tons, keeping the country in the position of the world's largest exporter and second largest producer of broiler meat, behind only of the United States. Data [3] showed that, of the total number of broilers produced by the country in 2017, 66.9% were for domestic consumption and 33.1% for export. The broiler meat consumption in 2017 was 42.07 kg/capita year, and total export volume was 4.3 million tons exported to more than 150 countries, with almost 40% participation in the world market of broiler meat.

The industrial poultry sector employs more than 5 million people, directly and indirectly, and accounts for almost 1.5% of the national Gross Domestic Product (GDP). Thousands of integrated producers represent this sector, hundreds of processing companies, and dozens of exporting companies, which highlights its importance for the country [3]. The scenario of Brazilian production and consumption is shown in Table 1.

**Table 1.** Production and consumption of broiler meat in Brazil.

| Year | Broiler meat production (kg/capita) | Consumption (kg/capita) |
|---|---|---|
| 2018 | 63.10 | 43.32 |
| 2017 | 62.83 | 42.78 |
| 2016 | 62.62 | 43.25 |
| 2015 | 64.04 | 41.10 |
| 2014 | 62.70 | 42.07 |
| Growth (%) | 0.99 | 0.97 |

Adapted from [3].

***Broiler Meat Supply Chain and the Production Costs***

The production cycle in each house begins when the producer receives the 1-day-old chicks to grow until 43 days old when the birds reach 2.7 kg. After that, the broiler is delivered to a cooperative that slaughters, processes, and markets the meat.

The studied commercial broiler farm has seven houses with an average capacity of 14 birds per square meter, which meet the required standards. Houses were equipped with lateral curtains and hadan automated system of lighting, ventilation, temperature control, and fogging. The broilers spend 43 days in an ideal environment for the development of the flock. The preparation for receiving the 1-day-old chicks in the rearing environment begins before the arrival of the birds, with the cleaning, disinfection of the house, verification of the perfect functioning of all the equipment ensuring the proper rearing environment. The development of the chicks, especially in the first week of life, is a necessary condition for the broiler performance, as the physiological development influences body weight and feed conversion at the age of slaughter [9]. Figure 1 shows the overall scheme of Brazilian broiler production chain.

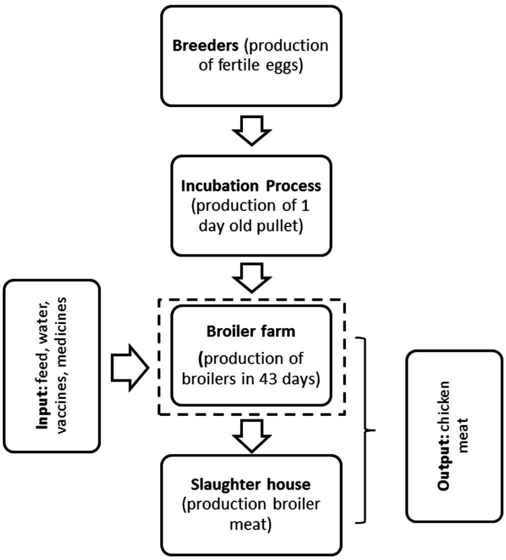


**Fig. 1.** Brazilian broiler meat supply chain (adapted from [10])

The production process has a period of 60 days. Cost accounting generates management information to be distributed across the organization to subsidize the operations' planning and control functions and the decision-making process [11]. Knowing the margin of the contribution of each product makes the manager has better control of the costs in the production process, thus maximizing profits and reducing the loss. The costs in broiler production are arranged according to the stages of the production process.

## 3 Methods

Data were recovered from January to December 2018. The sample studied is part of the production chain of a commercial broiler farm located in the metropolitan region of Teresina, in the State of Piaui (latitude - 5.04 S longitude - 42.57 W). The total area has a housing capacity of 15,205 $m^2$, distributed in seven houses where 625 thousand birds can be raised. The production process involved from receiving 1-day-old chicks to the delivery of grown broilers to the local cooperative. Each cycle lasts 43 days with a 20-day interval for the period of health cleaning, adding up to a total of five annual cycles.

The present study was a case study, where the data were collected on the farm. Data were converted into spreadsheets, which involved the production costs of broilers during meat production. Production costs were classified according to the items: feed, labor, cost of capital, depreciation, and others. In the other sort, vaccines and medicines, maintenance, commercialization, and electric energy were included.

Spreadsheet software Excel was used to compiling and processing the data. In the conversions of monetary values, the dollar exchange rate was used applying the arithmetic average of the considered periods (2017/2018). Prices of inputs and sales of the finished product were obtained, based on data from the local cooperative that receives the live broilers to slaughter. The production capacity was estimated according to the area of the houses considering a flock density of 14 birds/$m^2$.

## 4 Result and Discussion

Overall global annual meat consumption per capita is expected to reach 35.3 kg by 2025, an increase of 1.3 kg compared to the last 5 years period. This additional consumption will consist mainly of poultry meat, and nearly 90% is of broiler meat. In absolute terms, total consumption growth in developed countries over the projection period is expected to remain small relative to developing regions, where rapid population growth and urbanization remains the core drivers. According to [1] such a projection indicates an increase in the broiler meat per capita consumption growth, when compared to the previous period (average 2015 to 2017), will increase by 2.8 kg in developed countries and by half of this amount in developing countries. Over the next decade, production will benefit somewhat from better feed conversion rate and somewhat from positive meat-to-feed price margins as well as better feed conversion ratios. Increased productivity will also lead to a positive supply response and lower meat prices for the projection period. Poultry meat remains the primary driver of the growth in total meat production, mainly in response to expanding global demand in the developing world. Low production costs, high feed conversion ratios, and low product prices have contributed to making poultry the meat of choice, both for producers and consumers.

Based on the projection of the poultry market, Brazil is the world largest export market and the second largest producer [12]. The South region is characterized as the main producing region of the country, in the Northeast, the production of greater relevance is the state of Bahia occupying the 9th position with a total of 269 thousand birds in 2017.

It was verified, in the field research carried out, that the farm has an installed capacity of 625 thousand broilers/year, and such production represents 62.7% of broiler production in the municipality of Altos [5]. It was observed that it presents a guarantee of full consumption by the domestic market, confirmed by [3]. The report indicates that the State of Piauí is ranked 18$^{th}$ in the ranking of broiler production in Brazil, but it is not noted at the national level as an export market, as shown in Fig. 2.


**Fig. 2.** Brazilian states producers of broiler meat and the corresponding percentage of production in 2017. Source: [3]

The feed-ration represents 70.92% of the production costs of the farm, and four feed compositions are available according to the growth period. Feed management begins with the use of 0.20 kg/feed-ration for the bird in the first five days. Immediately after this period the initial feed is introduced for 21 days, allowing the consumption of 1 kg/bird, following the phase of growth for 10 days with the use of 2.2 kg of growth ration, closing the cycle with 0.9 kg of finishing ration in the last seven days of a cycle of 43 days. After the harvest of the birds for slaughter, the house undergoes into the process of sanitary cleaning, which ensures full sanitation and disinfection to receive a new flock after 20 days.

Due to its installed capacity, the area allows the production of 14 birds per square meter, a parameter that used in the Brazilian production process, which can vary from 12 to 18 head per square meter [13]. When analyzing the costs of production of a year, it was verified that it had an average cost/bird of US$ 2.11, which when compared to the cost of production of US$ 2.00 in the Southern region of Brazil. It is believed that in the case of the region of the largest production in the country, the scale of production influences the difference in cost of production in the order of 5.5%.

The AVIPE - Pernambuco Poultry Association [14, 15] presents an analytical study of datametrics that evaluate the poultry meat chain of the Northeast Brazilianregion, and assure that it should at least triple its production to fulfill the regional consumer market. The broiler production chain is growing on a large scale at the national level. In the Northeast, the consumption is 10.40 kg/capita, not yet reflecting the local consumption of 43.32 kg/capita. Given this perspective, the interest of growth in the productive capacity of the studied company is justified in order to reduce the average cost with the expansion of productive capacity by 70.92%, taking advantage of the economies of scale available in the years 2018 and 2019. The research sample suggested that the increase in production leads to better use of the economy of scale. However, the difficulties in the expansion of production in most broiler farms are related to the limiting factors of area and labor. Ina proper scale, there is a trend to pressure market pay-off for better price negotiations to make the activity viable.

The larger the scale of the business, the production operations facilitate the logistics of technical and veterinary assistance, as well as the supply of feed and 1-day-old chicks, in addition to negotiations of other inputs such as energy and maintenance. It is also allowed the poultry farmers to participate in the system of partnership with the agroindustry making the investments needed for production.

Table 2 presents the main costs that correspond to the selling price of broiler. The feed is the most relevant item, representing 76.4% of the total costs.

**Table 2.** Broiler meat production cost

| Expenses (10^2 US$) | National/2018 | National/2017 | Local/2018 | Local/2017 |
|---|---|---|---|---|
| Feed ration | 51.44 | 57.02 | 64.63 | 64.79 |
| Labor | 4.65 | 5.13 | 1.52 | 2.12 |
| Capital cost | 1.37 | 1.51 | 4.23 | 4.22 |
| Depreciation | 1.64 | 5.73 | 1.20 | 1.34 |
| Other | 14.78 | 16.29 | 18.71 | 18.32 |
| Total | 73.88 | 85.69 | 90.29 | 90.79 |

## 5 Final Remarks

Given the complexity of the market dynamics and because broiler meat is a commodity, there is a significant international oscillation of the purchase value. Because Piaui state is emerging as a producer of soybeans and corn, which are the primary input products of broiler feed-ration, producing broiler meat in the region should remain profitable. Such condition decreases the transport of raw material for processing the feed. It is also worth mentioning that in the case of buying the slaughtered broilers from the largest producer pole that is the southern region of Brazil, the average road distance would be approximately 3,000 km from the state capital (Teresina), where logistical costs appears as a determinant factors for raising the costs of broiler meat for the local market.

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# Collaborative Production Chains: A Case-Study of Two Agri-Food Companies in Brazil

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**Abstract.** A collaborative production chain is often understood as having a known degree of relationship among members of the chain to share risks and benefits that result in higher commercial performance than individual organizations. The current study aimed to analyze two production chains of cashew and honey in Northeastern of Brazil which work collaboratively. Characteristics of the chains were learned from interviews with technical personnel from agricultural extension office and farmers. Results indicate that despite the best harvest cashew farmers might have when the crops are pollinated by bees both partners are not fully satisfied with the collaboration. A partner might benefit from management items that help to assess collaboration performance more effectively such as joint efforts, sharing activities, collaboration value, adaptation, trust, commitment, continuous improvement, coordination, and stability. Supply chain collaboration improves the performance advantage and has a significant influence on firm performance; however, such an initiative needs to be understood as a win-win association by the partners to achieve the expected success.

**Keywords:** Collaborative supply chains · Cashew crop · Honey production

## 1 Introduction

A collaborative production chain means that two or more independent companies work in association to plan and execute production operations more successfully than when acting alone. This concept is often used in the supply chain, suggesting a known degree of relationship among members of the chain to share risks and benefits that result in higher commercial performance than individual organizations [1]. One of the ways collaborative chains work is through the sharing of research [2]. Resource sharing refers to the process of influencing skills and leveraging assets in the supply chain


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partners. Resources may include physical resources such as area, manufacturing equipment, facilities and technology [3].

The interaction between the actors of the business environment, acting cooperatively and sharing the same vision, reduces efforts, such as greater agility, flexibility, quality of products and services offered to customers. The maturity and efficiency of the operationalization of the strategy between two or more companies present a strong relation and direction of the efforts, that together cooperate in the co-creation of value [4]. The collaborative initiative of a supply chain often comes from integrated solutions that result in economies of scale that eventually reduce costs and increase revenues. In some cases, there is a common base of needs or even a way to solve a common problem. Using IT, for example, can be a good example of collaboration. Often IT associates supply chain collaboration with inter-organizational process improvements along with information systems, allowing chain members to effectively deliver products to end customers at minimal cost [5].

Value food chains are the financing of income for small farmers in most developing countries. Authors present an innovative model for improving the maize value chain in India [6]. The open innovation business model approach can strengthen farmers identified weak links. The business model explicitly developed promotes information sharing, innovation, collaboration and feedback cycles within the value chain, as well as support cases from similar approaches. Another form of collaboration was discussed in perishable foods in agribusiness in Tanzania [7]. The authors' findings show that, in a fragmented value chain of preprocessed fruits and vegetables, actors are aware of each other, but very little formal cooperation occurs, and the transactions are market-based and price-driven. The business strategy is the creation of a chain that provides values and that works from a multiplicity of diversified processes [8].

About one-third of the world's food crops depend on varying degrees of pollinators - including management bees (*Apis mellifera*) and native bees [9, 10]. Pollination is considered an important ecosystemic service, essential for food production, favoring the production of higher quality fruits, weights and seeds [11]. Mainly in large areas of monocrops, whose pollination services offered by ecosystems are not always able to meet the high demand for pollination of the target crops [12]. The potential of pollination as an ecosystem service can be highlighted when associated with food production. [13] estimated between US$ 235 billion and US$ 577 billion. In Brazil, it is estimated that pollination related to agricultural production has an annual value of US$ 12 billion [14]. In the U.S., the market for pollination services has grown so much in the past decade that beekeepers now receive a larger share of their income from pollination services than from honey production [15]. Pollination is crucial for the whole of flowering fruit plants. As cashew is highly pollinated by insects mainly bees, its activities in cashew intensive production play a vital role in increasing yield.

In Brazil, unlike the U.S. and European countries, the use of bees for pollination is quite scarce. In the Northeast region, it is common practice to rent hives for pollination of the melon, and in the South with the pollination of the apple. This fact, scarce pollination, can be explained by the diversity and presence of natural pollinators in Brazil, which has been decreasing considerably in recent decades due to deforestation, the use of agrochemicals and the lack of knowledge about the real importance of insects in pollination of crops [12]. The primary challenge of current beekeeping is the adoption of sustainable management practices appropriate to the different seasonality of the environmental conditions faced by these bees in most localities.

The present exploratory study aimed to investigate the collaborative production chain of two agricultural products (cashew and honey) in the semi-arid region of the state of Piauí, in the Northeastern region of Brazil.

## 2 Methods

A qualitative case study was carried out, through the analysis of a scenario and interviews to identify, categorize, and analyze the collaborative chains of cashew and honey productions in the Northeastern of Brazil.

A scenario of the production chains (cashew and honey) that was the goal of the current study was draw-up based on bibliographical research. The scenario was compared with data collected directly from interviews of the representatives of the producers of these crops (4) and technicians from public agencies of assistance to the rural producer (2). In the interview questions related to the collaboration terms and satisfaction of the partners were asked.

## 3 Results and Discussion

Piauí is in the second rank amongst the Brazilian states with the most significant number of businesses focused on cashew and in the fourth rank with the largest number of establishments focused on beekeeping. The scheme of interface of the production chains is shown in Fig. 1.

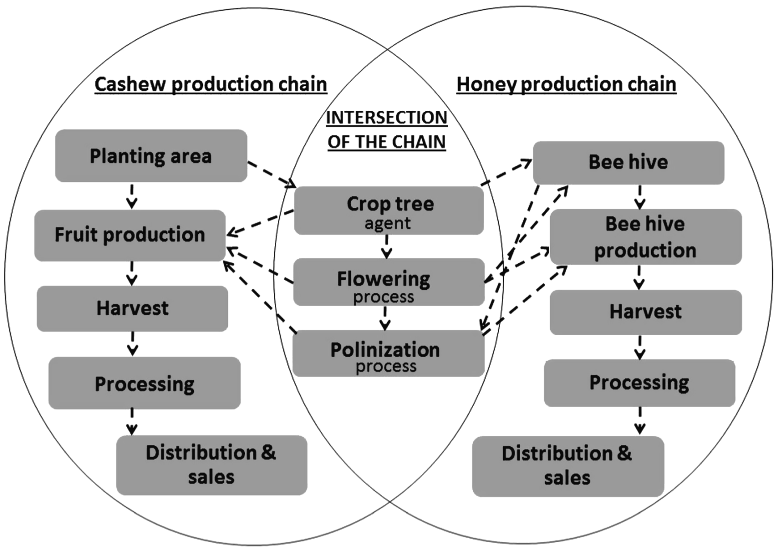


**Fig. 1.** Scheme of the two studied collaborative production chains cashew and honey.

Interviews with producers (4) and technicians (2) from the region's Technical Assistance and Extension Institute (EMATER) reported that the association between cashew production and honey production and that the percentage of honey production in this condition represents only 5% of all honey production the state. Such an issue is that because the costs are high. There are few beekeepers, classified as medium or large producers, and who has enough resources to cover the expenses of migratory beekeeping. While in the U.S. every winter (January to March), beekeepers move up to 55% of their bee colonies [16].

The movement of bee colonies throughout the country is driven mainly by two reasons: the provision of pollination services in different parts of the country (1) and the search for fodder to produce honey and guarantee the survival of the colonies in the winter (2). Farmers who grow crops that require or benefit from pollination (e.g., almonds) pay beekeepers to pollinate their crops [15].

Most of the income earned by beekeepers in the U.S. comes from pollination services that receive a higher share of their revenue from pollinating services than from honey production [10, 15].

In the Northeast of Brazil, especially in the states of Ceará, Piauí, and Rio Grande do Norte, there are large areas of cashew (*Anacardium Occidentale*) crops both for internal consumption, and export (nut and peduncle). Because it is an attractive crop for bees, it is possible to produce monofloral honey from this flower [17]. Collaboration between the cashew producer and the beekeeper is critical to a win-win outcome. Such an interaction between those involved in the business, working collaboratively, reduces efforts and can improve the quality and quantity of products that will be offered to customers.

Studying the same crops in Benin [18], the authors found that between 25 and 72% of cashew flowers were not pollinated in nature because of the limitation of pollinators and also stated that an increase of 157.8% would be possible if the flowers received adequate pollen. Honey production and pollination services are activities that do not always go in collaborative ways [16]. One of the main obstacles to the development of the pollination market has been the results obtained with the use of bees as pollinators since beekeepers do not care about the pollinating efficiency of their hives, but only in producing as much honey as possible. Pollination results usually fall short of what would be expected. The insignificant results mean that farmers do not incorporate pollination services as factors of production of their agricultural activities, nor do they attract other farmers to use pollinators in their crops. The concern of beekeepers to adopt rational pollination programs that considered these and other factors would certainly significantly increase the efficiency of pollinating agents and the demand for their services [15, 16].

The results from [2] indicate that supply chain collaboration improves the performance advantage and has a significant influence on the company's performance. The authors emphasize the fact that the production chain partners adapt to achieve appropriate synergies and create superior performance.

In the present case study, the collaborative initiative occurred aiming the improvement of the chains' production performance. The results from [2, 5, 7] indicate that supply chain collaboration improves the performance advantage and has a significant influence on the firm performance. The authors emphasize the fact that the production chain partners trend to adapt to achieve appropriate synergies and create superior performance.

## 4 Final Remarks

Despite the achievement on other urban-industrial collaborative supply chains, the key behavioral factors to enable an effective collaboration system for sustainable agri-food supply chains to require joint efforts, sharing activities, collaboration value, adaptation, trust, commitment, power, continuous improvement, coordination, and stability. The agri-food supply chain collaboration might benefit from these management items that help to assess collaboration performance more effectively.

It has been evident from the review of previous studies in the cashew production matter, that such collaboration has a broad scope to raise current cashew yields by supplementing pollination. Thus, learning from the success of beekeeping in other countries (The US, Benin, and Ghana), pollination can be complemented by the inclusion of beehives in the field to increase productivity.

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# An Evaluation of Brazilian Ports for Corn Export Using Multicriteria Analysis

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**Abstract.** Brazilian corn production has an expressive participation in world trade stage. Agribusiness has been growing and gaining an important position for economy in Brazil. The Brazilian corn harvest for 2017–2018 was 82 million tons, placing Brazil as the third largest global producer behind China and the United States. This study compares four south and southeast Brazilian corn exportation ports according to their operations, infrastructure and geographic position. A multicriteria decision tree was established and, with the analytical hierarchy process (AHP) tool, an informational database, and considering expert opinions about the gathered data, we were able to determine which ports are the better choices for corn exportation. Surprisingly, Rio Grande took a better place than Paranaguá's port. Its operations and infrastructure nodes have the same weight in terms of decision making. However, a port's geographical position has a very weak decision-make importance. Furthermore, Rio Grande is almost three times better than Paranaguá in Water Depth and this made Rio Grande beat Paranaguá from an infrastructure point of view. So, the operations node was the point to pay attention to, and this is the main reason for Rio Grande's position.

**Keywords:** Analytic hierarquy process · Port logistics · Agricultural commodities · Hinterland

## 1 Introduction

Agribusiness plays a prominent role in the Brazilian economy. New technologies for planting, expansion of planted areas, and increased productivity have allowed Brazil greater participation in global grain production [1]. In the 2017–2018 year crop, Brazil corn production, for instance, was 82 million tons, placing Brazil as the third largest global producer behind China and the United States, which produce 259 and 371 million tons, respectively.


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The port platforms are strategic for Brazilian corn exports. The practice of how the port is integrated into the process and its ability to generate value for the logistics chain are decisive factors for Brazil's competitiveness in the international market [2–8].

The aim of this article is to compare the main ports for Brazilian corn exportation regarding their operations, infrastructure, and geographical position. To this end, we establish a decision tree and by using the analytical hierarchy process (AHP), informational databases, and specialist opinions we could conclude that operations and infrastructure quality have the same impact in decision making.

The article as divided as follows: After this introduction, a methodology is detailed, while the results and discussion section present the paper's findings, and the conclusion highlights the most interesting results.

## 2 Methodology

The methodology of this work consists of a comparison of four Brazilian ports that export corn: Santos, Paranaguá, Rio Grande, and São Francisco do Sul, which are responsible for the disposal of corn exports from the Central-South macro-region (amounting to 71 million tons for the 2017–2018 harvest) [1].

To compare these corridors, we based on the considerations made by three operations managers of the main corn handling ports in Brazil, Santos and Paranaguá respectively [9], and we developed a decision four considering three areas: port infrastructure, port operations, and port geography. For each criterion was created several sub-criterions, Fig. 1.

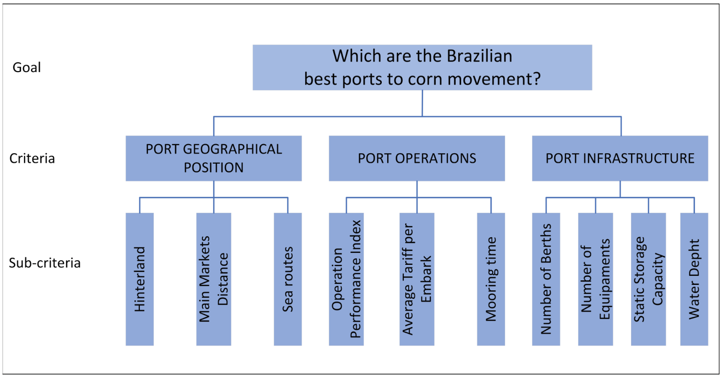


**Fig. 1.** Decision tree

To solve the decision tree and identify which was the main port to export corn we used AHP for the decision-making process.

The AHP method was developed by Tomas L. Saaty, being a multicriteria method more widely used and known in support of decision making, with problems with multiple criteria [10].

The criteria and sub-criteria are compared using an importance scale numbered between 1 and 9, where 1 indicates equivalent importance and 9 extreme importance. After that AHP converts the comparisons into fractions and the weight of each in the decision model is established [11].

Once the comparisons and relative weights between the criteria to be evaluated have been established, the numerical probability of each of the alternatives is calculated. Thus, it is possible to determine the probability that the alternative has met the established objective [12]. The participation of specialists in the judgment of any particular theme is fundamental for the construction of the decision tree in AHP [13]. This work specialists judged the comparisons considering the data provided [9,14–21].

## 3 Results and Discussion

The Fig. 2 presented the main results.

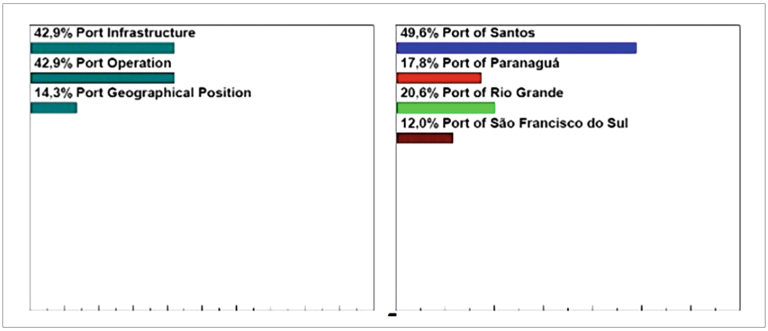


**Fig. 2.** General result

As shown in Fig. 1, the overall results point out that the port of Santos was the best choice for corn movement. This result is not surprising considering that Santos is the most important port in Latin America and responsible moving 67% of Brazilian GDP [7]. The same thing is true of São Francisco do Sul, which does not have good infrastructure and has difficult access.

The result that deserves a look is the ports of Paranaguá and Rio Grande. Both of these ports show similar results for port infrastructure. Nonetheless, Rio Grande's port operations are better than Paranaguá's. This latter reason has vaulted Rio Grande's position over Paranaguá, as Fig. 3 shows.

Also depicted in Fig. 3, another aspect that must be strongly considered is the dynamic sensitivity of nodes, port infrastructure, and port operations, which have the same sensitivity. However, a port's geographical position, where the port of Santos has the highest performance of all, and the port of Paranaguá is much better than that of Rio Grande, which has the weakest sensitivity.

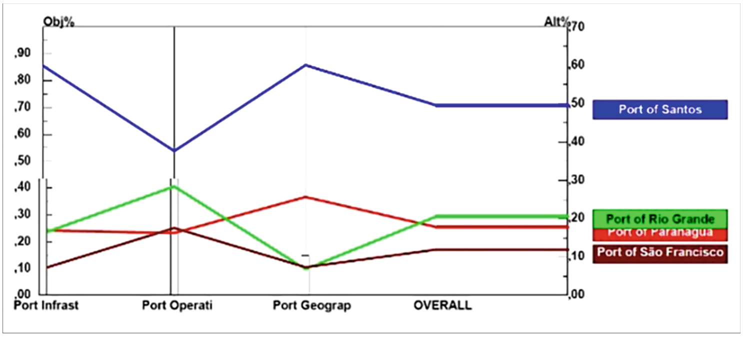


**Fig. 3.** Performance sensitivity nodes by criteria

One striking result indicates the port's geography has low influence on shipment movements going to Brazilian ports. One of main the reasons could be that any distance under 2,000 km between ports does not affect route decisions if shipments are traveling for more than 10,000 km. At the same time, there is no difference between port operations and port infrastructure in terms of decision making. Both have the same impact on corn movement decisions.

Once port operations and port infrastructure were considered to be the main criteria for decision making, we analyzed the sub-criteria in detail regarding just Paranaguá and Rio Grande once Santos was seen as the best option. Figure 4 presents sub-criteria for port operations.

Both Paranaguá and Rio Grande have almost the same score for the infrastructure node. Depicted in Fig. 4, we can see the four topics considered in analysis and their sensitivities: static storage capacity (0.381), water depth (0.335), number of berths (0.187) and amount of equipment (0.097). Rio Grande is better than Paranaguá only in terms of water depth, almost three times better. It was enough to tie Rio Grande and Paranaguá for this node.

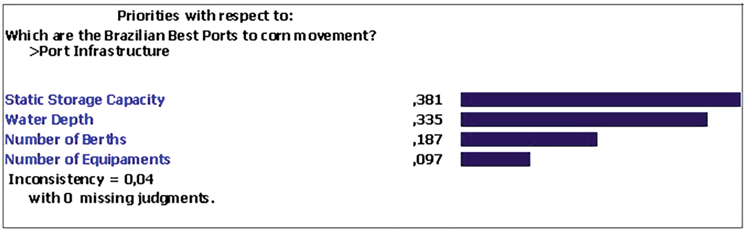


**Fig. 4.** Port infrastructure

Both Paranaguá and Rio Grande have almost the same score for the infrastructure node. Depicted in Fig. 4, we can see the four topics considered in analysis

and their sensitivities: static storage capacity (0.381), water depth (0.335), number of berths (0.187) and amount of equipment (0.097). Rio Grande is better than Paranaguá only in terms of water depth, almost three times better. It was enough to tie Rio Grande and Paranaguá for this node. Figure 5 presents the results for Port Operation criteria.

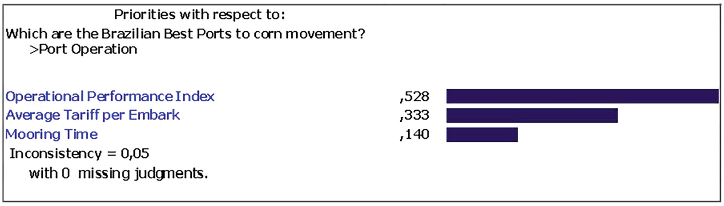


**Fig. 5.** Port operation

Eventually, as can been seen in Fig. 5, in port operations there are three sensitive topics, too: mooring time (0.140), average tariff per embarkation (0.333) and operational performance index (0.528). The port of Paranaguá was the worse choice in two of the three parameters. Paranaguá was better than Rio Grande only in its operational performance index.

## 4 Conclusions and Outlook

Regarding our results, we confirm that port of Santos is the main port for corn export due to having better port operations and infrastructure, despite its higher costs.

The port of São Francisco do Sul is of interest in terms of cost. However, its poor infrastructure and operations placed it last among the four options.

Nonetheless, considering the ports of Paranaguá and Rio Grande an unexpected situation occurred. The decision tree showed that the latter is a better choice than the former despite the longer distance to production areas.

Analyzing dynamic sensitivity for port infrastructure and port operation nodes (i.e., both being 42.9%) and port geographical position (14.3%), where the port of Paranaguá has a great advantage over Rio Grande (which has just 14.3% of dynamic sensitivity) we concluded that the port of Paranaguá urgently needs to improve its operations to avoid grain shipments migrating to Port of Rio Grande.

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# Port Terminals Assessment: An Empirical Analysis of Requirements of Brazilian National Plan of Port Logistics

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**Abstract.** Brazilian National Port Logistics Plan (PNLP) aims to develop strategic actions to increase operational efficiency in Port systems. The Port of Santos is the largest exporter of grains and has vital importance for the country economy. The present study objective to evaluate among the 13 strategic actions developed by the PNLP which are the most important for port terminals. Therefore, a survey was carried out with managers of all Santos terminals specialize in agricultural products. Our results showed that 75% of respondents highlighted port security as a top priority. Secondly, 62,5% of them point out improvements in operational processes (consolidate paperless port, waterway access, consenting bodies, the efficiency of navigation agents), and finally, 50% of interviewed said that actions to guarantee the accessibility of the vessels are essential.

**Keywords:** Port of Santos · Agricultural Commodities and Port Infrastructure

## 1 Introduction

Brazil is one of the world's leading producers and exporters of soybeans and corn. The country is the largest producer of soybeans with 120 million tons, and comes in third place with corn at 82 million tons, for the 2017–2018-year harvest. Regarding the exporter's ranking by tonnage, it ranks first for soybeans with 76 million tons, and second for corn with 22 million tons [1].

Facing port bottlenecks caused by this high quantity of commodities exported is a challenge. Hence, Brazil developed the National Port Logistics Plan (Plano Nacional de Logística Portuária-PNLP).


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Despite the fact that the Brazilian port system has made great strides over the last 35 years, where Law 8.630/93 (that changed the model of cargo handling, administration, and exploration for new ports), and Law 12.815/13 (that provided a new regulatory framework for the sector) [2–6], many challenges still exist [7–9] herefore, in 2014 the Brazilian National Secretary of Ports (SNP) extrapolated the PNLP over the period 2015–2042 [10]. Figure 1 shows the structure of PNLP.


**Fig. 1.** Structural basis of the National Port Logistics Plan. Source: [10]

The PNLP aims to identify vocations from several ports, defining short, medium, and long-term scenarios-by the year 2035, hoping to set and reaching goals through 2042. The main premise is to establish alternatives for intervention in infrastructure and management systems, ensuring an efficient allocation of resources from resource prioritization [10].

The first phase of the PNLP consisted of diagnosing the port sector for 2010–2014, establishing the following areas: economic management, operations, capacity, logistics, and environment. Afterwards, a cargo forecast was made based on demand projections for 2015–2042, as well as the allocation of cargo in ports for horizons through 2020, 2030, and 2042. The third phase defined the strategic objectives: monitoring indicators and goals, definition of strategic actions, and definition of the investment portfolio.

Our proposal in this article was to identify the dimensions of the assessment of port operators (maritime terminals) in relation to the strategic actions defined in the PNLP. Thus, we intended to answer the following question:

– Do the actions of PNLP meet the priority demands of port operators?

To this end, a survey was carried out with the eight terminals specialized in handling grains at the port of Santos.

### 1.1 Port of Santos

Sharing 28% of Brazil's international trade flow, the port of Santos is the main port of the country. Located on the coast of the state of São Paulo (southeast region) in the cities of Santos and Guarujá, it is a public port and has approximately 15 km of geographical extension, 55 maritime terminals, and 65 berths. The Santos port complex in 2018 accounted for 4,046 ship moorings and moved 133 million tons of cargo [11,12].

Accessibility and the existence of the economic influence zone are the two main factors drawing cargo to the port of Santos. Five states make up the primary area of influence of the Port (São Paulo, Minas Gerais, Mato Grosso, Mato Grosso do Sul, and Goiás), which together represent 67% of Brazil's gross domestic product [13].

## 2 Methodology

In order to identify the dimensions of the PNLP adopted for grain terminals in Port of Santos, we conducted a survey following three stages.

**First:** a literature review was performed to understand the goals, strategic actions and structure of the National Port Logistics Plan - PNLP.
**Second:** we conducted a survey with managers of eight terminals specializing in agricultural commodities shipping. They operate with soybean, soybean meal, and corn. These terminals have a static capacity of 1,281 thousand tons and are located five of them on the right bank of the port (Santos) and three on the left side (Guaujá) (Fig. 2).
**Third:** we applied a questionnaire to terminal managers based on the thirteen strategic actions developed by the PNLP (i.e., objectives and operations indicators) regarding five distinct areas: economic management, operations, capacity, logistics, and environment (Fig. 3).

## 3 Results and Dicussion

The survey results are presented in the Fig. 4.

Around 75% of respondents pointed out that port security was a high priority. The international Ship and port facility security (ISPS CODE) has been the basis of a comprehensive system of mandatory protection for international maritime transport [15]. Following the Sept. 11 attacks in New York, at the request of the United States, world ports had to take special security measures. In Brazil terminal inspections and certificate concessions are responsibilities of the National Commission for Public Safety in Ports, Terminals and Waterways - CONPORTOS, following the international code of the International Maritime Organization - IMO [16].


**Fig. 2.** Location of the eight terminals in the Port of Santos. Source: [14]

| Questions |
|---|
| 1. Automate operational procedures ? |
| 2. Consolidate the use of the Paperless Port for the release of vessels and cargoes ? |
| 3. Deploy ISPS in the port facilities of public ports ? |
| 4. Ensure operating conditions for waterway accesses ? |
| 5. Harmonize the Paperless Port (PSP) with the Single Foreign Trade Portal ? |
| 6. Implementing the Traffic Management System for Vessels in Brazilian ports ? |
| 7. Modernize the processes of agreement ? |
| 8. Promote the resolution of port 24 hours ? |
| 9. Reduce non-operational time before start-up and after and after completion of cargo handling operations of docked ships ? |
| 10. Simplify long-course navigation processes ? |
| 11. Simplify your home navigation processes ? |
| 12. Stimulating the search for efficiency by navigation agents ? |
| 13. To regulate the economic of the zones of practice and services of cabotage ? |

**Fig. 3.** Questionnaire questions. Source: Adapted of [10]

The main representatives of the port terminals report that international drug traffic is the main concern related to port security. The Port of Santos has been the main route of drug traffickers to the European continent [16].

Around 62,5% of respondents highlighted operational actions (e.g., consolidated paperless port, waterway access, consenting agencies, efficiency of navigation agents).

| | Main Results | % |
|---|---|---|
| Very<br>Very strong<br>Extremely strong | Deploy ISPS in the port facilities of public ports | 75.0 |
| | Consolidate the use of the Paperless Port for the release of vessels and cargoes | 62.5 |
| | Ensure operating conditions for waterway accesses | 62.5 |
| | Modernize the processes of agreement | 62.5 |
| | Stimulating the search for efficiency by navigation agents | 62.5 |
| | Ensure operating conditions for waterway accesses | 50.0 |
| Not importante<br>Equal importance | To regulate the economic of the zones of practice and services of cabotage | 50.0 |
| | Automate operational procedures | 37.5 |
| | Harmonize the Paperless Port (PSP) with the Single Foreign Trade Portal | 37.5 |
| | Simplify long-course navigation processes | 37.5 |

**Fig. 4.** Results. Source: Authors

Among these actions highlight the Paperless Port (PSP) that is a support system to facilitate the analysis and release of documents in Brazilian ports. This means that documents are converted into a single electronic document, the Virtual Single Document (DUV) [17]. According to the PNLP, the deadline to regulate the use of the Paperless Port system in Brazilian ports is until [10].

And half of the interviewed 50% cited actions that guarantee accessibility to the vessels. As effective actions, 236.9 million reais were invested in dredging in 24.6 km in the access channel of the Port of Santos [18].

In one minor issue, 50% indicated the regulation of practical and cabotage issues. In spite of the importance of cabotage in the operations of the world ports [19,20] the low importance here refers to the fact that the grains arrive from the producing states by rail and road, in addition the terminals only dispatch cargoes to the international market.

Eventually, around 37,5% of managers noted the desirability of automated operational procedures, harmonizing the paperless port and foreign trade portal, along with the long-haul navigation process.

## 4 Conclusions and Outlook

Although the port operators seek to improve processes to increase operational efficiency, the results presented indicate that among the strategic actions proposed by the PNLP security (i.e., international shipping and port facility security code) was highlighted as the main priority.

The goal for ISPS code deployment will be sought in 100% of the national ports until 2025. As for the improvements in operational processes, SNP has established five years (2015 to 2020) as a global goal. However, to date there is no governmental data that measures the results, which is the main limitation of the present study.

For future work, we intend to analyze the results of the PNLP strategic actions.

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# Brazilian Coffee Export Network: An Analysis Using SNA

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**Abstract.** Coffee is the most widely consumed beverage in the world, Brazil being its largest producer and exporter. The present study aims to identify the Brazilian coffee trade regarding import markets, main routes, volumes, and main grower states. The proposed methodology adopts a social network analysis approach using the software UCINET 6.0© and Netdraw 2,166©. A graphical network is developed to analyze the coffee flow among countries. Besides, the degree of centrality is measured using a matrix that considers 1 or zero. Our results show that Minas Gerais, São Paulo and Espírito Santo have more influence on the network and degree of centrality, inducing the fact that they export to several countries. Germany, United States, Italy, and Japan represent the most important markets. Finally, we conclude that Germany is the leading Brazilian partner with 21% of country coffee export and the most important player of the supply chain.

**Keywords:** Coffee · Brazilian production · International trade

## 1 Introduction

Coffee is one of the most consumed beverages globally. The 2018/19 year crop world coffee production is foreseen as 174.5 million bags of 60 kg [1,2]. Brazil is the largest producer and exporter of coffee and second largest consumer in the world [3,4]. In 2018, the country produced 61,200 thousand bags [5].

With favorable climate and abundant rainfall, Brazil offers an ideal place for the development of this type of plantation. However, Brazilian coffee is mostly exported as green coffee with low added value [6,7].

Currently, two species of grains were cultivated in the country: Coffea arabica and Coffea canephora. The arabica grain is used in high-quality blends, while the other species, known as robust or conilon, is used in the preparation of soluble coffee [3,4].

Brazil has a forecast of 61.7 million bags in the crop year of 2018/19, which means the country will continue as the world leader [8]. Based on this prediction,


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the importance of Brazil in the coffee exports market is evident. Thus, a rise of 32 % in its production is expected [4].

Given this scenario, it is essential to understand the coffee supply chain and investigate how trade works among countries. This overview is interesting not only for Brazil but also for countries and consumers connected to the Brazilian coffee supply chain.

Therefore, this study aims to identify the Brazilian coffee export network and main routes, volumes, and main grower states. The idea is to understand the flows identifying the importance of Brazilian hinterland for coffee exportation. To this end, we perform a social network analysis (SNA) using UCINET 6.0© and Netdraw 2,166©.

## 2 Methodology

As outlined in the Introduction, we aim to investigate the relations and flows of the Brazilian coffee supply chain. For this purpose, we conduct the follow steps:

- In the first step we collected the volumes of production coffee in order to identify the import countries and regions in Brazil responsible for exports. The data were collected from the COMEX STAT system of the Brazilian Ministry of Development, Industry and Foreign Trade (MDIC) [9], and the International Coffee Organization (ICO) [8].
- After, we processed them using Microsoft Excel in a relational matrix. The relations between import countries and Brazilian regions were established in two-fold: (1) considering the volume of exports in 2018 and (2) indicating the number 1 when a connection exists and 0 otherwise.
- The analysis considered the relations among Brazilian states and import countries in volume of coffee exported plotting a graphical network using Netdraw 2,166© [10], and
- Eventually, the degree centrality was performed with matrix 1 and 0 using UCINET 6.0© [10]. The degree specifies how many nodes were connected to a specific node, known for a "popularity" of a node (actor), divided into two dimensions: in-degree and out-degree [11].

## 3 Results and Discussion

As mentioned earlier, the relations among coffee-producing Brazilian states and import countries were studied using UCINET 6.0© and Netdraw 2,166©. Figure 1 shows the network plotted considering the number of relations and volume of exports.

Figure 1 shows that Minas Gerais, São Paulo, and Espírito Santo have more influence on the network centrality degree, because they export for several countries, as can be seen by the node size. Regarding the importers, Germany, United States, Italy, and Japan were highlighted with the major volume represented for the strength of lines.

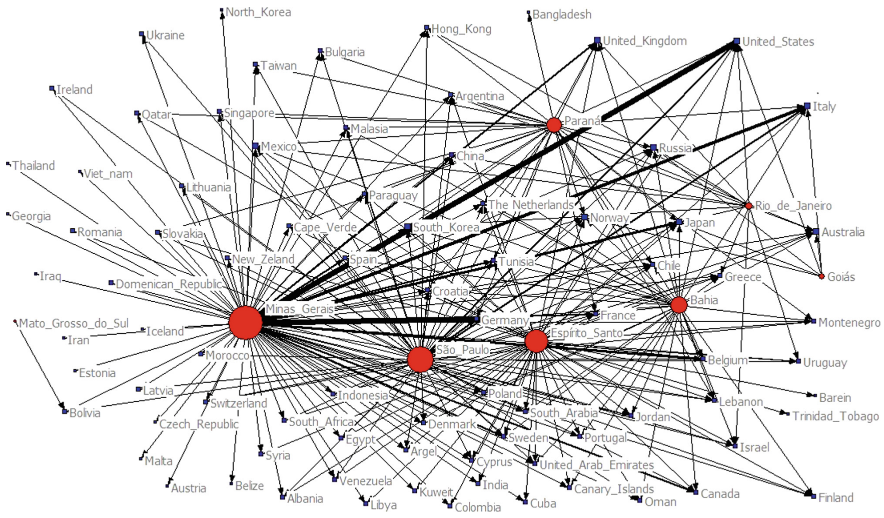


**Fig. 1.** Brazilian coffee exports network

Coffee production is of great importance for developing countries. For many of them, coffee production is essential to structure their economies, although it still remains a commodity.

With the impositions of consumers, who aspire to increasingly specific characteristics and ecologically correct values, coffee is gaining the status of "specialty" [12,13].

Minas Gerais, São Paulo, and Espírito Santo stand out as the largest producers of the grain in Brazil, and such volume can be attributed to the topographic and climatic characteristics of these states, which provide high-quality plantations [3].

Brazil has a favorable climate with different reliefs, which results in special characteristics for cultivation. In addition, a large amount of rainfall collaborates, making the country a producer of various grain qualities that were used for the production of blends [3,4,8].

Regarding the export of these grains, Brazil maintains a straight relation with the World Trade Organization (WTO) and is expected to continue being the world leader in coffee exportation, with a stake of around 32% [4,8,14].

The largest coffee importer is Germany, with 34% stake. It is an important hub of trade in Europe, playing an important role in the reexports of the grain, grounded in its logistical capacity. With a share of 53% of the EU market, it is considered the largest reexporter. The country is still responsible for about 20% of the grain consumption in Europe [15,16].

Germany is considered the largest European reexporter of green grains, followed by roasted and last soluble grains. Due to its diverse network of imports, the country can produce blends that are pleasing to the most demanding customers [17].

### 3.1 Degree of Centrality

An important measure for calculating the role of an actor in a network is centrality degree. As mentioned, we attempt to identify this degree by using numerical measures. Germany, for example, presented a low centrality degree in comparison with Minas Gerais due to its network, which reflects all relations.

Centrality degree demonstrates which actors are at the center of the relations [1]. It can be illustrated in two ways: outdegree, which measures relations from an export viewpoint - Table 1, and indegree, which measures relations from import perspective - Table 2.

**Table 1.** Relation of Brazilian coffee-exporting states

| Country | Outdegree | Nrm outdegree | Volume | % Volume |
|---|---|---|---|---|
| Minas Gerais | 79.000 | 0.888 | 20435673.000 | 0.816 |
| São Paulo | 59.000 | 0.663 | 2592659.000 | 0.103 |
| Espírito Santo | 52.000 | 0.067 | 1481201.000 | 0.059 |
| Bahia | 34.000 | 0.382 | 288808.000 | 0.115 |
| Paraná | 30.000 | 0.337 | 178248.000 | 0.007 |
| Rio de Janeiro | 13.000 | 0.146 | 25755.000 | 0.001 |
| Goiás | 6.000 | 0.067 | 16888.000 | 0.0006 |
| Mato Grosso do Sul | 1.000 | 0.011 | 263.000 | 0.00001 |

Source: Adapt from COMEX STAT [9].

**Table 2.** Relations among Brazilian coffee-importing countries

| Country | Indegree | Nrm indegree | Volume | % Volume |
|---|---|---|---|---|
| Germany | 5.000 | 0.056 | 309670080.000 | 0.214 |
| United_States | 7.000 | 0.079 | 304009696.000 | 0.210 |
| Italy | 6.000 | 0.067 | 155597344.000 | 0.107 |
| Japan | 7.000 | 0.079 | 101587232.000 | 0.070 |
| Belgium | 5.000 | 0.056 | 94607536.000 | 0.065 |
| Canada | 4.000 | 0.045 | 39715872.000 | 0.027 |
| France | 1.000 | 0.011 | 39548240.000 | 0.027 |
| Spain | 5.000 | 0.056 | 33496540.000 | 0.023 |
| Sweden | 4.000 | 0.045 | 32974272.000 | 0.022 |
| United_Kingdom | 6.000 | 0.067 | 27135916.000 | 0.018 |

Source: Adapt from COMEX STAT [9].

As seen in Table 1, Minas Gerais is the most important node, sending coffee to 89% of the countries of the network and representing 82% of the movements. The results confirm the role of Minas Gerais in Brazil's coffee exports.

In Brazilian history, São Paulo was a coffee producer and Minas Gerais was milk producer. They were so important at the beginning of the last century that they were used to influence the Presidential elections during the first republic period when candidates of both states altered in power [18]. At present, coffee production migrates to Minas Gerais to take advantage of the mountain regions and adequate climate for production [3,4].

Table 2 demonstrates that Germany, United States, Japan, and Italy are the most relevant importers. While the US and Japan consume a large amount of coffee, Germany and Italy, beyond the consumption, run some coffee blends.

Germany is a real case of success, with a huge and efficient logistics infrastructure linked with an ability to produce a peerless coffee blend. They buy large amounts of green-coffee for processing, industrialization, and resale all over Europe.

Given this situation, we can infer that Brazil and the most part of the producers do not have technology and knowhow for grain processing and end up selling their product as a commodity, allowing the roasting industry to gain huge profit in the sale of the grains [6].

The World Intellectual Property Organization reported in 2017 [5] that the producer sells 1 lb of grain for US$1.25 for the exporter, which passes to the industry at US$1.45. The roasting machines negotiate the final product on average for US$4.11.

## 4 Conclusions and Outlook

The main conclusion of our study is that Minas Gerais represents an essential node in the Brazilian coffee international trade. Using the SNA metric, we identify that the state is related with 89% of importer countries and responds for 82% of Brazilian coffee exports in 2018. This result shows the necessity of further investigation of coffee plantation and export process in this state.

Another striking conclusion is that Germany is the main Brazilian market with 21% participation and buying from the five producer states. However, the main purpose is not only to consume but to add value and revenue using their logistics and infrastructure and developing blends.

Therefore, the Brazilian coffee export network is part of a complex supply chain that involves many countries and provides value to customers. Our conclusions indicate that further analysis is necessary for revealing how this network operates.

Finally, the contribution of this study has been to confirm the need to explore a new scientific understanding about a network little explored from the viewpoint of trade and logistics.

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# CNN-Based Growth Prediction of Field Crops for Optimizing Food Supply Chain

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**Abstract.** Along with the aging of the Japanese agricultural population in recent years, the nation's food self-sufficiency rate has declined. The vitality of agriculture has also declined. This study specifically examines the food supply chain to integrate farm production, manufacturing, and sales. For the food supply chain, it is necessary to ascertain the harvest time of field crops for establishing proper sales strategies. A method to predict harvest time from field crop images using convolutional neural networks (CNN) is proposed. Then the effectiveness of the proposed method is verified using computer experiments. Results show that the discrimination rate is high in the early stage of the growth, even if misclassification occurs. Labels close to the correct answer are predicted. However, the discrimination rate is not so high and the deviation from the correct answer becomes greater in later stages of growth.

**Keywords:** Agriculture · Convolutional neural networks · Food supply chain

## 1 Introduction

Along with the aging of Japanese agricultural population in recent years, the food self-sufficiency rate has also declined. The vitality of agriculture has also declined [1]. Revitalizing agriculture requires optimization of the food supply chain, which combines agriculture as a primary industry, manufacturing industry as a secondary industry, and retail industry as a tertiary industry [2]. The food supply chain has four main actors: farmer, farmer manager, vendor, and consumer. To fulfill their role of establishing proper sales strategies for sellers, managers must infer the harvest time of field crops. At present, managers visit farmers to infer harvest times. Such visits entail time costs and other costs. Therefore, a method to predict field crops' growth from these images is proposed to support managers.

In recent years, deep learning has prospered. Convolutional neural networks (CNN) are said to be effective for image recognition [3]. For this study, a CNN is used to address difficulties of growth inference for head lettuce.


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An earlier report [4] described studies of crop classification, disease detection, crop counting, etc. Nevertheless, few reports have described studies that have predicted growth. Furthermore, no report of the relevant literature has described a study of head lettuce. This study specifically examines head lettuce growth prediction.

## 2 Proposed Method

An overview of the proposed method is portrayed in Fig. 1. The lettuce image is input with all pixels for each channel of RGB. Then the leaf age is output, which represents the number of leaves.

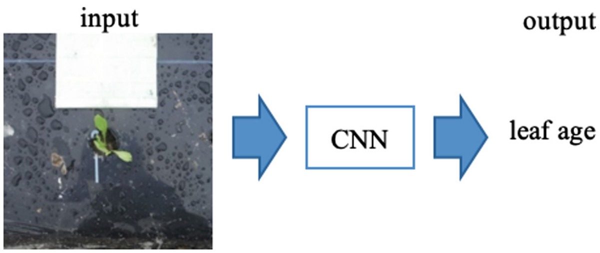


**Fig. 1.** Overview of the proposed method.

The proposed method has two stages: the image processing stage before forming input images and the image discrimination stage in CNN. In the image processing stage, all image ratios are adjusted, the target ranges of all images are cut out. The image size is changed. Furthermore, the image is classified into $G$ group ($G = 21$ in this research) according to the leaf age. Subsequently, one image is selected randomly in each leaf age group and is used as a testing image. The remaining images are used as training images. To improve the discrimination accuracy, training images in each group are increased to $N$ ($N = 100$ for this study). Subsequently, the image is input to CNN for discrimination.

The breed of target lettuce is “elegant,” cultivated in Minamiawaji city during 2015. The photograph frequency is once weekly.

### 2.1 Image Processing

**Adjusting Image Ratio and Cutting Out.** The lettuce’s image is adjusted and cut to 30 cm × 26 cm size to fit the gap separating two lettuces, as presented in Fig. 2.

**Image Size Change.** The image size is changed to input CNN. The 30 cm × 26 cm image size is changed to 75 pixels × 65 pixels.

**Image Classification.** Alabel is added to the image. In the previous research, the number of weeks after planting was given as a label [5]. At this time, labels should be

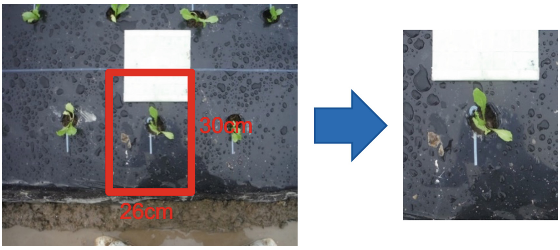


**Fig. 2.** Trimming to 30 cm × 26 cm.

grouped according to the leaf age. The number of groups is 21 from four leaf ages to 30 leaf ages. Table 1 shows the number of images for each leaf age.

**Table 1.** Number of images for each leaf age.

| Leaf age | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|
| No. images | 48 | 46 | 35 | 13 | 28 | 19 | 24 | 28 | 19 | 32 |

| 14 | 15 | 16 | 17 | 18 | 21 | 22 | 23 | 24 | 27 | 30 | sum |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 22 | 10 | 6 | 5 | 4 | 2 | 2 | 2 | 3 | 2 | 2 | 352 |

**Data Augmentation.** In CNN, a large dataset must be used to obtain high recognition accuracy [3]. To get a large dataset, data augmentation that changes a few images to increase the images is said to be effective [6]. The number of training images is increased until the number of images in each leaf age group reaches 100 by data augmentation. To increase the number, we reverse the image, and change the brightness and contrast of the image until the number of images reaches 100.

## 2.2 Image Discrimination

The CNN used in the proposed method is depicted in Fig. 3. As depicted in Fig. 3, there are two convolutional layers, two pooling layers, and three fully connected layers.

The convolutional layer performs an operation to convolve the filter on the input. The input sized $H \times W$ in each channel is convolved with $L \times L$ sized filters. The output for one channel is calculated such as Eq. (1) if the input is set as $y_{ijk}((i,j,k) \in [1,H] \times [1,W] \times [1,N])$ and the filter as $h_{ijk}((i,j,k) \in [1,L] \times [1,L] \times [1,N])$.

In this study, the input size is set to $75 \times 65 \times 3$. The first convolutional filter size is $5 \times 5 \times 40$. The second convolutional filter size is $5 \times 5 \times 50$.

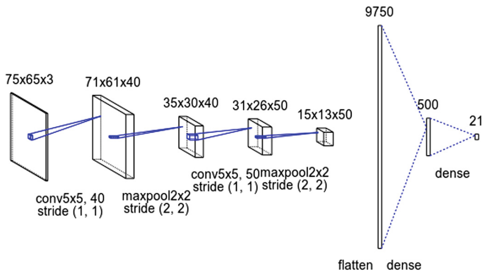


**Fig. 3.** CNN used in the proposed method.

$$x_{ij} = \sum_{k=1}^{N}\left[\sum_{p=1}^{L}\sum_{q=1}^{L} y_{i+p,j+q,k}h_{pqk}\right] + b_k \tag{1}$$

Pooling is defined as discarding extra information for recognition from extracted features and converting it into a new representation that retains information necessary for recognition. Unit $(i,j)$ of the pooling layer collects the output $y_{pq}$ of the internal unit $(p,q) \in P_{ij}$ for a small area $P_{ij}$ of a part of the input layer. In this study, maximum pooling is used as expressed by Eq. (2). In this study, the size of $P_{ij}$ is set to $2 \times 2$ in each pooling layer.

$$\tilde{y}_{ijk} = \max_{(p,q)\in P_{ij}} y_{pqk} \tag{2}$$

In addition, the ReLU function expressed by Eq. (3) is used after the output of the convolutional layers and the fully connected layers. In Eq. (3), $x_j$ represents the input.

$$f(x_j) = \max(x_j, 0) \tag{3}$$

Furthermore, in the classification problem such as the one examined for this study, the final output is assigned the same number of units as the classification group. The output of these units is not the activation function but the softmax function expressed by Eqs. (4) and (5). At the time of discrimination, the index $j = \operatorname{argmax}_j p_j$, in which $p_j$ takes the maximum value, is output as the expected group.

$$p_j = \frac{e^{x_j}}{\sum_{k=1}^{n} e^{x_k}} \tag{4}$$

$$\sum_{j=1}^{n} p_j = 1 \tag{5}$$

Adam [7] is used as a learning algorithm. By this learning method, batch processing is used to reduce the processing time for each image. The algorithm is not used to input images one by one, but to input and process plural images. At this time, the number of input images is called the batch size. In addition, one learning term is found from the input of the image for the batch size until the update of the weight is completed. Furthermore, the number of times during which all training images are input and the weight update is completed is called the epoch.

## 3 Computational Experiment

To confirm the effectiveness of the proposed method, computer experiments were conducted. The leaf age of the 21 groups above is discriminated using the proposed method. One image randomly extracted from each group is used as the testing image. The remaining images are used as the training image. Learning is performed using the training image. The training images and the test images are discriminated.

### 3.1 Experiment Conditions

The experiments were performed under the following conditions.

- Number of groups ($G$): 21
- Number of training images: 2100
- Number of testing images: 21
- Batch size: 32
- Number of epochs: 20
- Number of trials: 5
- Learning rates: 0.001

### 3.2 Result

First, results for the discrimination rate are shown. Table 2 presents the mean and standard deviation of the discrimination rates for the five trials, and shows the results for the 20th epoch.

**Table 2.** Discrimination result (%).

| | Avg. | S.D. |
|---|---|---|
| Training | 99.8 | 0.003 |
| Testing | 30.5 | 0.06 |

From Table 2, the discrimination rate at the end of the 20th epoch was 99.8% for the training image and 30.5% for the testing image. It is apparent that the testing image does not improve the discrimination rate even as the learning of the training image progresses.

Table 3 shows the discrimination rate for each leaf age in the testing images.

**Table 3.** Discrimination rate for each leaf age (%).

| leaf age | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|
| avg. | 100 | 60 | 80 | 40 | 60 | 20 | 40 | 0 | 20 | 80 |
| S.D. | 0 | 0.49 | 0.4 | 0.49 | 0.49 | 0.4 | 0.49 | 0 | 0.4 | 0.4 |

| 14 | 15 | 16 | 17 | 18 | 21 | 22 | 23 | 24 | 27 | 30 |
|---|---|---|---|---|---|---|---|---|---|---|
| 60 | 20 | 20 | 0 | 0 | 0 | 0 | 0 | 40 | 0 | 0 |
| 0.49 | 0.4 | 0.4 | 0 | 0 | 0 | 0 | 0 | 0.49 | 0 | 0 |

Table 3 shows that the discrimination rate is high when the leaf age is less and not so high when the leaf age is greater. When the leaf age is less, i.e., less than leaf age 14, the difference from the correct answer is within 2, even if it is misclassified. By contrast, when the leaf age is greater, i.e., leaf age 15 or more, the label which is far from the correct answer is predicted, when it is misclassified. It is considered that the original number of images affects the results obtained for each leaf age. As Table 1 shows, it is apparent that the images of leaf age 15 or greater are fewer than the images of leaf age 14 or less. Learning is insufficiently achieved because the original images are few.

The anomaly of the discrimination rate for leaf age 11 and 24 is explained next. The reason for the low discrimination rate even though the number of leaf age 11 images is 28 might be an error in labeling. As described above, the image of leaf age 11 is also predicted within 2 before and after the correct label. The discrimination rate of leaf age 24 is higher than that of the front and rear leaves because the number of images is greater than that of the front or rear leaves: CNN can learn the training images on a relative basis.

## 4 Conclusion

A method to predict leaf age has been proposed. Predicting leaf age engenders knowledge of the harvest time to optimize the food supply chain. The results obtained using the computer experiments showed a high discrimination rate for less leaf age. However, for greater leaf age, the discrimination rate is not so high, partly because the number of original images is small.

Future studies will include consideration of the increase in the number of images and application to the food supply chain.

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# Asymmetrical Evaluation of Forecasting Models Through Fresh Food Product Characteristics

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**Abstract.** Forecasting accuracy in context of fresh meat products with short shelf life is studied. Main findings are that forecasting accuracy measures (i.e. errors) should penalize deviations differently according to product characteristics, mainly dependent on whether the deviation is large or small, negative or positive. This study proposes a decision-based mean hybrid evaluation which penalize deviations according to type of animal, demand type, product life cycle and product criticality, i.e. shelf life, inventory level and future demand.

**Keywords:** Forecast · Error · Shelf life · Fresh food · Differentiation

## 1 Introduction

Today's competitive fresh food grocery market is growing with high requirements to price, availability and quality (i.e. freshness) [1, 2]. Particularly fresh meat products (FMPs) have down to only few days total shelf-life (production to expiration) [3]. This puts high requirements on planning for the wholesaler who merely balances converging and diverging flows between industry and stores [2]. As planning relies on forecasting (i.e. predicting) future demand, quality and cost-effectiveness of planning depends on the forecasting accuracy [4, 5]. Inaccurate forecasting of FMPs has double waste-impact. Over-forecasting creates risk of reduced sales price (at best) or obsolescence [6] and under-forecasting lost sales; both reducing the profit base. It is thus paramount to ensure that any chosen forecasting model performs best out of its alternatives. While a model' relevance relates to e.g. data characteristics, time periods to forecast and data availability, its performance relates to the forecasting accuracy i.e. error [7].

Forecasting errors for products with constant demand include e.g. "mean forecast error", "mean percentage error" and "weighted mean absolute percentage error" [7–12]. The errors mainly differ in the valuation of deviations (numerical/absolute/squared) and the inclusion of relative impact to total demand. However, they penalize positive/negative deviations symmetrically and uniform across all time-points, regardless of product characteristics such as e.g. shelf-life, product life cycle stage and demand type. Further, planning software tends to use the same (set of) error(s) for all products when evaluating forecasting models. This is especially challenging for FMPs


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at wholesaler, as a deviation' impact is different from product to product, from time to time. As example, while ground beef' shelf-life (8 days) permit excessive amounts from over-forecast to be stored at wholesaler and sold to stores the following day(s), ground fish' shelf-life (4 days) does not due to consumer perceptions thus creating waste if not sold at same day. Similarly, in terms of e.g. product life cycle stage; while under-forecast of a product in decline may be accepted due to soon being out of assortment, under-forecasting of a product in introduction may not. It is thus relevant to investigate how to penalize deviations and reflect the individual FMPs' characteristics when over-/under-forecasting, so the evaluation is hybrid and fits the individual FMP. By investigating traditional errors' evaluation and impact on inventory, it is possible to see how short shelf life impacts level of waste and service level to stores. The following presents theoretical framework, then methodology, case study, analysis, discussion and conclusion.

## 2 Theoretical Framework

### 2.1 Model Evaluation and Selection

Forecasting is per se always wrong [7], but to ensure as small deviations as possible when forecasting, statistical accuracy measures (i.e. errors) help practitioners and systems towards more consistently and efficiently choose one model above another. Yet, there seems to be a lack of trust in automatic model selection [13] – and research suggests that human evaluation of forecast models can outperform algorithmic selection [4]. Despite this, it is still utopia to think of human evaluation for all products in a typical wholesaler product portfolio with up to hundreds of thousands of different products, merely stressing the statistical errors' essential importance.

Multiple statistical errors exist for evaluating forecasting models [7–12], and Table 1 lists nine common measures for constant demand. For intermittent demand, other errors are applicable [9]. $Y_t$ denotes the real value at time $t$, $\hat{Y}_t$ the forecasted value at time $t$ for $n$ data points, and $Y_t - \hat{Y}_t$ the forecast deviation. The MFE, MSE, RMSE and MPE use numerical valuation and, MAE, MAPE, MASE, SMAPE and WMAPE absolute valuation. Numerical valuation allows positive and negative deviations to balance out through time. This is challenging as errors may report "0" in deviation – despite presence of (several) large errors. Absolute values comprehend this by accumulating the deviations. Further, MFE and MAE calculates deviations directly, MSE and RMSE penalize (particularly large) fluctuations through squaring of the deviations and, MPE and MAPE calculates deviations relatively to true demand, i.e. scale independent. For widely fluctuating demand WMAPE extends MAPE so that while "the classical MAPE sets absolute errors in relation to the actual values, the WMAPE considers percentage errors and again weighs them by actual values" [9] resulting in high weight on high-demand deviations and low weight on low-demand deviations. However, WMAPE assume stationary demand making it inappropriate when demand has trend, seasonality or other patterns [12]. To allow for non-stationary demand, MASE divide MAD for forecasting period with MAD from historical period derived from naïve method [9]. For demand with low or zero values the percentage-based errors (but WMAPE) become undefinable/infinite, hence SMAPE comprehends this by considering deviations in 200%-range thereby reducing the impact from zero and close to zero demands [11, 12].

**Table 1.** Common forecast error measures

| Error | Equation | Error | Equation | Error | Equation |
|---|---|---|---|---|---|
| Mean forecast error, MFE | $\frac{1}{n}\sum_{t=1}^{n}(Y_t - \hat{Y}_t)$ | Mean percentage error, MPE | $\frac{1}{n}\sum_{t=1}^{n}\frac{(Y_t-\hat{Y}_t)}{Y_t}$ | Weighted MAPE, WMAPE | $\frac{\frac{1}{n}\sum_{t=1}^{n}\lvert Y_t-\hat{Y}_t\rvert}{\frac{1}{n}\sum_{t=1}^{n}Y_t}$ |
| Mean absolute error, MAE | $\frac{1}{n}\sum_{t=1}^{n}\lvert Y_t - \hat{Y}_t\rvert$ | Mean absolute percentage error, MAPE* | $\frac{1}{n}\sum_{t=1}^{n}\frac{\lvert Y_t-\hat{Y}_t\rvert}{Y_t}$ | Symmetric MAPE, SMAPE* *(close-to-zero demand)* | $\frac{2}{n}\sum_{t=1}^{n}\frac{\lvert Y_t-\hat{Y}_t\rvert}{Y_t+\hat{Y}_t}$ |
| Mean squared error, MSE | $\frac{1}{n}\sum_{t=1}^{n}(Y_t - \hat{Y}_t)^2$ | Root mean squared error, RMSE* | $\sqrt{\frac{1}{n}\sum_{t=1}^{n}(Y_t - \hat{Y}_t)^2}$ | Mean absolute scaled error MASE*/** | $\frac{\sum_{t=1}^{n}\lvert Y_t-\hat{Y}_t\rvert}{\frac{1}{n-m}\sum_{t=m+1}^{n}\lvert Y_t-Y_{t-m}\rvert}$ |

**can also use median rather than mean, respectively MdAPE, RMdSE, SMdAPE and MdASE* [11],
***shown equation is for seasonal demand, in situation of non-seasonal pattern then m = 1.*

### 2.2 Characteristics Impacting Forecasting

Multiple different characteristics influence planning across the supply chain [14–18]. Given planning' dependence on forecasting [4, 5] we select four characteristics of particular importance to the forecasting at wholesaler: product life cycle, demand type, shelf-life of products and animal type. When under-forecasting, consumer requirements [1, 19] related to the product life cycle (i.e. demand stage) and, subsequently the desired accuracy in forecasting, should be appropriately penalized in the forecast error. Introduction and growth are crucial for a product' success in market (thus future demand) requiring high penalization, while maturity and particularly decline are less crucial requiring less penalization [17, 20, 21]. Similarly, for demand type (campaign and normal), where campaigns are considered more important [22] due to the (often strategic) underlying stimulation to demand, making under-forecasting relatively more critical than in case of normal demand. When over-forecasting and creating temporarily inventory, the risk of waste from obsolescence due to short shelf-life [23] is larger when seemingly not being able to sell excessive amounts before expiration. Hence, the error relative to upcoming days demand should be penalized accordingly. Similarly, for animal type; over-forecasting has different impact since different consumer perception of remaining shelf-life depending on if FMP is fish, chicken, beef or pork. Products with very sensitive perception should be penalized higher than those with less sensitivity.

## 3 Methodology

After investigating forecasting errors for constant demand, the purpose is to suggest an error that includes FMPs' characteristics when penalizing deviation. The goal is to evaluate forecast models so e.g. positive deviations causing excessive amounts (but no waste) are penalized differently than deviations where the FMPs cannot be sold and do cause waste. Since both context and product type is critical to this study, phenomena is studied in-depth in natural context, enriching both understanding and insight [24]. The case study focuses on Denmark' largest (independent) wholesaler, called ABC throughout this study. Information and data are obtained through semi-structured interviews with purchasers and purchasing manager, evolving from standardized questions about forecasting and ordering processes.

# 4 Case Description

ABC is one of Scandinavia' largest independent grocery wholesalers and uses a central warehouse to supply +330 stores with FMPs. ABC' overall goal is to be known as the most "value driven company", measuring performance primarily through service level to stores. Recently, ABC changed their logistics setup for FMPs from transit-flows (with a single replenishment cycle across industry-wholesaler-stores) to two replenishment cycles: industry-wholesaler and wholesaler-store. Now, ABC forecasts FMPs' demand (i.e. store orders) for the following day, at which the stores send actual orders. Wholesaler forecasts total store demand at daily level with consideration of weekday-patterns. Forecasting models are evaluated through one same error, WMAPE, as it allows an easily understandable and relative evaluation with independent scaling of the data (allowing cross-comparison across products). The applied forecasting model differ depending on if the demand in normal or campaign. The forecasts are generated and evaluated through R Studio, allowing efficient and consistent evaluation of the different forecasting models for the hundreds of FMPs.

## 4.1 Demand Forecasting and Errors

True and forecasted demand (on the left) and deviations between the two (on the right) for a limited amount of time of a given product is shown in Fig. 1. The solid line is true demand and dashed line forecasted demand. Black filled columns is for over-forecasted demand, and light grey columns for under-forecasted demand.

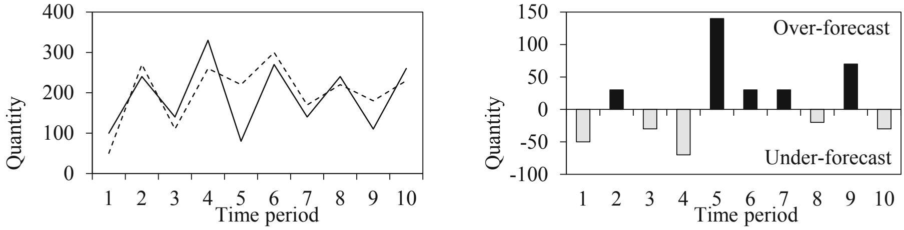


**Fig. 1.** Gaps between forecasted and true demand, an example

The deviations range from −50 to +140 units from true demand, i.e. from −50% to almost +175% deviation. The errors are: MFE = 10, MAE = 50, MSE = 3.680, RMSE = 61, MAPE = 40%, MPE = 17% and WMAPE = 26.18%. Since a total demand of 1,910 ranging from 80 to 330, MFE and MAE seem not critical. Similarly, since large fluctuation between time period 3 and 5, RMSE and MSE seem also not critical. For the relative errors, it is clear how WMAPE changes when considering the scaling relative to demand. In general, neither of the errors seem to reflect the deviations which are large enough to cause stored products to waste and seemingly stock-out situation.

### 4.2 Inventory Transactions and Shelf Life

Looking closer at the resulting inventory records, stock outs and waste are evident. Figure 2 depicts demand and forecasting related information, transactions from the inventory, and the products' distribution across shelf life days. Status of delivery is also shown. Each colour indicates different deliveries and their transactions across inventory and shelf life days. It is clear, that FMPs with one day less shelf life are consistently present due to over-forecasting, with some even wasted due to too short shelf life (circle in figure). Further, one day there is a reduction in service level of 6%. From the forecast deviation it also evident that in fact a deviation was up to 175%.

| Time | Demand | Forecast | Forecast deviation | Ending inventory | Remaining SL at next delivery | | Remaining SL for delivered | | Service level | Not delivered |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 3 days | 2 days | 4 days | 3 days | | |
| 0 | | | | 100 | 100 | - | - | - | - | - |
| 1 | 100 | 50 | -50 | 50 | 50 | - | - | 100 | 100% | - |
| 2 | 240 | 270 | 30 | 80 | 80 | - | 190 | 50 | 100% | - |
| 3 | 140 | 110 | -30 | 50 | 50 | - | 60 | 80 | 100% | - |
| 4 | 330 | 260 | -70 | 0 | - | - | 260 | 50 | 94% | -20 |
| 5 | 80 | 220 | 140 | 140 | 140 | - | 80 | - | 100% | - |
| 6 | 270 | 300 | 30 | 170 | 170 | - | 130 | 140 | 100% | - |
| 7 | 140 | 170 | 30 | 200 | 170 | 30 | - | 140 | 100% | - |
| 8 | 240 | 220 | -20 | 150 | 150 | - | 70 | 170 | 100% | - |
| 9 | 110 | 180 | 70 | 220 | 180 | 40 | - | 110 | 100% | - |
| 10 | 260 | 230 | -30 | 150 | 150 | | 80 | 180 | 100% | - |

**Fig. 2.** Inventory records of a selective product (Color figure online)

## 5 Proposed Framework for Asymmetrical Forecast Evaluation

To penalize the individual time points' deviation more relative to the FMP' characteristics it is necessary to use a hybrid error allowing different penalizations. Based on numerical valuation, the suggested Mean Hybrid Error (see Eq. 1) multiplies deviations with an alpha-factor. In Eq. 1, n = number of time points included in calculation, $t$ = time point in period, $Y_t$ = actual demand, $\hat{Y}_t$ = forecasted demand.

$$MHE = \frac{1}{n}\sum_{t=1}^{n} \alpha\left(\widehat{Y_{t,p}} - Y_{t,p}\right) \tag{1}$$

Please note that true and forecasted demand are reversed compared to those in Table 1, due to reflecting inventory levels. The α represents different characteristics' penalties for respectively positive and negative deviations. Different characteristics may be relevant to other products, however since focus is on FMPs, we use the four previously identified characteristics. The decision-making diagram when determining the alpha-value is depicted in Fig. 3.

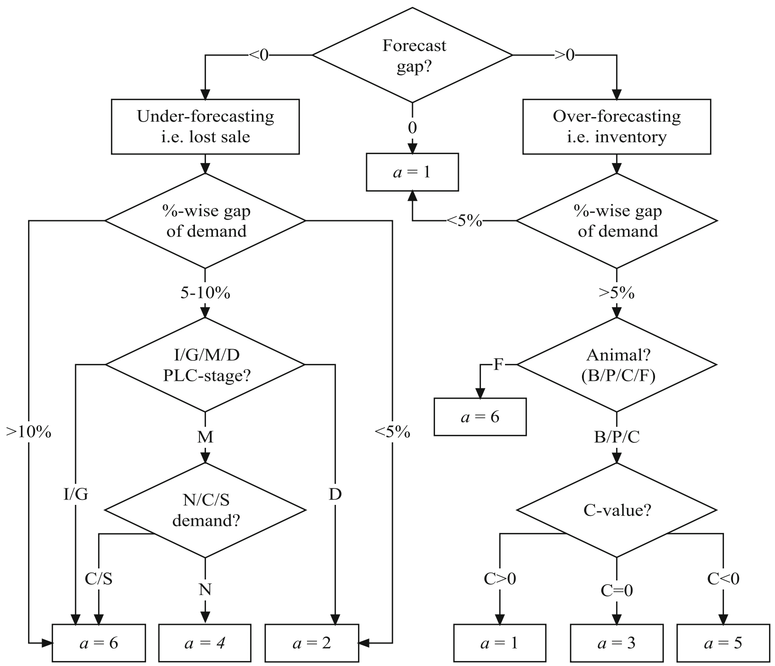


**Fig. 3.** Decision-making during forecast-evaluation, with exemplifying punishment-values

Depending on if the deviation is negative, zero or positive, the penalty will differ according to risk of stock out and inventory building. In terms of size of deviation, the alpha-value also differ between percentage-limits of deviation, as well as it takes product life cycle assessment and demand type into consideration when there is chance for stock out (i.e. under-forecasting). Similarly, when chance of inventory (i.e. over-forecasting), the alpha-value considers the animal type. From interview, consumers generally accept that pork, chicken and particularly beef FMPs are few days old from production date. For beef, there is even evidence of buying products at up to full price, when they expire same day. However, for fish products, consumers generally don't buy products more than one – maximum two – days old since production – despite three-four days remaining shelf life. To reflect this against consequent inventory levels in relation to chance of waste we develop a criticality value, $C$ (Eq. 2).

$$C_{t,p} = S_p - \frac{\left(\widehat{Y_{t,p}} - Y_{t,p}\right)}{\sum_{t+1}^{S_p} \hat{Y}_{t,p} + I_{t,p}} \quad \mathit{if} \begin{cases} C_{t,p} < 0, & \textit{products not sold before expiration} \\ C_{t,p} = 0, & \textit{products maybe sold before expiration} \\ C_{t,p} > 0, & \textit{products sold before expiration} \end{cases} \tag{2}$$

$C$ is the difference between the amount of inventory due to over-forecasting and the amount of days it is possible to store the given products, before selling at reduced price (best case) or wasting. In Eq. 2, $S_p$ = days product $p$ can be stored cf. shelf-life/guarantee days, $\left(\widehat{Y_{t,p}} - Y_{t,p}\right)$ = deviation between forecasted and true demand of product $p$ at day $t$, $\sum_{t=1+1}^{S_p} \hat{Y}_{t,p}$ = sum of demand for product $p$ the following number days $t$ that can be covered by the excessive amount in relation to shelf-life/guarantee days $S_p$ and $I_{t,p}$ = available inventory level of product $p$ at the beginning of the day, $t$, after subtracting the products that will be waste the following days due to expiration.

To exemplify, an evaluation through classical errors and MHE is performed. A random FMP (a mature fish product) is chosen and its demand is characterised by two sudden disruptions in the beginning of the period and again towards the end. Elsewise no significant impact from trend, seasonality or campaigns is observed. Nine models of naïve (3), mean (4) and exponential smoothing (2) model families are used, considered most widely used in practice [4].

From Table 2 the errors are shown for the different forecasting models. Light grey indicates which model has lowest error and dark grey second most favourable error. If choosing model according to the classical errors, weighted moving average is most favourable, followed by exponential smoothing and naïve with trend. However, MHE suggests basic naïve model. As second best performing models, mainly exponential and naïve models are suggested. If looking closer at the individual deviations for exponential smoothed, weighted MA and naïve model, it is evident that the pattern of deviations differs. When facing sudden disruptions in demand, exponential smoothing and weighted MA tend to have their deviations characterised by clusters of similar deviations (positive or negative). Hence, if a sudden disruption in demand, the models over/under-forecast for the following periods, entailing an extended impact on either potential lost sale or potential inventory building. Looking at naïve model and comparing, this indicates that albeit merely projecting last period' demand as current period' demand, the impact from periodically lost sale/inventory building is relatively smaller, even when not being able to have inventory (as in this example with fish cf. Fig. 3). By considering FMPs' characteristics, it is possible to evaluate the impact in relation to the individual products and thereby ensure effective evaluation of forecasting models.

**Table 2.** Forecast errors for selective forecasting models

| Forecasting model | MAE | MFE | MSE | RMSE | MAPE | MPE | MHE |
|---|---|---|---|---|---|---|---|
| Naïve | 16.29 | -0.20 | 473.37 | 21.76 | 26.55% | -6.83% | 0.18 |
| Naïve w/ T, type1 | 24.56 | -0.95 | 1,055.39 | 32.49 | 37.73% | -3.62% | 0.59 |
| Naïve w/ T, type2 | 16.47 | -1.41 | 484.21 | 22.00 | 27.10% | -8.68% | 4.21 |
| Average | 15.75 | -4.72 | 450.94 | 21.24 | 32.68% | -21.35% | 27.31 |
| Moving Average (MA) | 16.28 | -0.22 | 489.16 | 22.12 | 27.62% | -9.11% | -2.90 |
| Double MA | 20.06 | -0.61 | 674.26 | 25.97 | 35.90% | -13.93% | -8.85 |
| Weighted MA | 14.74 | -0.49 | 376.15 | 19.39 | 25.43% | -9.42% | -13.32 |
| Exponential smoothed | 15.42 | 0.08 | 431.98 | 20.78 | 27.71% | -10.98% | -1.91 |
| Exponential w/ T | 15.56 | 0.39 | 436.65 | 20.90 | 28.65% | -11.76% | -3.55 |

This study has demonstrated MHE through a single product and further research should aim at increasing validity by investigating multiple different products. This, to investigate how differences within e.g. shelf life may impact inventory levels, differentiate the penalties and ultimately choice of forecasting model. Additional research should also focus on how MHE may impact penalties for demand characterised by high campaign and/or seasonal demand, due to its focus on inventory coverage before expiration cf. positive deviations.

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# Horizontal Integration in Fresh Food Supply Chain

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**Abstract.** Demand information sharing during planning and control of fresh meat production and replenishment in franchise supply chain is studied. Main findings are that some demand information is received much later upstream than when created downstream. Horizontal integration of systems in the supply chain allows all parties access to same critical information about store demand and availability in real-time. A conceptual model for horizontal integration in the triadic supply chain, allowing differentiated and timely sharing of information is suggested, to increase service level and reduce waste from over-/under-production.

**Keywords:** Retail supply chain · Integration · Real-time information sharing · Fresh food products · MES

## 1 Introduction

In retail supply chains, information sharing [1, 2] is a large part of collaborative materials management (CMM) [3]. Sharing e.g. demand information allows transparency and visibility of product sales and availability in the supply chain. However, demand information is usually adjusted and aggregated downstream into orders before being shared, and is sent in batches at specified times or when manually initiating a transfer (e.g. sending purchase orders). It is often shared in dyadic structures via business level systems alike enterprise resource planning systems (ERP). Hence, supplier, wholesaler and retail stores plan (and schedule) and control their productions independently – based on (adjusted) historical rather than real-time information and internal plans cf. internal setup [4, 5]. Once scheduled, the production is frozen certain time into the future to reduce nervousness [4]. Albeit incremental planning is possible, options for changes continuously decrease, until finally impossible when production ends [4].

This is challenging when dealing with fresh food products. They need intensified and increased information sharing [6] during planning and control of production and replenishments, due to high demand variability and short shelf life [7]. Fresh meat


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products (FMPs) such as e.g. ground beef/pork/chicken/fish and ready-made meals are processed down to few hours before shipment to wholesaler; even while stores still send orders to wholesaler. Thus, sharing demand information longer time in advance of production start both increases demand uncertainty (cf.forecast) and reduces the supply chain responsiveness to unforeseen changes in demand. Even if possible, responses are costly and labor-intensive non-systemized exceptions management (through phone calls and emails). Instead, sharing centrally managed demand information [8] in real-time allows common understanding of demand, effective instant decision-making, reduced risks and greater forecast accuracy [9]. To not put more pressure on business level systems, interest is in horizontal integration of planning and control systems online/in the sky to share real-time. In addition, for franchise, all decision-making is decentralized to stores, as opposed to corporate retail chains. It is thus relevant to also investigate how a triadic supply chain (supplier, wholesaler and retail stores) seamlessly can share real-time demand information horizontally during planning and control.

We analyze and identify issues in information sharing during fresh meat production and replenishment planning and control in franchise retail supply chain. A conceptual model is proposed to integrate systems in the supply chain with real-time demand information sharing along suggestions for which information to share. Following presents theoretical framework, methodology, case analysis, framework and conclusion.

## 2 Theoretical Background

Collaborative materials management (CMM) is "operational planning and control of inventory replenishments in supply chains" [3]. Information sharing is a major part of CMM and governs the "capturing and dissemination of timely and relevant information for decision makers to plan and control supply chain operations" [2]. Especially demand information sharing influences CMM with direct impact on the planning and control effectiveness and waste from out-of-stock/oversupply situations [10–12].

In CMM there is differently increasing demand information sharing depending on the level of collaboration [8, 13, 14]. As example, in "vendor-managed inventory" (VMI) supplier may obtain full view of both historical demand, point-of-sales and inventory levels at wholesaler or retail stores (depending on whose inventory is managed). However, it only covers a dyadic supply chain limiting the efficient information sharing across *entire* (i.e. triadic) supply chain. Further, demand information sharing is through batch transactions from ERP or online access to ERP [13], causing redundant use of and pressure on ERP systems compared to if sharing directly between the systems where the information is created. The "collaborative planning, forecasting and replenishment" (CPFR) (VICS, 2014) includes demand exceptions and extends VMI with collaborative validation and synchronization of planning (incl. forecasting) by increasing demand information sharing. Yet, although information sharing is through special data transfer interfaces (e.g. EDI) [15] or even online applications for real-time/near real-time [16], it is still through ERP in a dyadic supplier-wholesaler relationship. Similarly for "process of collaborative store ordering" – although information sharing is through an online platform to enhance real-time demand sharing [14] it is dyadic between supplier and retail stores, i.e. without wholesaler' knowledge to and about demand information [8]. No CMM program entails real-time based triadic demand information sharing via planning and control systems to ensure complete (supply chain) demand visibility and efficient use of systems. Namely for supplier' manufacturing execution systems, wholesaler' warehouse management system and retail stores' cash register. For fresh food products with short shelf life there is stronger correlation between supply chain performance and level of information sharing, than long shelf life products [6]. Yet, although information sharing generally improves supply chain performance [17], responsiveness [18] and freshness of products [7], research also suggest that the level of improvement is not per se always positive as sharing too much/irrelevant information may decrease performance and "result in an expected loss" [19]. In turn, information sharing (and thus also collaboration) depends on factors such as e.g. specific demand situation [12, 20], type of product [6] as well as type of information shared, with whom it is shared and how it is shared [21].

From the production perspective, the concept of inter-enterprise integration and the supplier's involvement in the supply chain using information systems is not new. Level 3 systems as per ISA 95 standard set by 'International society of automation' also address the need for systems to interconnect, to provide value to the manufacturing enterprises and beyond. Enterprise systems are known to enhance the collaboration between the supplier and the end user by reducing transaction costs [22]. Since MES/MOM systems are real-time compliant, it becomes advantageous for fresh food supply chains to access the product centric data via factory control systems [23]. Supplier can thus play an important role in improving the supply network design as problems related to bullwhip tend to impact all chain parties.

There are various approaches to inter enterprise integration based on the need for information sharing. Owing to that, information exchange via web based MES/MOM systems can follow several classes of information interfaces such as: SCOR, CPFR, RosettaNet for process data; EDIFACT for structured data; and TCP/IP reference model & basic internet services for unstructured data [24]. Supplier and buyer integration in a supply chain for collaborative materials planning is a known method in the operations management. But the collaborative approach by integrating shop floor level systems is not well understood in theory. Over the last two decades, ERP systems have evolved from being monolithic to modular ERP II systems by extending into the supply chains [25]. Similarly, the scope of MES/MOM systems could also be extended into supply chains, for which we present web-based service-oriented architecture (SOA) as a suitable approach for horizontal integration. Modularity and remote access via internet technology are key reasons for considering service-oriented MES/MOM systems.

## 3 Methodology

After investigating demand information sharing in the supply chain and where different demand information is created, the purpose is to propose a conceptual model for real-time sharing through horizontal integration of planning and control systems. This, to ensure all parties access to same critical information about store demand and availability in real-time. The focus is on FMPs and ensuring decentralized order decision-making cf. franchise retailing. The goal is to ensure complete transparency of demand (i.e. store sales) and inventories across the supply chain in real-time, allowing live production scheduling at supplier. The case is studied in natural context to ensure enriched understanding and insight [26] as both context and product type is critical. To provide a generalizable view, focus is on beef, pork, chicken and fish with total shelf-life of 8 days or less which are produced short time before delivery to wholesaler. The supply chain is triadic, i.e. supplier, wholesaler and retail stores (franchisors) with retail chain (franchisee). Wholesaler is one of the largest grocery wholesalers in Denmark and supplies 328 franchise stores with FMPs from five suppliers each day through a central warehouse, via two replenishment cycles: supplier-wholesaler and wholesaler-store. The past year stores have ordered 10 to 47 SKUs each day; 4–25 beef incl. veal and cattle, 1–16 pork, 1–9 chicken and 1–4 fish; depending on season/campaigns. All FMPs are shipped from supplier, consolidated at wholesaler and delivered to stores. Waste levels in stores from theft and expiration are considered very low (<1%, estimated) but included in the calculation of inventory levels. Information and data are obtained via semi-structured interviews with IT-manager, purchaser and purchasing manager (wholesaler), purchasing assistant (retail chain), personnel (retail stores) and, sales manager, production planner and vice president (supplier), from standardized questions about planning/scheduling/control processes.

## 4 Information Sharing in Fresh Meat Supply Chain

First, wholesaler creates an order in the purchase planning system (PPS) and sends it to supplier via ERP by latest 16:00 (day 1). After confirmation (via ERP), supplier schedules the order for production during the night/following morning and deliver to wholesaler between 06:00 and 13:00 (day 2). While the production still runs (supplier) and FMPs are received (wholesaler), stores create orders in their ERP via hand-terminals and send to retail chains' ERP at latest by 11:00 (day 2). The store orders are then transferred to wholesaler' ERP and further to the warehouse management system (WMS), releasing orders for picking from 14:00 in two batches (dependent on delivery times to stores). The FMPs are physically delivered to the stores between 18:00 (day 2) and 05:00 (day 3). This results in a lead-time of down to 14 h for wholesaler, and down to 7 h for stores, from sending store order until received. Figure 1 depicts where the demand information is created and available, grouped vertically by supply chain stage and type of demand information (see 1/2/3 in figure). White boxes, except "R Studio" (forecasting), are real-time information systems and the grey are ERP.

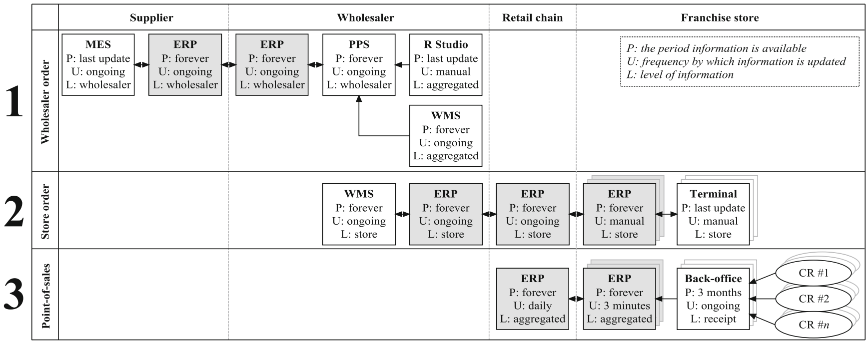


**Fig. 1.** Order-information creation and storing in systems

**Creation of Wholesaler Orders (1) and Transfer to Supplier (Cycle 1).** Wholesaler forecasts total store demand (via R Studio) at daily level considering weekday-patterns. Based on this, inventory levels (from WMS) and yesterday' store demand (from ERP), wholesaler estimates the following day' demand. Although (aggregated) POS from yesterday' sale in stores can be accessed, is not used since logging on retail chain' ERP and looking up each product' sale in stores is rather time-consuming. When order quantity is set (i.e. expected demand minus incoming pre-orders and inventory), the order is loaded into wholesaler' ERP. The purchaser manually sends the order to the supplier through EDI-FACT, awaiting an order confirmation. In Fig. 1, from right to left.

**Creation of Store Orders (2) and Transfer to Wholesaler (Cycle 2).** When stores order products, personnel walk around in the store and scan shelf labels with a handheld terminal as seem needed, i.e. less available than desired. The personnel can see usual sales the given weekday (manually uploaded to the terminal from ERP before starting the ordering process). Quantity is determined from what pre-determined amount to be available minus actual available amount in boxes – and adjusted for sales the following day if it is expected to increase. When the order is final, it is transferred from to the ERP. For each product, the personnel see what is usually sold at surrounding days, general historical sale, campaign information (last/current) and how much is in pre-order. When adjusted the order is sent to retail chain' ERP, and then to wholesaler' ERP and from here further to the WMS for picking. In Fig. 1, from right to left.

**Creation of POS (3) and Its Transfer Across Supply Chain.** POS is created and registered at an individual local database at each CR in each store (app. 1,100 for entire chain). Every three minutes, the POS is sent the store' back-office database, where it is consolidated with POS from the other 2–3 CRs in the store. This receipt-level POS is saved for three months and constantly deleted as time pass by, due to storage limitations. From here, the receipt POS is transferred to the ERP' database in each store which constantly aggregates with latest POS (aggPOS) cf. 3 min transfer interval. Here all sales data is saved on a native database, and this is the first time the store, retail chain and wholesaler can manually log on and access aggPOS data older than 3 months. Around midnight all aggPOS (amount per SKU per price per day) from all stores is transferred to the retail chain' database. From around 6–7 in the morning, procurement at retail chain can readily access the aggPOS in their ERP. Logging on to retail chain' ERP, wholesaler may also access the information. In Fig. 1, from right to left.

To sum up, one of the main-findings is that the true demand (POS) is aggregated and only available in certain systems in batches and from certain time-points. This cause unstructured manual exceptions management (by phone) and reduces the ability to immediately react to changes in demand in stores. Further, wholesaler decides order quantity on two days' old demand-data influenced by 328 different stores' decision-making rather than real sales. This, albeit different information is available at different supply chain stages in real-time, hereunder demand at cash register (CR) in stores (i.e. point of sale (POS)), inventory levels at wholesaler and production status at supplier. Another main-finding is the time it takes to transfer and save aggPOS from stores to wholesaler through ERP – and the consequent delay before being available for decision-making. Since supplier produces FMPs down to hours before shipment, decreasing transfer time and sharing information directly between relevant systems (CR, WMS and MES) will increase the ability to react to demand changes. Further to this, retail stores manually control amounts of products available when determining order size, albeit having a pre-determined max-amount of each product. Given the low level of theft and waste (cf. close-to-expiration products sold at reduced price), inventory levels may be derived from ordered quantities subtracted POS with only weekly/periodic check. And chosen max-amounts may even further be evaluated cf. amount of products sold at reduced price is registered in POS.

## 5 Proposed Framework for Real-Time Information Sharing Through Horizontal Integration

Not only does current systems integration make actual demand rather opaque, it also increases the risk of bullwhip effect. In literature, sharing of POS is argued as having positive impact on the supply chain performance, and a necessity for collaborative materials management [8, 13, 14]. To allow timely information sharing Fig. 2 illustrates a conceptual model for integration of systems via horizontal integration, allowing decision-making based on real-time information sharing. Given wholesaler' role in the supply chain [5], the model assumes wholesaler to be coordinator of information and product flows. Information about demand (i.e. POS) and derived inventories from stores, production execution and status (i.e. MES) from supplier as well as inventories at wholesaler is shared in real-time.

Based on this information, and (by store) pre-determined max-amounts in each store, wholesaler applies an ongoing fuzzification-process which is based on a knowledge repository (retrieving information from the web and business intelligence) and inference engine. E.g. if weather is expected to increase, then the derived expected consequence on demand is included in the suggestive actions. From this, the system will constantly evaluate ongoing demand and changes in demand (POS) against chances for changing already sent demand information to suppliers – filtered according to how far supplier is in production schedule.

If demand in stores sudden deviates, an alarm will occur informing the system about potential need for additional products (and vice versa, if no sale happens). Then,

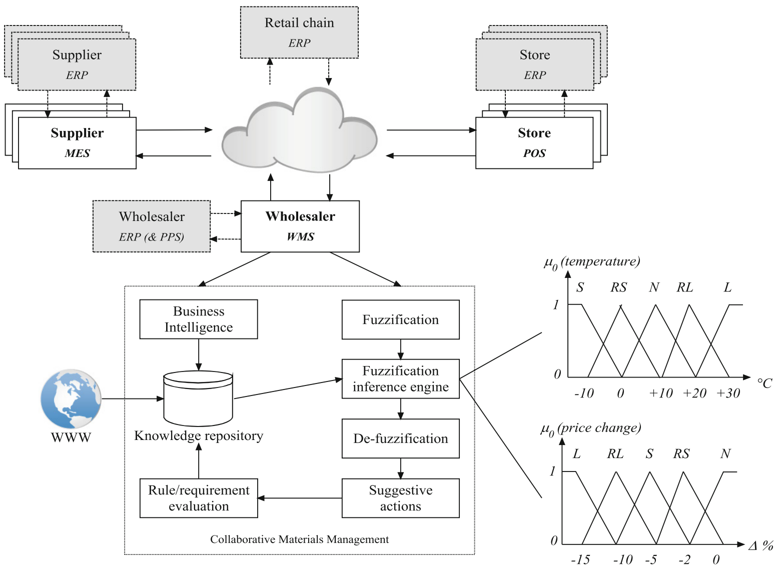


**Fig. 2.** Real-time information sharing through horizontal integration

based on supplier' production status, the system will inform MES about additional/ fewer quantities to be produced. Products which can be changed constantly follow open production orders in real-time. Thus if production of product A just finished, product A cannot be subject for any alteration. The further into the future the production is, the greater allowance for quantity changes. In this way systems across supplier (i.e. MES), wholesaler (i.e. WMS) and store (i.e. POS) will integrate horizontally, eliminating transfer through ERP. By allowing for "blanket" orders, the MES, WMS and CR will inform ERP about workload, opposite today, where ERP informs about workload. For reasons of speed, web-based information transfer is suggested.

## 6 Conclusion and Future Research Directions

The FMP production at suppliers is scheduled certain time after wholesaler sends order based on adjusted demand (i.e. wholesale order), despite actual sales is still recorded in stores – and it still runs while actual store orders are sent. No integration of planning and control systems challenges the timely information sharing [1, 2] with centrally adjusted demand [8]. By integrating the planning and control systems where demand information is created (MES, WMS and POS) across the supply chain then e.g. sudden changes to demand may be shared (near) live. Whether increase or decrease in demand it allows the entire triadic supply chain to react instantly and respond accordingly. This is particularly crucial for products processed each day e.g. ground beef/chicken/fish.

This research has focused on major common FMP-types in grocery industry in a conceptual model. More research is needed for other FMP-types to establish the validity in sharing POS in real-time and define what supply chain characteristics must be in place – when comparing against FMP with long shelf life. Also, the framework should be tested out empirically to investigate and quantify impact on service level across the supply chain, as well as ability to meet sudden changes in demand. The focus is regular demand, hence to test the generalizability, it would be favourable to test the model in different types of demand such as campaign, product introduction or seasonal demand. Also, this study has focused on franchise retail stores with decentralized decision-making. Additional research is needed for other store-types where centralized decision-making may be used such as corporate retail chain.

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# Reverse Logistics and Waste in the Textile and Clothing Production Chain in Brazil

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**Abstract.** The global environmental concern turns to the production of waste and its correct disposal. The chance of the natural degradation of this content is minimal, and logistics become an urgent discussion for all production chains. The lack of knowledge of Brazilians about recycling and non-education for conscious consumption hinders the development of initiatives in the segment. On the other hand, instead of adopting the necessary measures to implement reverse logistics and recycle these materials, companies are importing waste from other countries, neglecting the potential for income generation and sustainable business that could invest. The objective of this article is to evaluate the scenario of recycling initiatives and reverse logistics carried out in the textile and clothing industry in Brazil, through bibliographical research and surveys in Google and Facebook, internet sites and open data analysis of national and international bodies on the subject. There is a shortage of studies, and the appropriateness of the subject is urgent and necessary. From the results, it can be verified that without official records, government agencies' efforts to implement reverse logistics and recycling and encourage the benefits of the activity, there is no way to solve the issue.

**Keywords:** Circular economy · Recycling · Reuse · Textile data

## 1 Introduction

Some figures from the impact of the US textile industry: 1200 million tons of greenhouse gases, use of 93 billion cubic meters of water, 8 million tons of fertilizer for cotton, 200 thousand tons of pesticides for cotton, 42 million tonnes of chemicals and one million tonnes of dyes [1].

The textile and garment chain, which starts in the production of cotton fibers, is one of the most polluting and has a significant share in the Brazilian GDP, with an income of US$ 52 billion in 2017 [2]. The fast-fashion garment industry, which produces low-cost clothing and generates waste in excess, both for its vast production and for the rapid disposal of the product, in both cases have an inadequate destination.

How the waste from the textile chain and clothing is discarded, both by industries and by the population, is a recent field of study with few references. A portion of the textiles are discarded in household waste, but there are no numbers to measure the waste [3].


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Another side of this equation is that although Brazil is among the five largest producers of textiles and clothing, and therefore a significant generator of waste, the country imports textile waste instead of using household waste to this purpose [4]. There is conflicting information, and there is no governmental body that deals with the subject, the reason why no official figures on this activity were found. The complexity of the problem is further compounded by the lack of knowledge about recycling in Brazilian society. A national survey showed that 66% of Brazilians know nothing or very little about the selective collection and 39% of the population does not separate organic waste from recyclable waste [5].

The objective of this article was to evaluate the recycling and reverse logistics performed by the textile and clothing industry in Brazil and present the initiatives that have been tackling the problem.

## 2 Background

Sustainability, a global requirement after the 1990s, presents a dilemma with industry, which derives from the economic paradigm of 'linear' production, which seeks to extract, transform and discard, a model that depends on large quantities of materials, water, and energy [6]. By 2015, world garbage production has reached 2.2 billion tons of garbage per year [7]. In 2018, the Brazilian contribution to this mountain of garbage reached 64 million tons, of which 24 were improperly disposed of, according to the Brazilian Association of Public Cleaning and Special Wastes [8].

The industrial process of the textile chain, from the planting of cotton, or the production of synthetic fibers, and activities such as dying of fabrics and stamping, is chemically aggressive. Authors [9] attribute that at least 10% of the world's textile production is improperly disposed of and even if in garment production, 10% of production is lost in the cutting department. The Brazilian textile industry, in 2015, generated 175 thousand tons of solid textile waste, of which 90% had incorrect disposal [10]. The number is approximated only in one phase of the industry and by a calculation of loss of 10% of the fabric in the cutting process. Of this total, about 40% (70,000 tons) are re-processed by recyclers, and 60% are improperly discarded in landfills and landfills [11].

The impact of the use of inputs and recycling in the textile chain has been studied [9]. The authors found that it is a recent field of study, despite being a strategic area for the Brazilian textile industry. Khandelwal et al. [12] evaluated 153 studies on urban solid waste published since 2013 and found six studies related to Brazilian textile segment. In turn, [13] corroborated these figures by analyzing 91 studies conducted between 2006 and 2017 and verifying that in Asia it is also limited to a few countries, finding reasons such as difficulty, time-consuming and expensive data collection process.

The adoption of the circular economy can generate 1.8 trillion euros by 2030 [14]. Leal Filho [15] determines that recycling plastics can be an important contribution to making the European economy more circular and an action plan for this purpose has been adopted [16]. Recycling of textiles could be an important beginning in the paradigm shift to the circular economy, especially in the poorest countries, bringing sustainable development and reducing production costs for the companies involved. Recycling second-hand clothing can reduce greenhouse gas emissions by 53%, reduce pollution by chemical processes by 45%, and reduce water eutrophication by 95% [17].

## 3 Methods

Initially, the bibliographic research was used to find the most recent articles on the subject in Google Scholar and ScienceDirect and to build up the conceptual reference. We used government and area association data and specialized websites. A survey was conducted on Google and Facebook to find companies and other textile reverse logistics initiatives in Brazil, with the following keywords: textile industry waste, textile recycling, textile recycling, textile waste, reverse logistics textile industry. Other social networks were not used.

A search was made at Google on several different days in March 2019 to find companies and initiatives for reverse textile logistics, and the number was 14 of them related in the first five pages of the survey. On Facebook, the result came to 13 webpages dealing with the subject. Such pages were searched only in Portuguese.

## 4 Discussion

Textile production, cotton or synthetic, is a segment that moves US $ 797 billion worldwide and is significant for the Brazilian economy, comprising 27 thousand formal companies [15]. Brazil is self-sufficient to produce cotton garments. Along with synthetic products, cotton production totaled almost nine billion pieces a year, of which about seven billion are garments (numbers 2016). The country is a world reference in the production of denim jeans, beachwear, and bedding, table, and bath for the home [2].

### 4.1 Production and Import of Waste in the Textile and Clothing Industry

At the Bom Retiro garment factory in São Paulo county, it is estimated that 1200 companies produce 12 tons of textile waste/day, about 2% of the country's total, estimated at 175,000 tons/year, of which only 36,000 tons are reused to produce twines, blankets, new garments and yarns [18]. For comparison, US textile waste generation was 10 million (t/year) in 2003, reaching 13.09 million (t/year) in 2011 [19, 20]. At least 10% of the textile production is disposed of at the production stage. When considering that all clothes purchased will be discarded and sent to landfill waste, the problem is aggravated by the fact that 70% of the fabrics are made up of synthetic fibers, which makes degradation difficult [7].

In order for correct disposal to take place, infrastructure and attention to the macroeconomic and social aspects that this demand generates are necessary, a situation that is not yet adequate in Brazil. do Amaral et al. [4] show that the Brazilian textile recycling industries imported almost 10 thousand tons of textile waste, more than US$ 11 million, due to the disorganization of garbage collection. For the authors, the misinformation of the population and the disorganization of the collection of textile waste led the recycling companies to import them, because the material arrives in better conditions for use than the recycled in Brazil.

In 2010, a US $ 2 billion loss was attributed to the country for not recycling textiles, which could be improved through the formalization of cooperatives and compensatory incentives to raise the income of the collectors [21]. Data from 2018 show that the damage reaches $ 30 billion a year in products that could be recycled and go to waste. According to Table 1, between 2013 and 2018, the country paid about $ 42 million in freight for importing waste textile.

**Table 1.** Total of imported fibers waste in Brazil

| Year | FOB | kg |
|---|---|---|
| 2013 | 4.016.526 | 5.434.262 |
| 2014 | 8.553.100 | 14.886.680 |
| 2015 | 7.366.819 | 13.199.691 |
| 2016 | 6.242.472 | 12.926.299 |
| 2017 | 7.492.304 | 14.584.420 |
| 2018 | 7.955.204 | 13.107.156 |
| Totals | 41.626.425 | 74.138.508 |

Obs. The table includes the NCM codes of imported products indicated by ABIT as specific rags and wastes, which include wool, cotton, artificial and synthetic fibers (5003, 5005, 5103, 5202, 5301, 5302, 5303, 5305, 5505, 6310) Source [2]

The country recycles only 3% of the 64 million tons of tailings generated annually. An average American throw about 80 lb of used clothing per year and estimates at US$ 45/ton to eliminate the old clothes [20]. In the case of plastic, the return could be US$ 1.4 billion for the economy [22]. Incentives could be used to eradicate about 3,000 dumps and start regional landfills, which could help to minimize the problem [11].

Reverse logistics becomes an essential instrument in the control of natural resources and in mitigating the damages caused by manufacturing processes.

## 4.2 Reverse Logistics

The logistics process must return to the business sectors the solid waste from their products, to be reused in their production cycles or properly destined, through reverse logistics [23]. Rogers and Tibben-Lembke (1999) present the efficient and low-cost control of flows from raw materials, inventories, products, and information, in the opposite direction to logistics, from the point of consumption to the point of origin for recovering value or avoiding improper disposal.

An action plan was adopted in December 2015 by the European Union to make recycling and reuse of plastics a priority, and by 2030 all plastic manufactured in the EU is recyclable, with plastic for single use [16]. Recycling in general and the textile industry can mean business opportunities. Authors [19, 24] points out as advantages the reduction of space in landfills, water, and energy consumption, natural resources, and operating costs.

### 4.3 Textile Recycling

The actions carried out for the recycling and reuse of textiles, all over the world, point to charitable activities [15]. Charity actions provide directly to recycling companies [25]. In the United Kingdom, the collection of textile waste is done by charitable organizations that resell in their stores and surplus stocks sold to recycling companies [26]. Heidari et al. [27] analyzed Tehran's solid waste disposal methods and observed that increasing waste separation rate improves the performance of the disposal system about sustainability indicators. An article [15] points out on the Brazilian situation of collectors of recyclable material, most of whom live in poverty and are integrated into cooperatives or associations with the support of local governments, for the activity of waste cleaning.

The fabrics are composed of more than one type of material and still lacks technologies capable of making such separation. It is necessary to invest in a culture that encourages new social practices and attracts interest in the reverse logistics operation [28]. In research on industry reprocessing, [29] indicate the difficulty of establishing partnerships between the reprocessing industry and the manufacturing sector, and that partnership is fundamental to the transition to a circular economy.

## 5 Final Remarks

The main problems that make the country import instead of using its tailings are the lack of recycling culture and the waste being discarded with dirt and presenting several mixed raw materials, having a high cost for the separation, transportation, and logistics of the material, and there are no financial incentives for the activity.

The investigation of the aspects of the textile chain and garment production that implies in sustainability must go through the search for innovative solutions, such as the reuse of fabrics and clothes, through the recycling and reuse of materials, minimizing the disposal of these products which are polluting through reverse logistics. These attitudes could give rise to a paradigm shift leading to a circular economy, which makes the discussion of the issue both necessary and emerging.

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# Port Performance Measures in Brazil: An Analysis in Port of Santos

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**Abstract.** Competitiveness of Brazilian agribusiness depends on the capacity to sell products through the largest port in South America, Santos. The aim of this paper is to analyze the port efficiency indicators of Brazilian National Waterways Transportation Agency regarding the Port of Santos. To this end, we collected the indicator of port for handling, service time, and tariffs (fee) during of period of 2016–2018 and analyzed using time series. The results showed a tendency of slight growth for handling, moderate growth for the tariff, and a slight decrease in the service time.

**Keywords:** Logistics · Port performance indicators · Bulk cargo · International trade

## 1 Introduction

Population growth has boosted world consumption making logistics one of the main elements of global supply chains [1]. The world trade is highly dependent on maritime transportation due to cargo capacity and associated costs.

Maritime transportation depends on the existence of ports of cargo with a capacity to attend ships of different sizes and move the big volume of these commodities.

In Brazil, for instance, ports play a key role in international trade [2] where port terminals handled over 90% of the total cargo throughput in 2014 for foreign trade [3].

Despite this importance, the Brazilian ports lack policies for the sector and financial resources for new investments, the terminals, and port equipment are obsolete and inefficient, and costs are higher [4].

In Port of Santos, this reality is not different. Even being the main Brazilian port [2] and responsible for the most amount of Brazilian commodities exportation, agricultural handling is affected by the lack of efficiency of the Port.

To face this problem the country promulges two laws of port modernization (1993 and 2013) and established a National Agency to regulate the port activity.


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As a result, it was adopted operational and financial indicators to measure port performance based on the indicators of the United Nations on Conference and Trade Development (UNCTAD). However, is it possible to predict the behavior of these indicators along of time to define port strategy?

To answer this question the aim of this article consists of the application of time series method to verify if is feasible to predicate the behavior of the indicators established by ANTAQ to measure the efficiency of Brazilian ports. To do so, we collected bulk handling, service time, and port tariff from Port of Santos provided by ANTAQ during the period of 2016–2018. The results showed a tendency of slight growth for handling (cargo handling), moderate for tariff, and a decrease in the service time.

## 2 Port Performance Measurements

The measurement of port performance is relevant for port users, policy makers, port developers and other stakeholders [5]. Companies and policy makers can use them to improve port efficiency in order to respond to the demand of international markets.

Around 80% of world goods are transported by sea, thus port efficiency has a direct impact on the ability of countries export and import products [6]. In the case of developing countries, this value represents 90%, hence, local ports need to operate efficiently to allow them to integrate into the world economy.

In 1976 Unctad (United Nations on Conference and Trade Development) [7] developed a comprehensive system of indicators to measure port performance divided in two folds: (i) financial indicators: Tonnage worked (tons), berth occupancy revenue per ton of cargo (monetary units/ton), Cargo-handling revenue per ton of cargo (monetary units/ton), labour expenditure per ton of cargo (monetary units/ton), capital equipment expenditure per ton of cargo (monetary units/ton), total contribution (monetary units); (ii) Operational indicators: arrival late (ships/day), waiting time (hours/ship), service time (hours/ship), turn-round time (hours/ship), tonnage per ship (tons/ship), fraction of time berthed ships worked, number of gangs employed per ship per shift (gangs), tons per ship-hour in port (tons/hour), tons per ship-hour at berth (tons/hour), tons per gang hour (tons/gang-hour), fraction of time gangs idle.

Chung [8] in 1993 dealing with performance indicators suggests that operational performance of port is generally measured in terms of the speed with vessels is despatched while financial indicators are defined based on usual financial statements as the income statement, profit and loss account, and balance sheet. Since then other studies have been extended the knowledge revolving around port performance [9–12].

In Brazil, the first law for port modernization to reduce costs and improve competitiveness was created in 1993 and changed in 2003 for a new one that just confirmed the main questions involving port performance [2]. However, Galvão et al. point out the Brazilian ports cargo throughput decreased between 2013 and 2015, and the foreign trade flow in value has diminished by almost 20% between 2013 and 2015 [2].

The Brazilian National Waterway Transportation Agency was established in 2001 a system for measure performance of Brazilian ports considering financial and operational indicators according to the Unctad recommendations. These indicators are monthly handling in the port of Santos, average board, and berthing rate [13]. We used ANTAQ indicators available to evaluate port efficiency regarding the grains exports. The methodology section presents the details of the research.

## 3 Methodology

This research is an exploratory case of Brazilian port efficiency. The aim of the research was to evaluate the port indicators used by the National Waterway Transportation Agency regarding bulk cargo during the period of 2016–2018 [13]. In this respect, the study analyzes three performance indicators: monthly handling in the port of Santos (handling), average board (service time), and berthing rate (fee).

The data were collected of ANTAQ database [13] and processed using MS Excel© software to calculate time series. Time series analysis has been paid close attention due to the exponential growth of time-stamped data, such as economics and finance [14].

The functions tested in this research were: linear, exponential, polynomial of the 2nd degree, power, and logarithmic (classical methods).

## 4 Results

Given that time series methodology Table 1 shows the functions chosen for each series, according to the highest coefficient of determination or regression measure (R2). Values closer to 1 indicate a greater correlation between the dataset and serve as indicators for choosing the most adequate functions for predictions [15].

**Table 1.** Determination coefficient

| Equations | Handling | Service time | Fee |
|---|---|---|---|
| Exponential | 0.0128 | 0.0280 | 0.101 |
| Linear | 0.0087 | 0.0405 | 0.138 |
| Logarithmic | 0.009 | 0.0261 | 0.017 |
| Power | 0.0103 | 0.0216 | 0.009 |
| Polynomial 2 | 0.0087 | 0.0409 | 0.519 |

For the handling the best model was the exponential one, being that for medium board and mooring rates the polynomial model of 2 greatness. Table 2 indicates the trend functions provided by the software after selection, using the coefficient of determination shown in Table 1.

**Table 2.** Trend equations

| Index | Equations | $R^2$ | AMPE |
|---|---|---|---|
| Handling | $4E + 06e0.0024x$ | 0.0128 | 18% |
| Service time | $-0.0303x2 - 1.5618x + 716.34$ | 0.0409 | 26% |
| Fee | 152.55x2 − 4794.2x + 188303 | 0.5187 | 8% |

The mean absolute error is an indicator of the variations in the forecasts shown in the results section. This indicator was calculated by means of the average between the original and predicted values of each period studied.

## 5 Discussion

The Port of Santos bulk handling between 2016 and 2018 showed an exponential behavior, registering an average growth of approximately 500 thousand tons, Fig. 1.

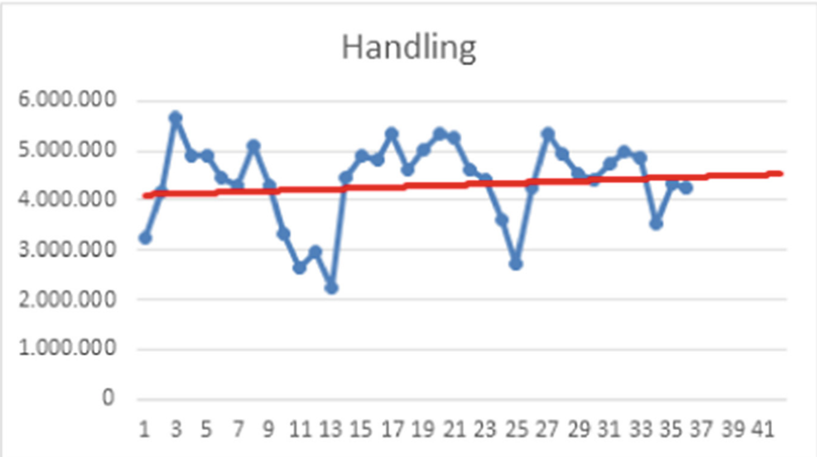


**Fig. 1.** B = Monthly handling behavior in Santos from January 2016 to December 2018 in tons.

As depicted in Fig. 1 a slight growth trend occur for the handling of this port with a projection of 4.4 million tons. However, when considering the charges applied for mooring in the same period to operate ships that moved cargo in bulk, there is an average value of BRL 154,709 equivalent to ($40,184) per vessel at a rate of conversion of BRL 3.85 until June 2019.

Figure 2 presents the behavior of mooring rates in the Port of Santos from January 2016 to December 2018 in BRL.

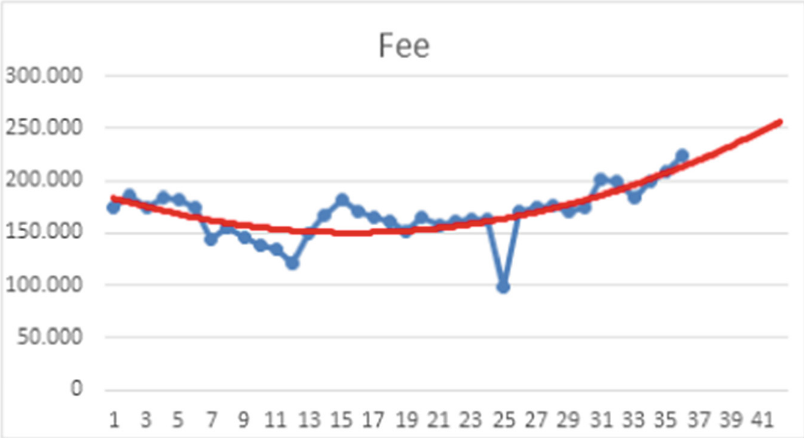


**Fig. 2.** Rate per mooring from 2016 to 2018.

As can be seen in Fig. 2 there is a growth in the tariff practiced, and a forecast of BRL 256,045 equivalent to ($66,505) for June 2019, a growth of 12.7% in 6 months. While the handling and rate indicators are on the rise, service level indicators, such as the average board, are not so encouraging, as these showed a downward trend for subsequent months, Fig. 3.

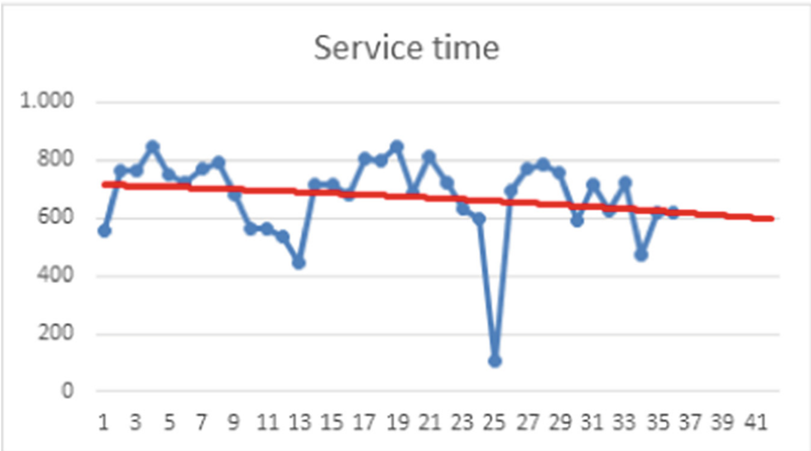


**Fig. 3.** Average plank rates of the port of Santos in the period from 2016 to 2018.

Although the tariff and handling showed an optimistic scenario with an estimated growth, the same did not occur in the service level of the port of Santos, which showed a slight decrease of 3.9% in its average board index, estimating the mark of 597 that is lower than the previous indices (Table 3).

**Table 3.** Forecasting

| Index | Jan | Feb | Mar | Apr | May | Jun |
|---|---|---|---|---|---|---|
| Handling | 4,371,448 | 4,381,952 | 4,392,482 | 4,403,036 | 4,413,616 | 4,424,222 |
| Service time | 617 | 613 | 609 | 605 | 601 | 597 |
| Fee | 219,759 | 226,406 | 233,358 | 240,615 | 248,177 | 256,045 |

Table 3 shows the projections made for each indicator based on the historical series that based our forecasts that are explained in this article.

## 6 Conclusion

The present study analyzed Port Performance Measures of Brazilian National Waterway Transportation Agency for the Port of Santos. The main contribution of this study is to validate the use of these indicators as a measure to improve port efficiency. In this sense, we adopted a time series method.

Our results showed predictability in the handling and tariff indicators, which may bring greater confidence to the sector. In further studies intents to analyze other Brazilian ports, other products and alternative methods to time series.

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# $CO_2$ Gas Emissions of Soybean Production and Transportation in the Different Macro-regions of Mato Grosso State - Brazil

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**Abstract.** Brazil is one of the largest producers and exporters of soybeans and its production is mainly transported via the road system. The growing concern on the impacts caused by anthropogenic greenhouse gas emissions from agroindustry production as well as the commitment to international treaties supports the relevance of controlling and estimating their emissions. The objective of this work is to calculate the emissions of the main sources of GHG in the cultivation and transport of soybean production in the macro-regions of Mato Grosso, pointing out the main routes and modal integration of the production sites to the main Brazilian ports. For this purpose, the Life Cycle Assessment methodology was adopted. The results show that in most cases, the production of one kg of soybean emits more $CO_2$ than transportation of the same mass. This trend is more evident when the best actual combination of transportation modals is considered for each macro-region. The substitution of some highway stretch by water and/or railway has a positive effect, and it is possible to affirm that the use of multimodality, allows a significant reduction in $CO_2$ emission.

**Keywords:** Soybean · Transport · Emissions of greenhouse gases

## 1 Introduction

Currently, the international market requires sustainable practices to minimize environmental impacts and reduce emissions of greenhouse gases (GHGs) [1, 2].

The Brazilian government launched in 2010 the program "Low Carbon Plan in Agriculture" coordinated by the Ministry of Agriculture, Livestock and Food Supply [3], regarding the reduction of carbon emissions.

Anthropogenic activities with intensive use of fossil fuels to support globalization, production and consumption lead to the emission of greenhouse gases. The sectors that most contribute to this increase in emissions are agriculture and transport, as highlighted by the Intergovernmental Panel on Climate Change [4].


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Brazil is one of the largest soybean producers in the world and the largest exporter. Soybean supply chain is not only devoted to human and animal food products but also it is involved in biodiesel production by supplying the main source of raw material [5].

Mato Grosso which is located in the Midwest, stands out in the Brazilian scenario for high grain production, and it is expected to reach 32 million tons (30.8% of the national soybean production), [6, 7]. According to the Institute of Agricultural Economy of the State of Mato Grosso [8], 59% of the production is destined to the foreign market.

With an average distance of 2,000 km for the main Brazilian ports, the State faces logistical problems (transportation costs, environmental impacts) [9–11]. The Port of Santos/SP represents 45.34% of exports and Porto de Barcarena/PA, 20.02%. Therefore, the ports of Arco Norte are a new alternative for the flow of production from the north of the country, according to the National Agency of Waterway Transportation [12].

The objective of this study is to calculate the emissions of the main sources of GHG in soybean cultivation and transport in the macro-regions of Mato Grosso, pointing out the main routes and modal integration for the Brazilian ports.

## 2 Materials and Method

### 2.1 Adopted Method

Life Cycle Assessment (LCA) identifies the environmental aspects of a particular product or service throughout its life cycle [13, 14]. There are four steps to achieve the results: goal definition and scope, inventory analysis (IA), impact assessment and interpretation. The present study is limited to global warming category assessment through calculation of the mass of $CO_2$eq emissions for soybean production and $CO_2$ emissions for transport.

Two scopes will be considered. The first scope includes the emissions of agricultural activities for the soybean production; and the second, considers the $CO_2$ emission from diesel combustion, according to the type of modal adopted for transportation.

GHG emissions, expressed in $CO_2$eq, are equivalent to the emissions of carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxide ($N_2O$), corrected by the corresponding global warming potential (time horizon of 100 years) [4].

The functional unit of the present study is considered as 1 kg of soybean, in order to allow comparisons with other related studies.

### 2.2 System Boundaries and Delimitations

**Scope 1:** It considers emissions of $CO_2$eq due to agricultural activities (those activities performed inside the gate). The activities are related to the production of soybeans and the combustion of diesel in all agricultural activities (soil preparation, planting, cultivation, harvesting, and limestone application) [4].

This study does not consider nitrogen fertilizer application since the presence of Bradyrhizobium enables the biological fixation of atmospheric nitrogen [15, 16], so direct nitrogen emissions due to the application are not accounted for. Calculation of GHG emissions due to herbicide and insecticide applications are not considered since they are negligible inside the gate.

**Scope 2:** It includes the identification of the main routes from its origin located at the main soybean producers' municipalities to the destination ports, as well as the transportation modalities used. From the identification of transport modals and distances traveled, the direct emission of $CO_2$ is calculated using the $CO_2$ emission factors for each type of mode used.

## 2.3 Presentation of the Macro-regions and Raw Data Obtention

Studies carried out by the IMEA [8] divided Mato Grosso State into seven macro-regions from the point of view of agroeconomic. Data collection provided by IMEA [17] regarding agricultural production costs for the year 2018/2019 compose the IA.

Data selection for each macro-region depends on the scope adopted. When the scope 1 is considered, diesel and limestone inputs must be calculated. In order to convert raw data expressed as costs into units adherent with emission factors, the input prices for the different macro-regions were considered. Thus, to carry out the conversion to mass units, the cost of diesel oil was divided by the diesel price from the National Petroleum Agency [18]. Analogously, the cost of the limestone was divided by the price practiced in the State [19].

To carry out scope 2 analysis, the main routes to the main Brazilian ports were obtained from data from the Ministry of Transport, Ports and Civil Aviation, and authors, including highways (transshipment stations) from to waterways and railroads, as shown in Fig. 1 [11, 20–22].

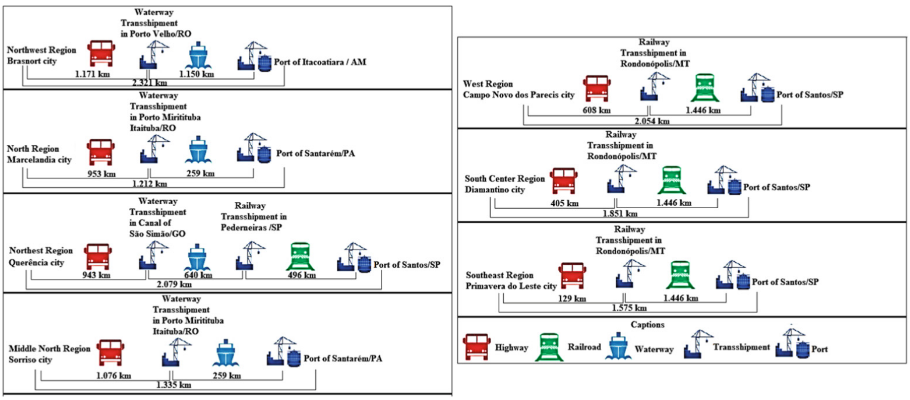


**Fig. 1.** Main routes used to export soybean produced in Mato Grosso State. Source: Authors.

The most productive municipality in terms of the largest soybean production [23], was considered as the representative one for each macro-region and thus it was set as the origin for distance to destination calculation. Thus, the emission factors for each transportation model are used to calculate the emission of kg $CO_2$/kg of soybean transported via the different intermodal routes. The ports considered (j) are: MA = Manaus; SL = São Luiz; ST = Santarem; SN = Santos; PR = Paranaguá.

## 2.4 Calculation of Emissions

The calculation of GHG emissions from diesel combustion and the application of the limestone used in the agricultural phase are carried out by multiplying mass and volume, respectively by the emission factors presented in Table 1.

**Table 1.** Emission factors for all inputs considering at scope 1 and scope 2. Source: the authors based on data from [4, 24].

| Emission source | Type of emission | Unit | Emission factor | Reference |
|---|---|---|---|---|
| Fuel | Direct | kg $CO_2$eq/L diesel | 2,68 | [4] |
| Diesel | | | | |
| Limestone | Direct | kg $CO_2$eq/kg limestone | 0,48 | [4] |
| Application in soil | | | | |
| Transportation modal | | | | |
| Highway | kg$CO_2$/t * km | | 0,11917 | [24] |
| Railway | | | 0,0346 | |
| Waterway | | | 0,018 | |

**Emission of Diesel**

$$Emission\ of\ CO_2eq = Q_{diesel} \times FE \tag{1}$$

Emission of $CO_2$eq is expressed in kg/kg soybean, $Q_{\mathrm{diesel}}$ corresponds to the quantity of liters of diesel/kg soybean, and FE to the emission factor, in kg of $CO_2$eq per liter diesel.

**Application of Limestone**

$$Emission\ of\ CO_2eq = \left(M_{kg\,limestone} \times FE\right) \tag{2}$$

Emission of $CO_2$eq is expressed in kg/kg soybean, M corresponds to the annual mass of calcium limestone in kg, and FE to the emission factor of calcium limestone.

**Emission of $CO_2$ from Diesel Fuel for Each Transportation Mode**
The calculations of $CO_2$ emissions from each Mato Grosso soybean route is composed by the combination of the distance (D), and $CO_2$ emission factor of each modal of transportation ($FE_i$).

$$Ejk = \sum (FEi * Djk) \tag{3}$$

$E_{jk}$ corresponds to total $CO_2$ emission per municipality of origin j and port of destination k; $FE_i$ corresponds to the $CO_2$ emission factor of each transportation modal i, in kg/t * km; D is the distance traveled via each modal, in km.

## 3 Results and Discussion

### 3.1 From Scope 1

Figure 2 compares the $CO_2$eq emission during soybean production stage (inside the gate) for each Macro-region. Notice that for all cases, limestone application is largely the most impacting issue during production, while the diesel involved in culture practices ranges from 7% to 18% of the total emissions.

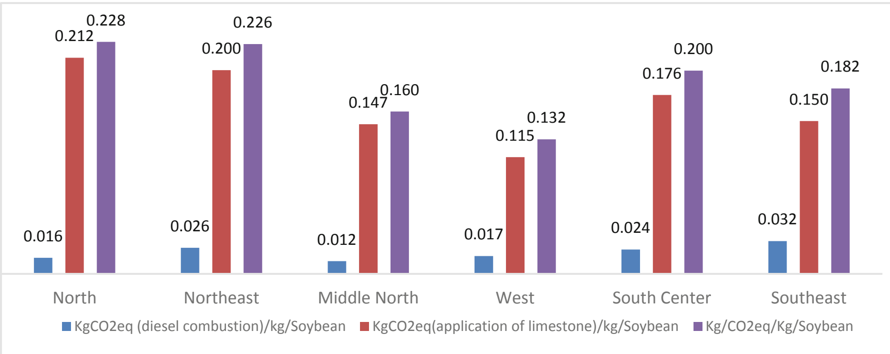


**Fig. 2.** Emission of $CO_2$eq in the soybean farming activities in the different macro-regions of Mato Grosso Brazil. **Source:** Authors.

The limestone input represents the largest emission for agricultural activity in all cases. Since annually large amounts of limestone are used to correct soil acidity, and considering its contribution to global warming, it deserves a judicious evaluation of the required amounts to attain the proper pH. In this sense, the adoption of precision agriculture techniques could be useful.

The Northern and Northeastern macro regions show the largest emissions of $CO_2$eq, 0.228 and 0.226, respectively. The Middle North and West result in the lowest emissions, varying from 0.160 to 0.132 kg of $CO_2$eq/kg of soybean, fact that can be justified by the applied technology and improved agricultural practices [2, 25].

The average of emissions is 0.188 kg $CO_2$eq kg of soybean produced. [1] shows comparable values, although it also includes the emissions corresponding to inputs production.

### 3.2 From Scope 2

Although an interval of $CO_2$ emission values is obtained depending on the alternative routes covering each origin with destination ports, Fig. 3 evidences the best routes (and combination of modals) for each macro-region. Santos is the destination port which shows the best route in terms of emission for four of the seven macro-regions. Each representative municipality is considered in the figure. The best-routes values range from 0.065 to 0.140 kg $CO_2$.

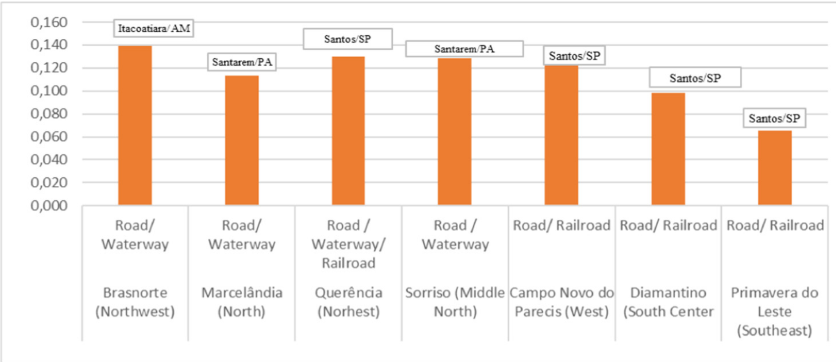


**Fig. 3.** Emission of Kg $CO_2$/Kg of soybeans/transport of the port final. **Source:** Authors

The North-western macro-region (represented by Brasnorte) presents the largest emission. The road modal, which corresponds to a high emissions modal when combined with other transportation modals minimize emissions of the total route.

Figure 4 shows the comparison of production emissions and emissions in the route ($CO_2$eq and $CO_2$, respectively) for 1 kg of soybean.

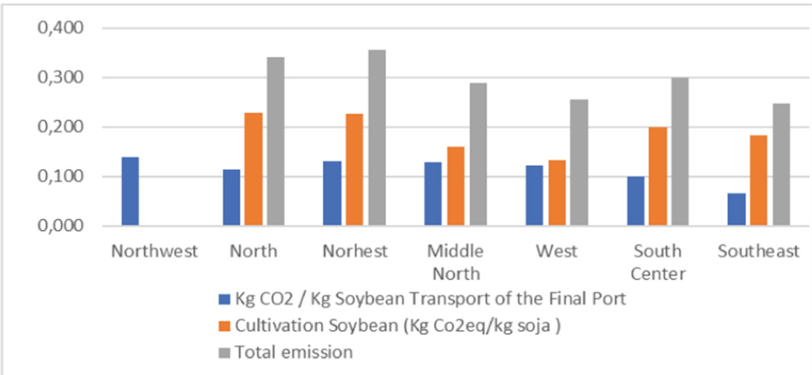


**Fig. 4.** Comparison of $CO_2$ Emissions/kg of soybean in the production and transportation stages. **Source:** Authors

The results show that in most cases, the production of one kg of soybean emits more $CO_2$ than transportation of the same mass. This trend is more evident when the best combinations of transportation modals are considered for each macro-region (as in Fig. 4). The substitution of some highway stretch by water and/or railway has a positive effect, and it is possible to affirm that the use of multimodality, allows a significant reduction in $CO_2$ emission. It is important to mention that for transportation only direct $CO_2$ emission was considered by the emission factors, since it is the quantitatively most important gas emitted during combustion. Anyway, quantities of other GHG should be considered depending on type of engine, vehicle, maintenance, etc. This is not considered in the present work.

## 4 Findings and Conclusions

This study calculated the GHG emissions of agricultural activities and transportation intermodal routes towards the main ports for the different macro-regions of the Mato Grosso State.

Results at production shows emission values varying between 0.132–0.228, with an average of 0.188 $KgCO_2eq$. It is evidenced that use of limestone is the largest emitter in the field. The adoption of more careful practices concerning limestone application according actual necessity will improve emission impacts. Public incentives for innovative technologies, such precision agriculture, should be promoted.

It has been observed that routes using road modal over 500 to 700 km increase the emission and must be combined with other transportation modals.

Public policies directed towards investments in logistics solutions that could assist in transportation infrastructure improvement could be a way to minimize environmental impacts.

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# Sustainability and Reconfigurability of Manufacturing Systems

# Classification of Optical Technologies for the Mapping of Production Environments

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**Abstract.** Indoor localization systems are becoming more and more important with the digitalization of the industrial sector. Sensor data such as the current position of machines, transport vehicles, goods or tools represent an essential component of cyber-physical production systems (CCPS). However, due to the high costs of these sensors, they are not widespread and are used mainly in special scenarios. However, especially optical indoor positioning systems (OIPS) based on cameras have certain advantages due to their technological specifications. In this paper, the application scenarios and requirements as well as their characteristics are presented and a classification approach of OIPS is introduced.

**Keywords:** Optical indoor localization systems · Cameras · Marker-based tracking · Changeable and reconfigurable manufacturing

## 1 Introduction

In order to meet the requirements of Industry 4.0, a high degree of adaptability of production systems is required [1]. In this context, there is a focus on the so-called smart factory, in which people, machines, objects and products are intelligently linked with each other through the provision of hardware and software. This enables increasing automation and autonomous reaction to unpredictable events [2].

For this purpose, embedded systems are integrated into objects, devices, buildings, forklifts as well as into production facilities and logistics components, whereby these become cyber-physical systems (CPS). These systems, also known as intelligent objects, can then autonomously and decentrally communicate with each other and optimize themselves. The result is a virtual image of reality, which is continuously updated with the help of real-time data [3].

Westkämper [4, 5] considers the ability to unambiguously identify and localize objects and the individuality of systems, processes, objects and products as well as the controllability of the increasing complexity to be particularly important. Indoor positioning systems (IPS) are architectures of tags, location sensors, a locating engine and a locating application that can be used to determine the position of a person or an object in buildings [6]. Tags are used as spatial reference points or for unambiguous


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identification and the location sensor provides ID and position values. The location engine uses this data to derive the actual position of the specific location object. The location application is the software solution for further processing the position data [7].

Positioning can be relative or absolute. The relative positioning determines the position of the location object relative to a reference point. In absolute position determination, the position is specified in a global coordinate system [8]. A variety of systems and technologies using different algorithms, techniques and technologies are available for the unambiguous identification and localization of objects, which differ in their degree of maturity and their performance [9–11]. Due to the high cost of these systems, they are actually only applied in a limited amount of scenarios, such as the navigation of autonomous transport vehicles [12]. In particular, optical indoor positioning systems (OIPS), which use cameras or other optical sensors to determine the position of localization objects in their field of view, [13, 14], have proven to be precise and robust in industrial applications [15–17]. Compared to radio-based approaches, which have also gained popularity, they are not influenced by reflections on metal, multipath propagation, interferences, scattering or absorption by liquids [18]. They are highly scalable and can work with tags that can be printed by the user inexpensively, or even without any tags. Therefore, they seem to be especially promising for the application within small and medium sized enterprises (SME).

## 2 Characteristics and Requirements of Indoor Location Systems

The wide field of application of indoor localization systems leads to a multitude of requirements. An overview of requirements mentioned in literature is given in Table 1. The authors have been assigned to the requirements mentioned in their works.

**Table 1.** Identified requirements towards indoor positioning systems (IPS)

| Author | Günthner et al. [19] | Hohenstein [6] | Mautz [18] | Liu et al. [20] | Han [21] | Malik [7] |
|---|---|---|---|---|---|---|
| *Localization function* | | | | | | |
| Continuity | | x | x | | | x |
| Output data | | x | x | | | x |
| Required infrastructure | | x | x | | | x |
| *Localization performance* | | | | | | |
| Accuracy | x | x | x | x | x | |
| Coverage | x | x | | x | x | |
| Repeat accuracy | x | | x | | | |
| Update rate | x | x | | x | x | |
| *Overall system* | | | | | | |
| Scalability | x | x | x | x | x | x |
| Availability | | | x | | | |
| Robustness | x | x | x | x | | x |

In the following section, a short description of the requirements is provided.

- **Continuity** refers to the ability of a system to repeat a certain function in time and space. An IPS is continuous if position determination is not limited to a few pre-defined measurements [6].
- **Output data** refers to the location data provided by an IPS, e.g. 2D or 3D coordinates, orientation, ID, etc.
- **Required infrastructure** refers to the infrastructure needed for position determination that goes beyond the location sensor and the location engine. Mautz [18] distinguishes between OIPS with or without markers.
- **Accuracy** refers to a numerical measure in a given metric unit and results from the deviation between nominal and actual position.
- **Coverage** refers to the maximum range between an IPS and a location object, in which the object can still be identified and its position be determined.
- **Repeat accuracy** or precision, describes the repeatability of a measurement result, given that the measurement is carried out under the same conditions.
- **Update rate** refers to the frequency at which the position data can be determined by a system. An important aspect of the update rate is the latency, which is the time required by a system to determine the actual position of a localization object.
- **Scalability** refers to the achievable number of localizable objects and structures.
- **Availability** refers to the amount of time a system is available for use with the required accuracy and integrity.
- **Robustness** refers to the resistance towards unwanted influences of a system, e.g. changes in temperature, reflections, occlusion, etc.
- **Architecture** refers to the fact that systems can be realized in a way that the localization system is attached to the localization object, the position data are thus recorded directly at the object to be located (inside-out). In contrast to this approach in an outside-in approach, the localization system is attached to the infrastructure [6].

| **Requirements** | **Characteristics** | | | | |
|---|---|---|---|---|---|
| Continuity | continuous | discontinuous | | | |
| Output data | undefined | xy position | xy position, ID | xyz position | xyz position, ID |
| Required infrastructure | none | markers | | | |
| Accuracy | < 5 cm | < 10 cm | < 5 cm | < 1 m | |
| Coverage | < 1 m | < 5 m | < 10 m | | |
| Repeat accuracy | 69 % | 93,3 % | 99,96 % | | |
| Update rate | on request | event-driven | periodically | | |
| Latency | < 1 s | < 15 s | | | |
| Scalability | low | medium | high | | |
| Availability | low | regular | high | | |
| Robustness | occultation | reflection | interferences | changing environments | |
| Architecture | inside-out | outside-in | | | |
| Number of objects | ≤ 10 | ≤ 50 | ≥ 50 | | |
| Computing power | low | medium | high | | |
| Power supply | active | passive | | | |

**Fig. 1.** Requirements towards indoor positioning systems (IPS) and their characteristics

Moreover, the number of localization objects, the required computing power and power supply are important aspects, as they influence the costs and the components of a system. Based on a literature review (see e.g. [6, 16, 18, 22, 23]), the characteristics of the requirements were determined. The results are shown in Fig. 1.

## 3 Application Scenarios of OIPS

After the introduction of the requirements for OIPS in Sect. 2, this section presents various application scenarios explored in the literature and clustered according to their main application area. A short description of the application scenario is given (see Tables 2 and 3). The list of scenarios represents the use cases mentioned in literature. The objective of the collection was not so much absolute completeness, but rather a representative selection, which makes it possible to assign the application scenarios to basic system configurations in the following section.

**Table 2.** Application scenarios of optical indoor positioning systems (OIPS) in logistics

| Area | Application scenario | Description |
|---|---|---|
| Logistics | Automatic goods recognition at arrival | Delivered goods can be automatically identified and posted directly at the arrival [17] |
| | Component search | Comprehensive localization of components and intermediate products [27] |
| | Intelligent tool control | Through the localization of tools and the intelligent analysis of this data, it is possible to determine and optimize the utilization [27, 28] |
| | Inventory management | Stocks are often unnecessarily increased because the storage location or filling level of containers cannot be determined [24] |
| | Navigation and localization of mobile robots | Equipped with an RTLS, mobile robots can find their way around in industrial environments. The determination of their absolute position at any time is crucial for optimal navigation [26] |
| | Optimization of routes | Optimization of in-house transport routes to avoid empty runs and traffic jams |
| | Quality management | Reduction of picking errors, packed goods are counted and compared with the packing list [17, 24] |
| | Route inspection | Before a transport process is started, the system checks whether the route is blocked or not. |
| | Tracking of intralogistics transport vehicles | Current position determination of transport vehicles (e.g. forklifts, tugger trains) and their status. Optimization of availability, assignment, routes and transparency [24] |
| | Tracking of material flows, load carriers or workpieces | Material movements can be recorded with Real-Time Locating Systems (RTLS) and passed on to higher-level system for analysis purposes and process optimisation [6, 24, 25] |

**Table 3.** Application scenarios of optical indoor positioning systems (OIPS) in production and production-related areas

| Area | Application scenario | Description |
|---|---|---|
| Production | Automation in production lines | The position data of work pieces or containers are used to improve automation in transportation and feeding processes avoiding delays in the production process [27] |
| | Digital twin of factory, layout of the production system | Creation of the digital twin of the production system. The constant position determination of machines and vehicles enables the digital representation of the physical production system and the proactive reconfiguration of production systems. This information plays a decisive role especially in the case of increasing automation or even the introduction of autonomous system components [27] |
| | Intelligent tool control | Depending on the position of a tool (e.g. a screwdriver) relative to a work piece to be machined, its control is automatically enabled. For instance the torque is adjusted depending on the tool position [24] |
| | Operational optimization | The position determination of every single batch, tool and employee enables extensive process optimization by means of analysis [28] |
| | Quality management | Observation and reduction of assembly errors [24] |
| Security | Access control | Monitoring of safety areas, increasing workplace safety [24, 27] |
| | Anti-theft protection | Continuous presence check, inspection of a known object [18] |
| | Evacuation management | In emergencies (e.g. fire, release of dangerous substances, danger of terrorism, etc.) companies must be able to determine whether employees are still in the building and ideally in which areas [29] |

## 4 Classification of OIPS

The biggest challenge for (potential) users is the fundamental definition of the architecture and identification method of the overall system. While the technological capabilities of individual components can easily be adapted on the basis of the specific requirements of the scenarios, the decision whether the camera system is located on the object to be localized or not and if a marker-based system or a non-marker based like a feature-based-tracking system should be used. Therefore, four classes were formed based on their characteristics (see Table 4) and the application scenarios are evaluated to determine, which of these classes could be used to implement the respective scenario (see Table 5).

**Table 4.** OIPS-classes based on architecture and infrastructure

| Class | Architecture | Required infrastructure |
|---|---|---|
| OIPS Class 1 | Outside-in | Markers |
| OIPS Class 2 | Outside-in | None |
| OIPS Class 3 | Inside-out | Markers |
| OIPS Class 4 | Inside-out | None |

The results show that the outside-in architecture where the localization system is attached to the infrastructure (Class 1 and 2) covers a significantly wider range of scenarios than the inside-out architecture. In practice, this gives an initial indication of a technology to be introduced if the concrete application is still unspecified. All scenarios except the self-navigation of mobile robots can be solved with the outside-in architecture. For a detailed specification, further aspects of Fig. 1 have to be considered.

**Table 5.** Classification of optical indoor positioning system (OIPS)-scenarios

| Scenario | OIPS Class 1 | OIPS Class 2 | OIPS Class 3 | OIPS Class 4 |
|---|---|---|---|---|
| Access control | x | x | | |
| Anti-theft protection | | x | | x |
| Automatic goods recognition at arrival | x | | | |
| Automation in production lines | x | x | | |
| Component search | x | x | | |
| Digital twin of factory | x | x | x | x |
| Identification workplace | x | x | | |
| Intelligent tool control | | x | | x |
| Inventory management | x | | | |
| Navigation and localization of mobile robots | | | x | x |
| Operation optimization | x | x | | |
| Optimization of routes | x | x | x | x |
| Quality assurance (reduction of picking errors) | x | | | |
| Route inspection | | x | | |
| Tracking of intralogistics transport vehicles | x | | x | |
| Tracking of material flows, load carriers or workpieces | x | x | | |
| **Number of viable scenarios** | **12** | **11** | **4** | **5** |

The minimum specification of an OIPS that can meet the requirements of all the scenarios listed in Class 1 must have an accuracy of better than 5 cm, a coverage of at least 10 m, a frame rate of more than 15 frames per second (fps) to track moving objects, a periodic update rate, a latency of under 1 s, a high scalability, the ability to identify more than 50 objects, and use an active power supply. This gives users an indication how to set up an OIPS with a maximum of flexibility in relation to the scenarios. Individual application requirements of each scenario are shown in Fig. 2.

| Classes | Accuracy class | Application scenarios | Architecture | Required infrastructure | Accuracy | Coverage | Frame rate | Update rate | Latency | Number of objects | Scalability | Computing power | Power supply | Output data |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| OIPS Class 1 | 1 | Automation in production lines | outside-in | markers | < 5 cm | < 5 m | ≥ 15 fps | periodically | < 1 s | ≥ 50 | medium | low | active | xy position, ID |
| | 2 | Identification work station | outside-in | markers | < 10 cm | < 1 m | < 15 fps | periodically | < 1 s | ≥ 50 | low | low | active | xy position, ID |
| | | Inventory management | outside-in | markers | < 10 cm | < 10 m | ≥ 15 fps | periodically | < 1 s | ≥ 50 | high | low | active | xy position, ID |
| | | Quality assurance (Reduction of picking errors) | outside-in | markers | < 10 cm | < 1 m | < 15 fps | periodically | < 1 s | ≥ 50 | low | low | active | xy position, ID |
| | 3 | Automatic goods recognition at arrival | outside-in | markers | < 50 cm | < 5 m | < 15 fps | event-driven | < 1 s | ≥ 50 | low | low | active | xy position, ID |
| | | Component search | outside-in | markers | < 50 cm | < 10 m | < 15 fps | on request | < 1 s | ≥ 50 | high | low | passive | xy position, ID |
| | | Digital twin of factory | outside-in | markers | < 50 cm | < 10 m | ≥ 15 fps | periodically | < 1 s | ≥ 50 | high | low | active | xy position, ID |
| | | Operation optimisation | outside-in | markers | < 50 cm | < 10 m | ≥ 15 fps | periodically | < 1 s | ≥ 50 | high | low | active | xy position, ID |
| | | Tracking of material flows, load carriers or parts | outside-in | markers | < 50 cm | < 10 m | ≥ 15 fps | periodically | < 1 s | ≥ 50 | high | low | active | xy position, ID |
| | 4 | Access control | outside-in | markers | < 100 cm | < 5 m | < 15 fps | periodically | < 1 s | ≤ 10 | low | low | active | undefined |
| | | Optimisation of routes | outside-in | markers | < 100 cm | < 5 m | ≥ 15 fps | periodically | < 1 s | ≤ 50 | medium | low | passive | xy position, ID |
| OIPS Class 2 | 1 | Automation in production lines | outside-in | none | < 5 cm | < 5 m | ≥ 15 fps | periodically | < 1 s | ≥ 50 | medium | high | active | xy position, ID |
| | 2 | Identification work station | outside-in | none | < 10 cm | < 1 m | < 15 fps | periodically | < 1 s | ≥ 50 | low | high | active | xy position, ID |
| | | Intelligent tool control | outside-in | none | < 10 cm | < 1 m | < 15 fps | event-driven | < 1 s | ≤ 10 | medium | high | active | xyz position |
| | 3 | Component search | outside-in | none | < 50 cm | < 10 m | < 15 fps | on request | < 1 s | ≥ 50 | high | high | passive | xy position, ID |
| | | Digital twin of factory | outside-in | none | < 50 cm | < 10 m | ≥ 15 fps | periodically | < 1 s | ≥ 50 | high | high | active | xy position, ID |
| | | Operation optimisation | outside-in | none | < 50 cm | < 10 m | ≥ 15 fps | periodically | < 1 s | ≥ 50 | high | high | active | xy position, ID |
| | | Route inspection | outside-in | none | < 50 cm | < 5 m | < 15 fps | event-driven | < 15 s | ≥ 50 | high | high | passive | xyz position |
| | | Tracking of material flows, load carriers or parts | outside-in | none | < 50 cm | < 10 m | ≥ 15 fps | periodically | < 1 s | ≥ 50 | high | high | active | xy position, ID |
| | 4 | Access control | outside-in | none | < 100 cm | < 5 m | < 15 fps | periodically | < 1 s | ≤ 10 | low | high | active | undefined |
| | | Anti-theft protection | outside-in | none | < 100 cm | < 1 m | < 15 fps | periodically | < 1 s | ≤ 10 | low | high | active | undefined |
| | | Optimisation of routes | outside-in | none | < 100 cm | < 5 m | ≥ 15 fps | periodically | < 1 s | ≤ 50 | medium | high | passive | xy position, ID |
| OIPS Class 3 | 2 | Navigation and localisation of mobile robots | inside-out | markers | < 10 cm | < 10 m | ≥ 15 fps | periodically | < 1 s | ≤ 10 | high | low | passive | xy position |
| | 3 | Digital twin of factory | inside-out | markers | < 50 cm | < 10 m | ≥ 15 fps | periodically | < 1 s | ≥ 50 | high | low | active | xy position, ID |
| | | Tracking of intralogistics transport vehicles | inside-out | markers | < 50 cm | < 10 m | ≥ 15 fps | periodically | < 1 s | ≤ 10 | high | low | passive | xy position, ID |
| | 4 | Optimisation of routes | inside-out | markers | < 100 cm | < 5 m | ≥ 15 fps | periodically | < 1 s | ≤ 50 | medium | low | passive | xy position, ID |
| OIPS Class 4 | 2 | Intelligent tool control | inside-out | none | < 10 cm | < 1 m | < 15 fps | event-driven | < 1 s | ≤ 10 | medium | high | active | xyz position |
| | | Navigation and localisation of mobile robots | inside-out | none | < 10 cm | < 10 m | ≥ 15 fps | periodically | < 1 s | ≤ 10 | high | high | passive | xy position |
| | 3 | Digital twin of factory | inside-out | none | < 50 cm | < 10 m | ≥ 15 fps | periodically | < 1 s | ≥ 50 | high | high | active | xy position, ID |
| | 4 | Anti-theft protection | inside-out | none | < 100 cm | < 1 m | < 15 fps | periodically | < 1 s | ≤ 10 | low | high | active | undefined |
| | | Optimisation of routes | inside-out | none | < 100 cm | < 5 m | ≥ 15 fps | periodically | < 1 s | ≤ 50 | medium | high | passive | xy position, ID |

**Fig. 2.** Optical indoor positioning system (OIPS)-application scenarios and their characteristics

## 5 Summary and Conclusion

In this paper, the literature in regard to IPS and OIPS was analyzed and application scenarios as well as their requirements and characteristics were derived. The classification framework can be used by practitioners to determine the technical requirements to realize a specific application scenario. It was shown that OIPS is a relevant technology that can cover a wide range of scenarios and that an outside-in architecture with localization system attached to the infrastructure (mounted set of cameras and marker- or non-marker-based identification and localization of the objects) covers a significant higher range of scenarios in the production environment that the inside-out architecture. Here it could be proven that this architecture has the broader application possibilities.

The high proportion of low-cost computing power and image sensor chips on the market make cost-effective positioning solutions that can meet the requirements more attractive for a wider range of scenarios. This in combination with the possibility to paper-print a marker for identification purposes for literally no costs, opens up a cost-efficient realization of high number of scenarios presented and characterized.

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# A DRC Scheduling for Social Sustainability: Trade-Off Between Tardiness and Workload Balance

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**Abstract.** A dual resource constrained (DRC) with fewer operators who could control parallel semi-automatic simultaneously potentially faces the unbalance workload problem that is related to social topics in Global Reporting Initiative Sustainability Reporting Standards (GRI Standards). Balancing the operator workload, on the other hand, could change the schedule structure resulting in some additional delay. This proposed study develops a multi-objective mixed integer non-linear programming (MINLP) with total tardiness and workload smoothness index (WSI) as the objective functions to measure the delay and workload balance respectively. To solve the model, a well-known non-dominated sorting genetic algorithm II (NSGA-II) is used to yield the non-dominated solutions showing the alternative schedule options. The results show that the effort in balancing the workload could raise the lateness. The important finding is that WSI can be improved significantly in the small proportion on the most left side of the total tardiness range.

**Keywords:** DRC scheduling · Social · Total tardiness · WSI · NSGA-II

## 1 Introduction

Dual resource constrained (DRC) scheduling allows the operators to move between workstations to perform a task [1]. This scheduling matches as a strategy for manufacturers equipped by semi-automatic machines in which the operators can move while the machining time. Although this strategy could increase labor productivity, an inappropriate schedule will cause large tardiness [2]. Also, it could generate workload unbalance causing jealousy feeling between operators.

Many studies in DRC scheduling that deals with fewer operator allow their moving between machine but only supervising one job at the time [3,4]. In contrast, DRC scheduling which considers simultaneous supervision that may cause the increment of the execution time is still rare [5]. A study manage operators to move between workstations to perform setup activity with zero moving time [6].


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Then, a recent research extends it by considering two activity assignment (setup and unloading) and the transport time between machines [7]. Both studies have the same objective function which is to minimize the makespan. However, this proposed research considers the total tardiness instead.

DRC scheduling problem that includes a social indicator as an additional objective function is very few even for all scheduling problem type [8]. Two recent papers analyze the trade-off relations of tardiness-operator productivity [2] and makespan-workload balance [9]. To extend those, this proposed research investigates the impact of workload balance on total tardiness. Because the scheduling problem is still new, this study is the first one in analyzing the relation. Global Reporting Initiative Sustainability Reporting Standards (GRI Standards) confirms that treating people unequally by imposing unequal burden is discrimination that belongs to the social dimension [10]. Therefore, this study hopefully could generate a better schedule but also to contribute for sustainable manufacturing development. Besides, this study also proposes a metaheuristic technique, which is an adjusted non-dominated sorting genetic algorithm II (NSGA-II) [11].

## 2 Problem Formulation

The objective of this study is to analyze the impact of the workload balance as an additional objective function when attached to the basic single-objective DRC model in an identical parallel machine environment [2]. The production system consists of a set $I = (i_1, i_2, ..., i_m)$ of $m$ semi-automatic machines with a set $K = (k_1, k_2, ..., k_w)$ of $w$ operators, where $w < m$, to execute a set $J = (j_1, j_2, ..., j_n)$ of $n$ jobs. For the modeling purpose, a set $J' = (j_0, j_1, j_2, ..., j_n)$, which includes a dummy job $j_0$, also exists to assist the precedence constraint.

Each job through setup, machining, and unloading processes in one machine. Operators can only contribute to setup and unloading activities in a set $A = (a_s, a_u)$ of tasks, and they could go to another machine after finishing a task. The duration time to perform task $b$ of job $l$ is $o_{bl}$. Then, the machining time of job $l$ is $p_l$. Finally, $m_{hi}$ represents the operator moving time between machine $h$ and machine $i$. Another parameter is a big number $B$ needed in the modeling.

There are two objective functions in the model formulation, namely, total tardiness and operator's workload smoothness index (WSI) [9] as shown in Eqs. 1 and 2 respectively. A schedule with smaller WSI has better workload balance. And it becomes a perfect balance if the WSI equal to 0. Since the WSI is non-linear, the model becomes a mixed integer non-linear programming (MINLP). The following mathematical model shows the decision variables and problem formulation. Please note that the $x$ variable accommodates two types of precedence relation, i.e., task order performed by each operator and job sequence assigned to each machine. Therefore, this variable needs seven suffixes to indicate those.

*Decision Variables*

$x_{khajibl}$: a binary variable that equal to 1 if operator $k$ performs task $b$ of job $l$ in machine $i$ after finishing task $a$ of job $j$ in machine $h$

$o^c_{bl}$: the completion time of task $b$ of job $l$

$p^c_{bl}$: the machining completion time of task $b$ of job $l$
$m^c_{bl}$: the operator moving completion time to perform task $b$ of job $l$
$t_l$: the tardiness of job $l$
$nw_k$: the total non-waiting time of operator $k$
$nw_{max}$: the maximum total non-waiting from all operators
$q_{fl}$: a binary variable that equal to 1 if setup of job $l$ starts before unloading job $f$ on the same machine

*Model*

$$\text{minimize } f_1 = \sum_{l \in J} t_l \tag{1}$$

$$\text{minimize } f_2 = WSI = \sqrt{\sum_{k \in K} (nw_k - nw_{max})^2} \tag{2}$$

$$\sum_{k \in K} \sum_{h \in I} \sum_{a \in A} \sum_{j \in J'} \sum_{i \in I} x_{khajibl} = 1 \qquad \forall b \in A; l \in J \tag{3}$$

$$\sum_{k \in K} \sum_{h \in I} \sum_{i \in I} \sum_{b \in A} \sum_{l \in J} x_{khajibl} \leq 1 \qquad \forall a \in A; j \in J \tag{4}$$

$$\sum_{h \in I} \sum_{i \in I} \sum_{b \in A} \sum_{l \in J} x_{kha_u j_0 ibl} \leq 1 \qquad \forall k \in K \tag{5}$$

$$\sum_{h \in I} \sum_{i \in I} \sum_{b \in A} \sum_{l \in J} x_{kha_s j_0 ibl} = 0 \tag{6}$$

$$\sum_{k \in K} \sum_{h \in I} \sum_{a \in A} \sum_{j \in J'} x_{khajia_s l} - \sum_{q \in K} \sum_{g \in I} \sum_{c \in A} \sum_{f \in J'} x_{qgcfia_u l} = 0 \qquad \forall i \in I; l \in J \tag{7}$$

$$\sum_{h \in I} \sum_{a \in A} \sum_{j \in J'} x_{khajibl} \geq \sum_{g \in I} \sum_{c \in A} \sum_{f \in J} x_{kiblgcf} \qquad \forall k \in K; i \in I; b \in A; l \in J \tag{8}$$

$$o^c_{bl} - m^c_{bl} \geq o_{bl} \qquad \forall b \in A; l \in J \tag{9}$$

$$m^c_{bl} - o^c_{al} \geq \sum_{h \in I} \sum_{i \in I} \sum_{k \in K} m_{hi} \times x_{khajibl} - B \times (1 - \sum_{h \in I} \sum_{i \in I} \sum_{k \in K} x_{khajibl}) \qquad \forall b \in A; l \in J; a \in A; j \in J' \tag{10}$$

$$o^c_{a_u l} - p^c_l \geq o_{a_u l} \qquad \forall l \in J \tag{11}$$

$$p^c_l - o^c_{a_s l} = p_l \qquad \forall l \in J \tag{12}$$

$$\begin{cases} o^c_{a_s l} - o^c_{a_u f} \geq \sum_{k \in K} \sum_{h \in I} \sum_{a \in A} \sum_{j \in J'} o_{a_s l} \times x_{khajia_s l} \\ -B \times (2 - \sum_{k \in K} \sum_{h \in I} \sum_{a \in A} \sum_{j \in J'} (x_{khajia_s l} + x_{khajia_s f}) + q_{fl}) \\ o^c_{a_s f} - o^c_{a_u l} \geq \sum_{k \in K} \sum_{h \in I} \sum_{a \in A} \sum_{j \in J'} o_{a_s f} \times x_{khajia_s f} \\ -B \times (2 - \sum_{k \in K} \sum_{h \in I} \sum_{a \in A} \sum_{j \in J'} (x_{khajia_s l} + x_{khajia_s f}) + 1 - q_{fl}) \end{cases} \quad \forall i \in I; f \in J; l > f \tag{13}$$

$$o^{c}_{a_u j_0} = 0 \tag{14}$$

$$t_l \geq o^{c}_{a_u l} - d_l \qquad \forall l \in J \tag{15}$$

$$t_l \geq 0 \qquad \forall l \in J \tag{16}$$

$$nw_k = \sum_{h \in I} \sum_{a \in A} \sum_{j \in J'} \sum_{i \in I} \sum_{b \in A} \sum_{l \in J} x_{khajibl} \times (o_{bl} + m_{hi}) \qquad \forall k \in K \tag{17}$$

$$nw_{max} \geq nw_k \qquad \forall k \in K \tag{18}$$

$$x_{khajibl} \in \{0; 1\} \qquad \forall k \in K; h \in I; a \in A; j \in J'; i \in I; b \in A; l \in J \tag{19}$$

$$q_{fl} \in \{0; 1\} \qquad \forall f \in J; l > f \tag{20}$$

Constraints 3 and 4 force each task of jobs is dedicated only to a unique machine and operator. Those also keep each task having only one predecessor and at most one successor task. Constraints 5 and 6 ensure that only unloading task is performed as the first task of each operator for job $j_0$. Constraint 7 forces each job only utilizes one machine. Then, Eq. 8 sets the tasks precedence constraint performed by each operator. Equations 9 and 10 define the relation between moving activity and the tasks done by operator. Meanwhile, Eqs. 11 and 12 connect the machining activity to the tasks on each machine. The twofold Eq. 13 sets the jobs precedence constraint on each machine. Equation 14 ensures that the unloading time of $j_0$ is zero. Then, Eqs. 15 and 16 set each job tardiness value. Equation 17 computes each operator non-waiting time and Eq. 18 stores its maximum value used to compute the WSI. Finally, the rest of the Eqs. 19 and 20 are the binary constraints.

## 3 The Metaheuristic Methods

This study uses the famous NSGA-II [11] to solve the multi-objective MINLP. Some adjustments needed in this scheduling problem are the encoding scheme representing the solution space and the decoding scheme translating the code becoming objective values. The proposed NSGA-II applies a single chromosome which is used in the previous research [7]. The chromosome represents the jobs sequence when evaluated in the decoding scheme. The chromosome decoding procedure yields the scheduling solution and its objective functions as described in Algorithm 1. In detail, Fig. 1 illustrates how the decoding procedure work for chromosome 4-2-1-3 in case with 4 jobs, 3 machines, and 2 operators. It also shows the complexity of the DRC scheduling problem where the Gantt chart must include the operator assignment to describe the schedule. The developed NSGA-II uses the binary tournament, two-point crossover [7], and block swapping schemes [13] for generating the offspring on each iteration. The binary tournament selects the chromosome based on the non-domination rank for the initial iteration and the crowded-comparison operator on the following iterations.

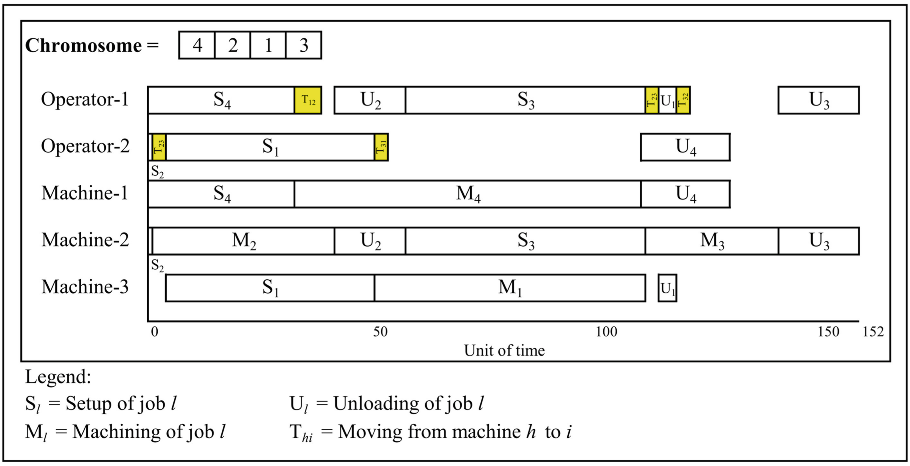



**Fig. 1.** An example of a chromosome conversion

**Algorithm 1.** Pseudocode for the Decoding Procedure

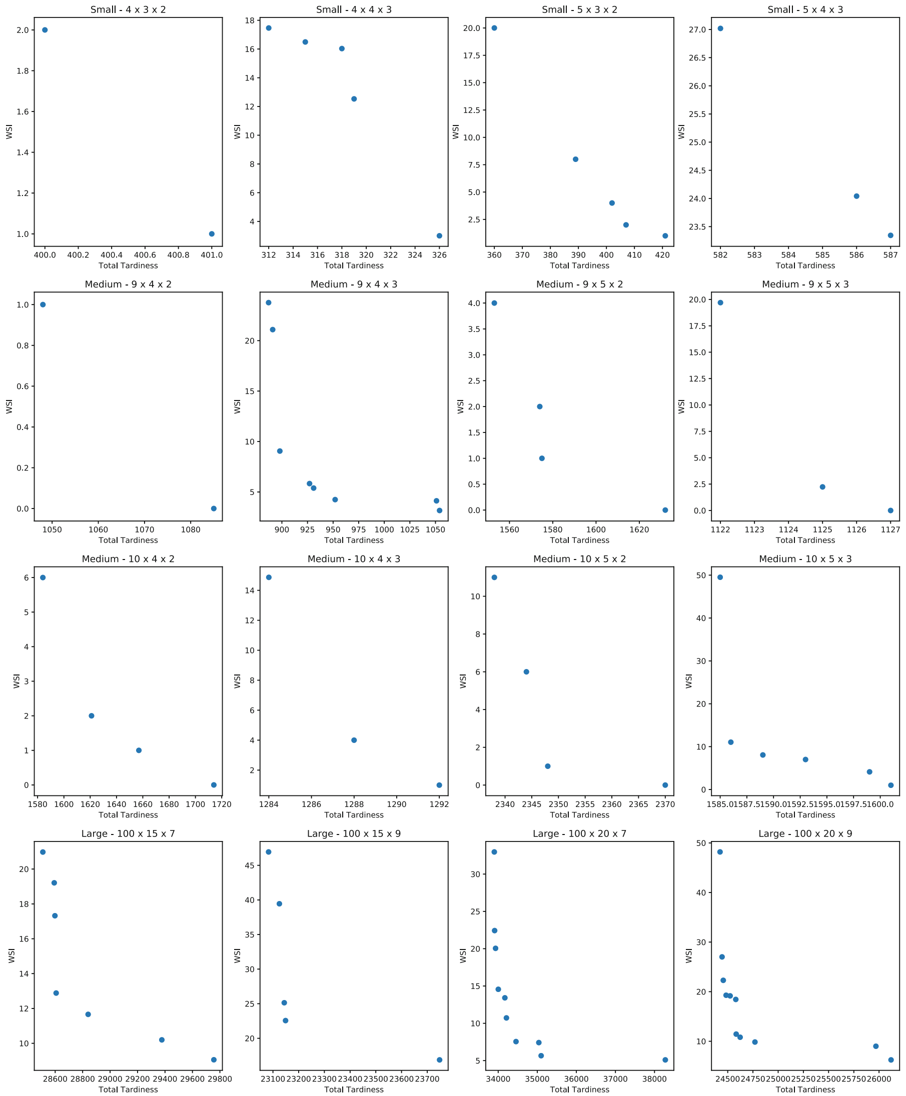
**INPUT:** A chromosome containing job sequence information
**OUTPUT:** The schedule with the total tardiness and WSI values.

**while** the number of allocated task smaller than $2n$ **do**
  assign one machine that could start the earliest;
  assign one operator that could start operating the selected machine the earliest
  **if** the previous task on the machine is setup **then**
    allocate unloading task for the same job of previous task
  **else** allocate setup task for a job picked from unassigned gene of the chromosome
  update the schedule

## 4 Numerical Examples and Results

This study codes the NSGA-II using Python® programming language run on 16-GB RAM PC powered by an octa-core 3.6-GHz processor. There are 16 cases from three different problem sizes, namely, small, medium, and large as grouped on [7] which is identified by $n \times m \times w$ (jobs number $\times$ machines number $\times$ operators number). The time parameters come from uniform distribution, which are U[1, 79], U[1,99], U[1, 20], and U[3,10] respectively for setup, machining, unloading, and moving. Besides, the due dates dataset also comes from the uniform distribution, i.e., $U[Q(1-T-R/2), Q(1-T+R/2)]$ as used in [12]. $Q$ is computed using Eq. 21, $T$ is the mean tardiness factor and $R$ is the relative range of the due dates. This experiment chooses $T = 0.8$ and $R = 0.4$ for generating very tight due dates dataset. NSGA-II uses trial-and-error to find the appropriate parameters, which are generation number, population size, crossover probability, and mutation probability until it reaches the same or lower tardiness value compared to the results of single-objective MILP as in [2].

$$Q = \frac{\sum_{l \in J} o_{a_s l} + p_l + o_{a_u l}}{m^2} \tag{21}$$




* Parameter setting for each problem: generation number – 10 (S), 100 (M), 250 (L); population size – 20 (S), 200 (M), 350 (L); crossover rate – 0.5 (S), 0.8 (M), 0.9 (L); mutation rate – 0.1(S), 0.2(M, L)

**Fig. 2.** Non-dominated set of the NSGA-II results for selected cases

Figure 2 shows non-dominated set results for 16 selected cases from each problem size. It confirms that reducing the WSI will cause the increasing of total tardiness. In the small-sized problem instances, the non-dominated solutions, which few in number, approach straight line form. However, the solution points approach curve form separating solution in two groups when the problem becomes more complicated. The first part is located on the small proportion of the most left near the minimum value of total tardiness in which the WSI decreases significantly. This range is the most important thing if a manufacturer wants to increase the workload balance sacrificing only a small delay. Meanwhile, the second part that comes after the first range distributes the points near a line with a small gradient. It means that the total tardiness changes significantly while the WSI does not. Most non-dominated solutions flock in the first part for the large-sized instances, but they assemble in the second part for the medium-sized ones. Therefore, this study could assist the manufacturer to find the appropriate scheduling with better WSI if the small addition of the tardiness is tolerable.

## 5 Conclusions

This proposed study extends the previous studies on scheduling for social sustainability. It develops a multi-objective MINLP model of a complex DRC scheduling problem to minimize the total tardiness and WSI. The objectives pair, as far as known, has not been considered together on the previous multi-objective sustainable scheduling problems. The DRC scheduling is also relatively new problem in which fewer operators could perform setup or unloading tasks and they could move between machines in the machining time. This study adopts the famous NSGA-II in generating the non-dominated solutions. The results show that the effort to increase the workload balance will raise the total tardiness. The important finding is that WSI can be improved significantly in the small proportion on the most left side of the total tardiness range. For future research, it suggests to apply other better metaheuristic methods that suits to this DRC problem by performing comparative study.

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# Towards Reconfigurable Digitalized and Servitized Manufacturing Systems: Conceptual Framework

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**Abstract.** Based on an analysis of research and industrial trends, the paper introduces the basis of a conceptual research framework for an innovative methodology dedicated to design, implement and manage Reconfigurable Manufacturing Systems (RMS). The authors present key challenges extracted from the literature and key industrial needs for RMS, drawn from expert interviews via an industry study. A conceptual framework for reconfigurability management is proposed, which opens several avenues for future research.

**Keywords:** Reconfigurability · Industry 4.0 · Servitization · Digitalization

## 1 Introduction

Dynamic product/service life-cycles, globalization and shortage of resources are megatrends with a strong impact on production management. The industry is forced to high customization, inducing a clear increase in production complexity. Flexible and reconfigurable production lines intend to answer these challenges [1]. The adaptability of Reconfigurable Manufacturing Systems (RMS) aims at reducing reconfiguration time, effort and costs, through proactive adjustment of the production system and its correlating processes, with minimal effort for a specific product family [1]. Current approaches still do not cope with the full RMS complexity. Besides the hardware and software complexity, which induces production downtimes, many different production processes are affected [2]. Responsiveness to changes requires highly modular systems, with easily interoperable resources and reconfigurable organizations.

The research approach presented in this paper consists of analyzing both research trends and industrial needs, then use these results as key inputs to structure a proposal for a conceptual framework for an innovative reconfigurability management methodology. The structure of the paper follows this approach, with the two following sections providing respectively (i) literature survey on RMS and (ii) the results of an industrial requirements analysis. Section 4 presents the conceptual framework proposed, with the


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explanation of key concepts (conceptual basis of the framework), then the description of the overall structure of the framework. Section 5 underlines the main perspectives.

## 2 Current Trends on Reconfigurable Manufacturing Systems

### 2.1 Key Concepts for Reconfigurable Manufacturing Systems

The idea of Reconfigurable Manufacturing System (RMS), first introduced in [3], was formally defined by Koren et al. [4] Based on modular components, these systems are designed to support changes in their physical configuration in order to be more responsive to the quick transformations of product demand. The main features of a RMS are:

- **Modularity:** in a RMS, all the major components should be modular (system, software, control, machines and process, conveyors). Selection of basic modules and the way they can be connected provide systems that can be easily integrated, diagnosed, customized, and converted.
- **Integrability:** new modules can be easily integrated within the system to extend its capabilities and their integration rules must be established.
- **Scalability:** possibility to adjust the production capacity to the actual demand by adding or removing resources.
- **Customization:** this type of system is open-ended and provides customized flexibility for a particular part family.
- **Convertibility:** ability to switch from a configuration to another and quick system adaptability for future products.
- **Diagnosability:** detection of machine failure and identification of the root causes of unacceptable part quality to allow a quick correction.

Contrary to Flexible Manufacturing Systems (FMS), which are usually designed for a large family of products, RMS are usually considered when there is little knowledge on future production volume or product changes. If globalization increased the unpredictability of market and as a consequence the need for more responsive production systems, recent studies highlighted the numerous opportunities associated with the new technologies of Industry 4.0 and of Artificial Intelligence in the development of RMS [5]. Beside the technological aspects, research works on RMS also considered the organization of RMS as a whole in order to optimize its performance. Two main questions are emphasized in the literature:

- What do RMS change in the design of production systems and how to define an efficient process to do it [6, 7]?
- How to properly evaluate the capacities of different possible configurations of RMS [8, 9]?

Additionally, reconfigurability management needs to integrate the latest advances on manufacturing systems for the Factory of the Future (FoF), as underlined just below.

### 2.2 New Challenges for Reconfigurability Management

Within the framework of FoF the 3 following challenges should notably be considered.

**Digital Control of Production Systems.** The rise of communication and information technology has a strong influence on production technology. Digital Twins, providing the virtual representation of real manufacturing components play a central role in the digitalization of production systems [10]. It can provide autonomous decision making and control on the production [11]. Furthermore, as key technology of digitalized production, Cyber Physical Systems (CPS) are defined as integrations of computation and physical processes [12]. CPS are enhanced mechatronic systems. An increased decentralization and autonomy in order to achieve higher efficiency and transparency in production systems are the key factors [13]. CPS possess the ability of self-description, so that information about its own state and individual functionalities is available. The ability of CPS to communicate among themselves generates an overall Cyber Physical Production System (CPPS) supporting the overall reconfigurability.

**Servitization and RMS.** Service-oriented strategies have been progressively transforming industrial business models over the last decade, notably with the emergence of so-called Product-Service-Systems (PSS) which gather product and service components within an integrated added-value offer [14]. This new type of business model is currently spreading in B2B applications, typically for innovative manufacturing solutions. A large potential of services (performance traceability, maintenance, upgradability…) can be delivered along the life-cycle of manufacturing technologies to increase the added-value delivered to the customer [15]. This is a key issue for RMS: depending on the deepness of the reconfiguration, distinct levels of services can be required, with strong challenges in balancing new economic models [16] and managing the risks of provider-customer relationship. To the best of our knowledge, servitization strategies have not been integrated in RMS until now.

**Sustainability Through Reconfigurability.** Research on the connection between sustainability and reconfigurability remains recent [17, 18]. Sustainable manufacturing is defined as ‘The creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities and consumers and are economically sound’ [19]. Creating sustainable manufacturing systems can be facilitated by considering reconfigurability as a new strategy [20]. Challenges in environmental performance and energy consumption can be addressed in industrial companies through the use of RMS [18, 21].

## 3 Industrial Requirements for RMS

### 3.1 Introduction: Qualitative Analysis of Industrial Requirements

Semi-structured interviews with 15 industry experts of eight different companies were conducted following the approaches of [22]. Their aim was to better understand the industry requirements for RMS. All interviewees are representatives of companies which assured their contribution to the underlying research project. Five out of eight companies are engaged in the mechanical engineering sector, two in the automotive sector and one interview partner is a state authority. The interviewees covered different functionalities ranging from upper management to technical development as well as production planners and personnel directly responsible for production lines. Two companies in the mechanical engineering sector consider themselves as sellers of RMS, four companies can be classified as users and two interview partners are not directly involved in developing nor using RMS. Five of the interviewed companies employ over 500 people and can therefore be considered as large companies, whereas two companies are mid-sized with a number of employees between 40 and 50. Thus, the selected companies and experts cover a broad range of industry interests and perspectives.

### 3.2 Qualitative Evaluation of the Interviews Concerning New Challenges

**Sustainable Reconfigurability.** The interviews showed that there are still multiple hurdles which prevent an increase of reconfigurability in production. The majority of answers focused on the technical problems during implementation and operation of RMS. The machines currently offered do not fulfil the level of modularity and flexibility the companies would wish for. The adaptation of the existing production lines can be challenging and e.g. induce downtimes and unintentional influences. Besides this technical perspective, the economic consideration of reconfigurability is also proving difficult. The determination of the most sustainable trade-off between flexibility, controllability and efficiency represents a major challenge. The fact that no specific metrics are able to describe the degree of reconfigurability contributes to this problem. Another topic, which was repeatedly mentioned, was the challenges and problems which workers have to face in a reconfigurable environment. They might feel overwhelmed by the uncertainty imposed by the constant changes in equipment, planning and required skills. However, the interviews also indicated a high level of interest to deal with the topic of reconfigurability which is mainly driven by economic factors. It was stated several times that more flexible production systems are necessary to efficiently control the growing complexity. RMSs are therefore seen as a promising means to increase productivity and thus financial sustainability. Additionally, one company stated that their motivation is to ensure an optimal integration of human workers in the challenging future production environment, as workers are considered as the most important and most flexible production resource available. Consequently, the better integration of human workers and their knowledge into production was also discussed as a potential solution to overcome the hurdles of introducing RMS. Possible solutions to reach this goal are to keep the workers informed through standardized interfaces, as well as a continuous integration in the planning process. The answers also revealed that an effective change management is seen as a key factor to allow a more efficient handling of changes. It can be concluded that the interviewees especially highlighted the economic and socials aspects of reconfigurability, whereas the ecological aspects were only covered marginally. Nevertheless, the ecological potential of RMS must also be taken into account, as described in Sect. 2.2.

**Digitalization.** The conducted interviews concerned the opportunities and risks of digitalization with regard to RMS. It could be observed that small and larger companies deal with the arising changes. The automation of repetitive tasks or the traceability of products are only two mentioned advantages of digitalized RMS. Nevertheless, there are several challenges occurring. Whereas software implementation and the interoperation between different tools only seems to be an issue for large companies with high degree of automation, human aspects are very important for almost all respondent companies. The need of a new employee's skillset is observed. Furthermore, digitalization processes are often difficult to introduce because of doubts or even fears among the employees. In addition to human aspects, data processing is an existing problem in most cases. A lack of focused analysis of the increasing amount of acquired data is mentioned. In comparison to the occurring challenges, the interviewed companies recognize several advantages of digitalized RMSs. Increased productivity and reduced production costs are expected. Besides that, the improvement of working conditions is another promising opportunity. Especially the large companies surveyed are already developing solutions in order to exploit the observed advantages. The interviews showed that useful solutions in any kind of application should be modular, standardized and interoperable. If these requirements are met, machine-to-machine communication can be improved, the implementation of new software tools can be abbreviated and methods of artificial intelligence can be applied. The benefits of approaches such as predictive maintenance, process bottleneck detection or digital machine twins have been recognized especially in the larger companies. In addition to the technical requirements, the solutions should be suitable for employees, which requires recurrent teaching as well as user-friendly operation.

**Servitization.** Six of the interviewed companies are familiar with the concept of servitization, where it is used for different reasons and stages of the life-cycle. In one case, servitization allows more accurate previsions on the demand and thus enables the company to reduce stock and losses. Another company uses servitization as a marketing instrument to highlight their offers and increase demand. As changes in the production system are often customer-driven, the modular concept that can go along with servitization is an asset for two of the interview partners. Offering a service instead of a product can decrease time needed for adaptation, as stated by one interviewee. Servitization can create a stronger relationship between user and provider. For two companies, service models are an important purchase factor. One of those stated, that fast maintenance and constant availability of service are important purchase factors for them. For another company, the possibility to integrate predictive maintenance as a service in their system is crucial. One company stated that, at the moment, very little interest in servitization exists among their customers, as they are not used to rent machines and do not see any advantages. Another interviewee added that, at the moment, services are only considered at design time but not in the production system. For some of the interview partners, there is still potential to increase the usage of servitization models.

# 4 Conceptual Basis for RDS Production Systems

## 4.1 Concept of RDS Production Systems

Two structural dimensions of manufacturing technologies appear as critical for future innovations on reconfigurability: digitalization and servitization. This leads us to define below the notion of *Reconfigurable Digitalized and Servitized Manufacturing Systems*.

Digitalization is a usual and intrinsic component of reconfigurability. Digitalization embeds several key manufacturing issues, notably (i) to manage the interoperability among interconnectable production components and software solutions; (ii) to increase the efficiency and added-value of digital twin models; (iii) to integrate artificial intelligence techniques and mathematical optimization to improve reconfiguration decision-making processes. Digitalization still requires strong advances on data capture (technological digitalization), information management (consistency and added-value of production information), and knowledge management (decision-making use).

Servitization has not been addressed until now in the context of RMS. It involves to integrate reconfigurability management within a service-oriented framework, leading to new business models. The question is no more to sell a technology to a client, but to manage the full life-cycles of the technology implementation, utilization, reconfiguration and, when necessary, retirement. Servitization is not a technological change, but a change of mindset and management relationship applied to the relationship between technology providers and manufacturers. Together with the capacity to design and implement new service packages, key challenges concern the capacity to anticipate and prove the economic advantages for all stakeholders, and to manage the risks induced by service contracts. Servitization adds a new dimension to support reconfigurability, making the link between production system configuration and business model selection. In the approach proposed, manufacturing systems become Smart Manufacturing Product-Service-Systems, where digitalization is a key way to enlarge drastically the service offer provided to manufacturers, while the technology providers find key solutions to increase the efficiency and quality of services and reduce the service costs. Reconfigurability management is very context dependent. In this perspective, this approach aims at developing new abilities to ensure a high level of reconfigurability, adapted to the internal needs, skills and abilities of each manufacturing company.

## 4.2 Overview of Conceptual Framework for Reconfigurability Management

Referring to this concept of RDS Manufacturing Systems, our objective is to propose, a research framework resulting into a methodology for reconfigurability management.

This framework is based on the following three key pillars (Fig. 1):

1. Life-cycle management applied to manufacturing systems is at the heart of reconfigurability management. Our ambition is to structure, within this methodological framework, the various decision processes and Decision Support Systems contributing to a full life-cycle management of RMS.

2. Uncertainty management is a key transversal approach, fully required at various levels of life-cycle management. The potential of uncertainty modelling and assessment can be increased by the added-value of digitalization at all levels of manufacturing systems, together with current advances on artificial intelligence and optimization techniques.
3. In the context of Factory of the Future, agility of production systems has to be managed while maintaining a higher-level strategy of sustainability. We consider that reconfigurability management is meant at achieving a higher degree of sustainability for production systems. This induces that sustainable objectives should be defined at all decision levels contributing to life-cycle management.

This leads us to structure the framework, with four decision levels of life-cycle management, each of which can be supported by several decision-aid methods or tools, constituting the so called 'Toolbox for the reconfigurability and life-cycle management of RDS Manufacturing Systems'. Digitalization and servitization are integrated as two transversal dimensions, to be integrated at every level of the toolbox.

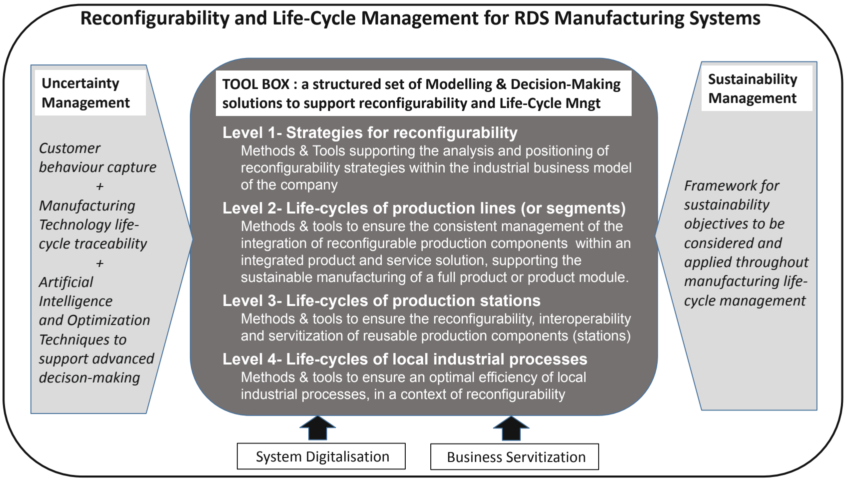


**Fig. 1.** Overview of reconfigurability framework for RDS manufacturing systems

The four levels of the framework correspond to a granularity decomposition of the manufacturing systems, leading to identify complementary reconfigurability and life-cycle management challenges. Level 1 addresses the strategical factors on reconfigurability, linked to business model definition. Levels 2 to 4 correspond to different levels of production system, where life-cycle management needs to be implemented. Each of these four levels gathers a set of decision-processes for which modelling and decision-aid solutions can be developed, in order to provide industry with a consistent decision-making toolset, making possible to address reconfigurability while maintaining a strong sustainability of the entire manufacturing system.

Of course this framework proposal requires to be validated in next research steps. A first validation proposed is a validation by expertise: capture the decision-making needs of several key users of RMS, to confront their precise decision-process requirements with the structured proposal. The second validation steps will be proof of concepts on pilot cases. This will be planned in next collaborative research phases.

## 5 Conclusion and Perspectives

This paper emphasized key research and industrial challenges for the next generation of RMS. Based on the analysis of current issues and trends, a conceptual framework was introduced with two main contributions: definition of the key notions of Reconfigurable Digitalized and Servitized Manufacturing Systems; and proposal of generic reconfigurability framework for RDS manufacturing systems. The framework is also structured as a research roadmap: next research steps consist in developing a detailed description of all the components of the framework, at the four levels proposed, validating the overall proposal, and then answering research gaps at each level.

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# Simulation of Reconfigurable Assembly Cells with Unity3D

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**Abstract.** This paper introduces a Unity3D-based simulation of reconfigurable assembly cells. A systematic approach defining flexibility ranges and comparing product requirements and cell capabilities allows the automated proposal of reconfigurations in the assembly cell. With this approach, the suitability of an existing cell can be examined for different variants of products while taking reconfiguration aspects into account. The simulation simplifies the process of introducing a new product to an assembly line. Through the virtual approach, designing of the product and line planning can be executed simultaneously, thereby decreasing cost and time-to-market for new variants in an existing production system.

**Keywords:** Simulation · Reconfigurability · Assembly · Unity3D

## 1 Introduction

With the dynamization of product life cycles and the increasing number of variants, manufacturing companies are facing new challenges. The trend towards individualized mass production leads to the need of frequent modifications in the assembly system. Manufacturers need to adjust to the increasing number of variants using flexible and reconfigurable systems [1]. Flexibility describes the ability of a production system to adapt quickly and cost-effectively to changing influencing factors. Reconfigurability focuses on special manufacturing facilities that combine the advantages of highly specialized and adaptable systems [2]. Autonomous and standardized functional units allow for new machine configurations [3].

To be economically successful, reconfigurable production systems alone are not sufficient. The necessary changes also need to be identified, planned and implemented with reasonable effort [2]. In view of this, digital tools like simulation are of great importance. Through a simulative examination, the suitability of existing assembly cells for new products or variants can already be determined in early development phases. By detecting possible problems at an early stage, effort for redundant planning can be reduced [4]. The use of simulation tools thus contributes to exploiting the potential of reconfigurable assembly cells. In this paper, we present Unity3D as a software for the simulation of reconfigurable assembly cells.


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## 2 State of the Art

### 2.1 Simulation of Reconfigurable Assembly Cells

Simulations can support the planning process of reconfigurable assembly cells in different ways. Gyulai et al. [5] develop a two-level, simulation-based approach, making the model capable of evaluating production plans and analyzing the emulation of the cell control. Their model is able to support the management of a modular cell and is proposing a possibility to decrease the commissioning time of new cells. A framework for the modelling of reconfigurable manufacturing systems by using hybridized discrete event and agent-based simulation is provided by Khedri et al. [6]. With the simulation, the authors provide insights on the emergent behavior of the agents of an intelligent manufacturing system. Further, Deif and ElMaraghy [7] use simulation augmented with Design of Experiment to analyze the performance of a reconfigurable manufacturing system with scalable capacity. Multiple performance measures lead them to propose a hybrid capacity scaling and marketing policy.

### 2.2 Introduction of Unity3D

Though Unity3D was primarily developed as a game engine, it offers a variety of advantages for the simulation of manufacturing systems. It is highly customizable and by using the integrated C#-code-base and physics engine various assembly line behaviors can be simulated. The simulation can consider mass, drag, springiness, bounciness and collision of objects. Furthermore, simulations generated with Unity3D can be easily used for demonstration purposes. They can be released on virtual reality, augmented reality and as program- and browser-exports [8]. Not being bound to a specific medium, the display of the simulation can be ensured across different systems and locations. Being used as the games engine for half of the games worldwide, Unity3D provides an extensive documentation and tool library for the user [9].

### 2.3 Unity3D as a Simulation Tool

Through a systematic literature review, previous work concerning Unity3D as a simulation tool has been identified. On the level of factory and systems, Sun et al. [10] propose a method to design a production line based in a multi-channel controller. Gaisbauer et al. [11] introduce a concept to integrate arbitrary motion simulations in common frameworks with standardized motion model units. Um et al. [12] use a Unity3D-based simulation to develop a concept if a modular factory which makes it possible to reconfigure individual machine stations without extensive engineering effort. Furthermore, the possibility of Unity3D to be used in virtual reality applications is examined for designing a lean manufacturing environment [13] and to develop interactive practice systems [14, 15]. On the level of cells and stations, Koechling et al. [16] present a procedure to enable production planners to virtually inspect the production including the material flow before the actual implementation. No publications have been found covering the topic of reconfigurability in manufacturing systems connected to Unity3D.

## 3 Approach for the Simulation of Reconfigurable Assembly Cells with Unity3D

The proposed approach aims to decrease time and effort when introducing a new product variant into an existing assembly line. It simplifies the production planning process for new products on existing assembly systems. By simulating the process with Unity3D, it is determined if a new variant can be produced in the existing assembly cell configuration. Through modelling the existing flexibility ranges in the reconfigurable assembly cells they can also be automatically considered. If the current line configuration is not suitable for the new product, but the line can be reconfigured to allow production, proposals on how to change the configuration are automatically made to the production planer. For this purpose an approach for modelling flexibility ranges of assembly cells is developed. The flexibility ranges are defined automatically via calculations based on the possible cell configurations. Basis for the suitability evaluation is a detailed model of the processes that are to be performed. The process requirements are then compared with the cell's capabilities.

The proposed approach consists of seven steps, as shown in Fig. 1. As preparation for the simulation, relevant data is obtained, processed and entered. The input for the simulation consists of constraints, predetermined tasks, the process, available resources and products. The proposed approach contains five preparation steps: task definition, CAD-Model preparation, cell assembly and product import, definition of the flexibility ranges and identification of product requirements. After the complete data import, the simulation can be started, and the comparison between requirements and cell capabilities and the derivation of solutions can be executed in the application. For the detection of possible collision errors or reachability problems in the examined process, a high level of detail has to be chosen to describe process and product.

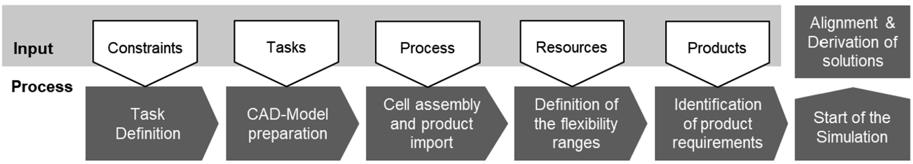


**Fig. 1.** Simulation procedure

### 3.1 Simulation Preparation

First, the assembly task and the product requirements must be defined. Further relevant information are the characteristics of the current cell configuration. In order to achieve applicable results, the simulation model has to correspond to reality as closely as possible. Required data is therefore integrated by importing CAD-files of the cell into Unity3D. As Unity3D is not offering the possibility of importing those files directly, the models have to be converted to Unity3D format *filmbox* (.fbx). For this work, the CAD-program Autodesk 3DS Max was used. Further, the converted files are scaled to Unity3D standard, where one standard unit equals one meter. To be able to move the parts in the simulation relatively to each other the cell is rebuilt before the import in individual parts.

The product requirements must be identified before the start of the simulation. It is possible to load any product variant with differing requirements into the simulation. A program code automatically loads an object with default settings into a defined position in the simulation. First, it has to be determined how many and which process steps have to be carried out, what is required for the respective process step. Product requirements can be divided into direct and indirect. Direct requirements are defined by the dimensions of the product, number of machining steps, the resources required for the processes and the configuration of the needed equipment. Indirect requirements are independent of the product, like cycle times, quality standards and the use of certain components. Geometric dimensions are the only product feature that can be analyzed in Unity3D without additional information. Other parameters have to be inserted by the user and are stored in string variables to make them available for the comparison.

### 3.2 Depiction of Reconfigurability in the Simulation

To integrate flexibility, reconfigurability and modularity in the simulation model of the assembly cell the option in Unity3D to customize the program with C# scripts is used. For this the total flexibility of a cell is divided into two levels, as shown in Fig. 2.

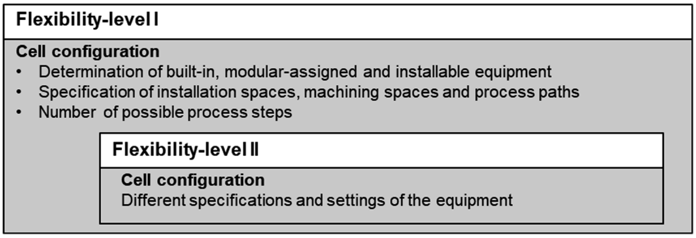


**Fig. 2.** Levels of flexibility in an assembly cell

The cell configuration provides the first flexibility range. This is done by determining whether equipment is built-in or modularly planned. For this purpose, the construction and processing areas, the process paths and the number of possible process steps in the cell are defined. At the equipment-level, flexibility is determined by the characteristics and settings of these. Together with the cell configuration, the equipment configuration determines the cell's solution space. The geometric representation of the equipment does not provide sufficient data for an informative simulation. The flexibility ranges are defined by specific queries and inputs. For individual process steps, it is defined which component is installed, if the concept is modular and retrofittable and if a new module has to be installed. This information is later used in the simulation process.

### 3.3 Comparison of Product Requirements and Cell Capabilities

In addition to geometric checks the parameters describing product requirements and cell skills are compared. The simulation can be used to examine if the components fit into the fixtures, if the machining areas are sufficient and if all processes can be executed without collisions. Entered parameters, information derived from the CAD-model and detected problems are stored automatically. In the next step it is checked whether the product requirements can be fulfilled within the defined flexibility ranges.

### 3.4 Automatic Derivation of Possible Solutions

The identified problems have to be converted in proposed solutions. Certain rules are defined for this purpose. The suggestions for solutions can be expressed product- or cell-related. In the present approach, changes can only be done to the cell, not to the product. The solution possibilities can be classified into three levels, as shown in Table 1. Category 1 includes modifications within the flexibility range [3]. According to industry needs, the two further classifications divide the solutions into whether the user or the cell-manufacturer has to make adjustments. Each individual process step is compared, the result categorized and the user is shown the necessary steps for the reconfiguration of the cell. Finally the option to rebuild of the cell according to the proposals is offered.

**Table 1.** Categorization of solution possibilities

| | |
|---|---|
| Category 1 | The assembly cell can adapt itself within the flexibility range |
| Category 2 | The assembly cell user can implement new operating resources in modular provided areas or change them |
| Category 3 | The assembly cell provider has to adjust the cell |

## 4 Validation of the Approach

The approach is evaluated based on an application case. The application example is the assembly of a surround view camera for vehicles at a large automotive supplier company. The selected process is *dispensing*, which is complex assembly process. In the process, glue is applied to the housing. The simulation is used to test which product requirements (e.g. connector geometries, dispensing-medium) necessitate a cell conversion. The simulation can run as an exported program without Unity3D. The program in Unity3D is structured in different scenes, representing different program windows.

At the beginning of the simulation, the machining areas of the processes and the possible, previously defined process areas are displayed, as shown in Fig. 3. These behave according to the inputs of the process paths and their geometric restrictions and are automatically adapted in the visual representation.

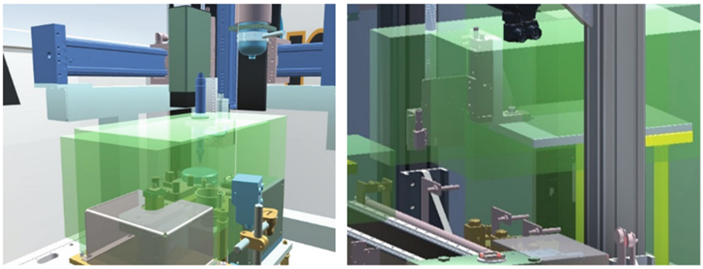

**Fig. 3.** Machining and process areas

The structure of the cell corresponds to the previously defined configuration. If the product requirements of the new variant are entered and the CAD-model has been successfully imported, the simulation can be started. The comparison starts in the simulation with accessibility studies and collision monitoring. The product is moved to the processing position with a shuttle axis and the glue is dispended according to the requirements. If post-treatments and security methods are selected, these are performed via the transfer system. After the comparison, the cell can be rebuilt according to the product requirements. This is done either within the flexibility ranges or by automatically adding further operating resources. The detection of a collision is displayed in Fig. 4. The information is saved and serves as a basis for the comparison, which is largely parameter-based. The comparison takes place for each process and all parameters declared process-relevant. An output window is generated, showing the results and the possible solutions.

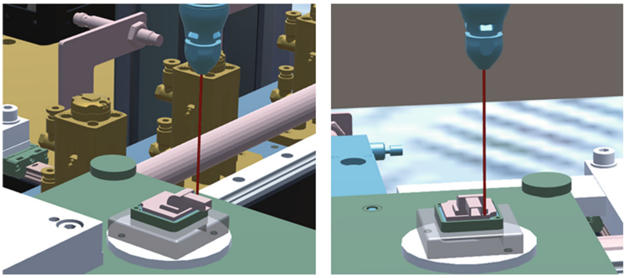

**Fig. 4.** Collision detection

The implementation in the application case allows the comparison of the skills of the current assembly cell to the requirements of two new and different variants in just one simulation. The created process transparency helps the company to quickly recognize necessary changes in the reconfigurable cell.

## 5 Conclusion and Outlook

The simulation of reconfigurable assembly cells enables an accelerated reaction to changing economic conditions. The development and introduction of the presented method can reduce planning efforts and support simultaneous engineering. In addition, the simulation enables the user to virtually validate the modularity of the manufacturing cell. The next step is to further evaluate the usability and quality of the results. Therefore, further different applications have to be tested. The input, data collection and the attachment of the requirements to the product has to be automated and simplified in further research.

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# Decision Support System for Joint Product Design and Reconfiguration of Production Systems

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**Abstract.** Reconfigurable manufacturing systems (RMS) are designed to be able to be reconfigured to produce new items. Nevertheless, reconfigurations of a RMS may be time consuming and costly if they are not considered since early steps of new item design. This work describes a decision support system to automatically generate and test configurations for such RMSs based on a computer-aided design (CAD) model of a new product. The proposed methodology consists of two main steps. First, a matrix of possible assembly plans (taking into account resource/tool compatibility, geometric constraints, …) is generated with a skill-based comparison between the new item and the production resources. Second, the assembly plan with minimum reconfiguration cost is found through mathematical optimization. The solution is analyzed by a simulation model in the end. Experiments performed on small use case validate the proposed methodology.

**Keywords:** Decision support system · Reconfigurable manufacturing system · Skill-based approach · Production graph · CAD model · Optimization

## 1 Introduction

Reconfigurable manufacturing systems (RMS) [1] allow to manufacture any products of a family within a given set of specifications, due to the possible rearrangement of the tools allocated to each station. Nevertheless, the reconfiguration of a RMS is still time consuming and costly [2], if a newly introduced product is not well designed. Consequently, the RMS reconfiguration costs should be accounted for during the design of the item.

This paper presents a decision support system to automatically generate the assembly plans with minimum reconfiguration cost starting from the computer-aided


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design (CAD) model of a product. Therefore, product design and production system reconfiguration can be undergone simultaneously [2]. The novelty of the proposed approach allows to jointly make decisions usually made separately by the marketing, engineering and production department. The joint design of product and manufacturing systems has a significant impact on the cost and time of production [3]. Different approaches exist for the automated assembly plan generation [4–6]. The design and reconfiguration of production lines are considered in many publications, see for example [7–10]. A recent state of the art presentation on optimization of RMS is given in [11]. However, to the best of our knowledge, the present paper is the first to simultaneously consider the design of a new product and the line reconfiguration through CAD-models and mathematical optimization.

In this work, we consider a RMS with sequential workstations, a single resource (a robot or a worker) located at a fixed position in each workstation, and a conveyor to transfer the items within the line. Each resource can be equipped with different tools (e.g., griper and screwdriver), and we assume that each task requires a single tool and a single resource for processing. Each tool and resource can execute multiple tasks. In a given configuration of the line, a set of tools is located in each workstation, whereas a set of unavailable tools exists in a tool library. Moving tools between stations or from the tool library to a station results in a reconfiguration cost. More precisely, a reconfiguration cost $e_{rt}$ is associated with the move of a tool $t$ to resource $r$.

The proposed decision support system is described in Sect. 2. Section 3 presents a case study to validate the proposed approach, and a conclusion completes the paper in Sect. 4.

## 2 Methodology

Figure 1 gives an overview of the proposed methodology. First, a production graph is generated from the CAD models of product and production system with a skill-based approach (see Sect. 2.1). The production graph contains all the data required to reconfigure the line and produce the new item. Second, the solution of an integer linear program (ILP) gives the best tools and tasks affectation. This solution meets the desired takt time and minimizes the reconfiguration cost (see Sect. 2.2). Finally, a simulation model checks the geometrical and technological feasibility of the solution taking into account for example collision freedom and reachability (see Sect. 2.3). If the solution is not feasible, the production graph is updated and a new iteration of the mathematical optimization executed.

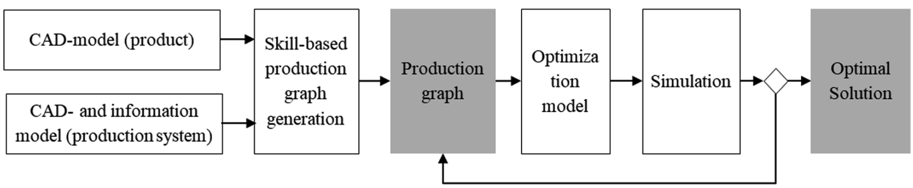


**Fig. 1.** Schema of proposed approach

## 2.1 Automatized Skill-Based Generation of Production Graphs

The proposed approach is described in Fig. 2. For the product analysis step, product requirements are generated through assembly-by-disassembly approach. The assembly-by-disassembly is a multibody simulation where parts of the CAD-model are disassembled collision free. Generated assembly sequences form a precedence graph. In addition, there are CAD-models of the assembly line and its resources. Specific resource parameters are described in a resource library which is built in a structured database. Each resource is described through an information model which describes resource functional skills. In this context, skills (e.g., "moving" or "joining two parts") represent hardware neutral functionalities through semantic modelling [12]. Automatized planning systems often inherit skill-based concepts, since functionalities of abstracted assembly resources are described universally via commands, functions or interfaces [5]. The communication between different production resources and the product to be assembled can be enabled through skills. The assembly of a specific product is defined by demands on production resources to execute individual assembly tasks. Tasks are a set of actions to fulfil specific product requirements such as screwing or joining two parts [13]. Automatized planning systems are therefore enabled by the solution independent representation of product requirements through tasks. Besides technical and economic aspects, the information model takes reconfigurability aspects into account. The outcome of this analysis is a semantic description of the skills of an assembly line.

The requirement skill comparison identifies possible matches between the generated assembly processes and described assembly line skills. The comparison is based on a semantic matching process, that checks if the resource's skills (e.g., join, screw, …) match the requirements of the task. The resources passing the semantic test are checked through a quantitative parameter analysis, to ensure the parameters (distance of the gripping points, toque of the screw, …) of the resource match the required parameters of the task (gripping point defined in the CAD model, …). For each positive match, the tool is added to the set $M_{ir}$ of tools that can execute task $i$ on resource $r$. The processing time $h_{irt}$ of task $t$ on resource $r$ with tool $t$ is automatically calculated based on position and path information obtained from CAD-models as well as resource information gained from the library. The entire information from product and production system analyses as well as semantic matching process is gathered in the production graph.

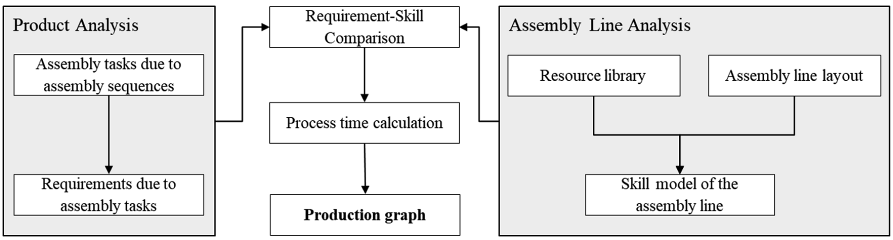


**Fig. 2.** Flowchart of the production graph generation approach

## 2.2 Optimization Model

The production graph contains the input of the optimization model, namely, the set $I_i$ of immediate predecessors of each task $i$, the set $M_{ir}$ of tools that can execute task $i$ on resource $r$, the processing time $h_{irt}$ of task $i$ if executed on resource $r$ with tool $t$, and the takt time $T$. Based on this data, the following ILP (Integer Linear Program) is solved to find the assembly plan with minimum reconfiguration cost. The model has two binary decision variables, namely, $x_{ir}$ is equal to 1 if task $i$ is assigned to resource $r$ (0 otherwise), and $y_{rt}$ equals to 1 if tool $t$ is assigned to resource $r$ to process task $i$ (0 otherwise). The proposed ILP is given in Eqs. (1)–(7), where $P, N$, and $R$ denote the sets of tasks, tools and resources, respectively.

$$Min \sum_{r \in R} \sum_{t \in P} e_{rt} . y_{rt} \tag{1}$$

s.t.

$$\sum_{r \in R} x_{ir} = 1 \qquad \forall i \in P \tag{2}$$

$$x_{ir} \leq \sum_{t \in M_{ir}} y_{rt} \qquad \forall i \in P, r \in R \tag{3}$$

$$\sum_{r \in R} y_{rt} \leq 1 \qquad \forall t \in M_{ir} \tag{4}$$

$$\sum_{t \in M_{ir}} \sum_{i \in K} h_{irt} . x_{ir} \leq T \qquad \forall r \in R \tag{5}$$

$$\sum_{r \in R} r . x_{ir} \leq \sum_{r \in R} r . x_{jr} \qquad \forall i, j \in P, i \in I_j \tag{6}$$

$$x_{ir}, y_{tr} \in \{0, 1\} \qquad \forall r \in R, i \in K, t \in M_{ir} \tag{7}$$

The objective function (1) is to minimize the reconfiguration cost. Constraints (2) state that each task must be processed by exactly one resource. Constraints (3) ensure that a tool is available on the resource to process each assigned task. Constraints (4) prevent to assign a tool to more than one resource. Constraints (5) state that the total processing time on each resource cannot exceed the takt time. Constraints (6) ensure the precedence between the tasks. Constraint (7) gives the domains of the variables.

## 2.3 Analyzation of Feasibility Through Simulation

A multi-body simulation model is required to analyze the feasibility of the assignment of a tool to a resource to perform a task. Indeed, the skill-based comparison of step 1 does not ensure collision freedom and reachability. However, as the simulations are time consuming, testing all possible triplets (resource, tool, task) is not possible.

Consequently, the optimization step is run first, and it might return a solution with assignment (tool, resource, task) leading to collisions. Therefore, the simulation step is run after optimization to check the proposed solution for collision freedom and reachability. The simulation is based on a 3D environment using kinematics (see [6]), and it uses all available information from the CAD-model and the resource library. In the simulation, collisions between product and resource, resource and surrounding and between different resources are checked to ensure the safety of the process. Further, the simulation analyzes if every position can be reached by the worker or robot to secure feasibility. If the simulation identifies that a tool $t$ cannot be assigned to a resource $r$ to perform a task $i$, $t$ is removed from the set $M_{ri}$ in the production graph, and the optimization is repeated. If the simulation gives a positive feedback, the optimal solution is found.

## 3 Validation of the Methodology

Figure 3 shows a use case where a new product made of five parts (A, B, C, D, E) must be assembled on an existing line. The line has three stations (R1, R2, and W), where R1 and R2 are operated with robots and W is operated by a worker. Three automatic tools T1, T2 and T3 are currently located on R1, but they can as well be moved to R2. Similarly, the line contains three manual tools T4, T5, and T6 located on W (they cannot be used by robots). Finally, the automatic tool T7 can be acquired.

Based on the CAD model, the assembly-by-disassembly approach generates all the necessary processes. In our example, 4 “joining” tasks are created: I1 (Placing B on A), I2 (Placing C on B), I3 (Placing E on B), and I4 (Placing D on B). The assembly-by-disassembly also generates the precedence graph shown in Fig. 3a.

As shown in Fig. 3b, the skill model of the current line, the current configuration of the tools in the stations, and the list of the tools existing in the library. Figure 3c, describes the type of tasks which can be performed by each pairing of resource and tool. Processing time of each task depending on the pair of tools and resource, and reconfiguration cost of the tools in the line are also shown in Fig. 3c. The qualitative analysis assigns the resource to the task types, whereas the quantitative analysis checks whether the parameters match (e.g. necessary torque). The production graph contains information about the feasible tasks, reconfigurations (including time and costs), task parameters (e.g. assembly paths, processing times) and precedence graph (e.g. screwing – primary; handling – secondary).

Finally, the ILP (1)–(7) is solved with CPLEX, leading to the optimal solution shown in Fig. 4 with a defined reconfiguration cost. To produce the new item regarding to the obtained production graph, tool T1 must be reassigned from station 1 to station 2. According to the task assignment in the optimal solution tasks I1 and I2 respectively are assigned to the stations 1 and 2. Moreover, two tasks I3 and I4 are executed in station 3 by a worker.

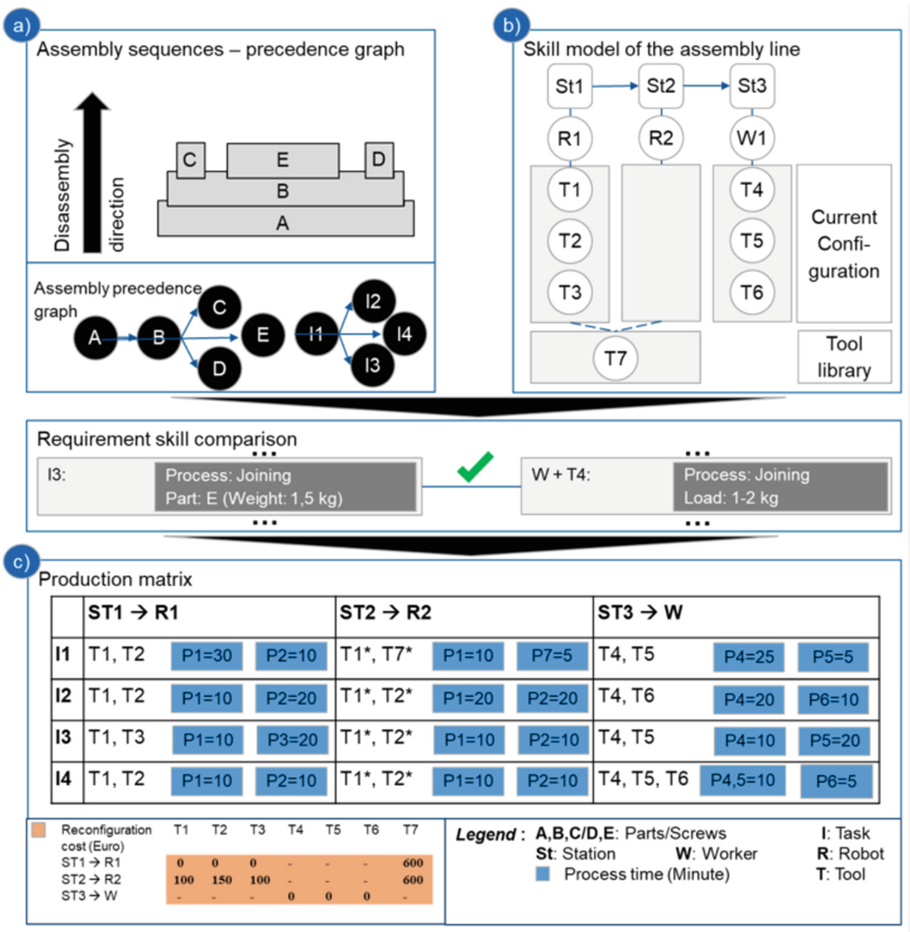


**Fig. 3.** Generation of the production graph by analysing the CAD model and assembly line

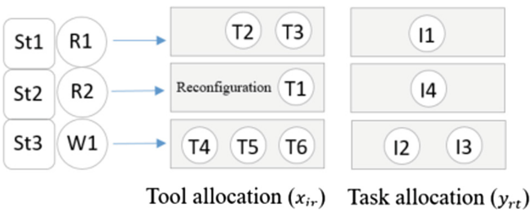


**Fig. 4.** Optimal solution of use case

## 4 Conclusion

In this paper, the authors propose a three-step methodology to automatically reconfigure RMS based on the CAD models of new product and existing RMS. First, the set of feasible assembly plans is described using a skill-based comparison of the product and RMS. Then, an ILP is solved to find the new RMS configuration with minimum reconfiguration cost. Finally, a simulation validates the collision freedom and reachability feasibility of the process plan of the new RMS configuration.

While the case study validates the approach, further work is required to implement such a system in practice. First, advanced optimization technics must be designed to handle complex product and large size RMS encountered in practice (with a large number of operations, multiple optimization criterions, …). Second, to enhance the user experience, an estimation of the reconfiguration costs should be provided in a short amount of time, and suggestions to reduce the reconfiguration cost should be provided to the user. Finally, the generation of constraints directly by the user or by the simulation model should be investigated (similarly to [14]).

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# Simple Assembly Line Balancing Problem with Power Peak Minimization

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**Abstract.** The increased environmental awareness of these days urge companies towards energy efficient production. This work focuses on the consideration of power consumption since the design stage of a production system. A new Assembly Line Balancing Problem is introduced in which each task is associated with a power consumption. The aim is to find an assignment of tasks to workstations that minimizes the overall power peak while complying with given maximum cycle time and number of workstations. An Integer Linear Programming formulation is proposed and tested on benchmark instances enhanced with power features. Numerical results are discussed.

**Keywords:** Simple Assembly Line Balancing · Power Peak Minimization · Integer Linear Programming

## 1 Introduction

According to the International Energy Agency, in 2014 the industrial sector was responsible for 36% of the global total final energy consumption (TFEC), and since then its energy consumption has grown by 1.5% annually [1]. Hence, it is expected that in the future the most consistent reduction of greenhouse gas (GHG) emissions will come from an improved energy efficiency of industries [2]. Moreover, this period represents a transition phase for the industrial sector. The forth industrial revolution or *Industry 4.0* will respond to economical, technological, organizational, societal and environmental issues. Among the objectives due to the environmental concern is the reduction of carbon footprint by optimizing the energy consumption. Therefore, it is important to rise awareness of the necessity to control the related consumption of manufacturers, since the power demand and energy consumption are steadily increasing.

In order to address this problem, one of the existing solutions is to reorganize the energetic consumption in order to obtain a lower power peak. The growing attention paid in the last decades to energy-aware manufacturing and production systems has led to an increased scientific effort to design decision support


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methods capable of achieving an optimized energy management. However, the number of works dealing with energy-driven optimization of scheduling or line balancing in manufacturing systems was still relatively scarce only a few years ago, as pointed out by [3].

In this paper, a new Assembly Line Balancing Problem with power peak minimization is considered. The rest of the paper is organized as follows. Section 2 introduces the literature review. Sections 3 and 4 present the new ALB problem and an integer linear program for it. Section 5 analyses the results of numerical tests. Finally, Sect. 6 presents the conclusion and future research perspectives.

## 2 Literature Review

*Assembly line balancing* (ALB) problems are among the most investigated optimization problems arising in production systems. ALB problems aim to optimally assign the elementary *tasks* involved in the assembly of a series of products to a set of *workstations* of a production line while complying with *precedence constraints* among tasks. These problems occur during the design of a production system and determine some of its main features, e.g. *cycle time* and number of workstations. The simplest and most studied variant is the *Simple ALB Problem* (SALBP) [4], in which the line is paced and synchronous, task process times are deterministic and independent of workstations and only one product is considered. In the case of *type I SALBP* (SALBP-1), the number of workstations $m$ has to be minimized, given the cycle time $c$; the minimum $c$ for a given value of $m$ is sought for in *type II SALBP* (SALBP-2); finally, SALBP-E (efficiency) aims at minimizing the product $c \cdot m$, or equivalently the total idle time, while SALBP-F (feasibility) tries to find out whether given values for both $c$ and $m$ admit a feasible solution. Despite its simple statement, SALBP is NP-hard and remains a challenging problem [5] and best known solution approaches are relatively recent [6–8]. A huge literature exists concerning ALB problem variants issued from several different application contexts. For more in-depth reading on ALB problems, the reader is referred to the excellent literature review of [9]. *Assembly line design* problems are also worth mentioning. In them, some special equipment must be assigned to workstations to enable them to perform tasks, as it is the case with robots in the *Robotic ALB* (RALB) [10].

For what concerns ALB problems with energy-driven optimization criteria, as far as the authors are aware of, few works can be found to date. In [11], a two-sided RALB is proposed, along with a Mixed-Integer Linear Programming (MILP) formulation. A simulated annealing-based metaheuristic algorithm is yielded to seek for Pareto-optimal solution w.r.t energy consumption and cycle time. In [12], two evolutionary algorithms, namely a Particle Swarm Optimization (PSO) and a Differential Evolution algorithm, are used to minimize the energy consumption of a U-shaped robotic assembly line. A RALB variant minimizing the total energy consumption, a Nonlinear Programming formulation and a PSO-based approach are the main contributions of [13]. The benchmark instances for type II RALB of [14] are used to test the effectiveness of the proposed approach.

This short literature review shows that few works exist that consider energy on a strategic level, i.e. since the design phase, in a production system, and in those works the concerned aspect is the minimization of energy consumption of equipment associated with workstations. The authors are not aware of works that tackle the power peak involved in the processing of the production tasks at a strategic level. However, power peak minimization or a power peak constraint can be found in works dealing with other production-related optimization problems at a more tactical or operational level, especially in scheduling.

In flow-shop scheduling, [15] proposes a mixed-integer linear program (MILP) to minimize energy consumption, makespan and carbon footprint, while [16] resort to a heuristic to minimize total tardiness and makespan of a flexible flow-shop, both under a power peak constraint. The scheduling of a job-shop with makespan minimization and power peak is addressed by [17] and tackled by means of a MILP, while [18] introduces a power peak constraint in a production system with parallel machines and proposes a heuristic method. Finally, [19] tries to minimize energy cost in a job-shop under makespan and power peak constraints. In this work, a new ALB problem is addressed which aims at minimizing the overall power consumption peak and does not seem to have yet received attention in the literature. An Integer Linear Program is proposed and tested.

## 3 Problem Definition

In the following the *Simple Assembly Line Balancing Problem with Power Peak Minimization* (SALB3PM) is introduced, along with the related notations and an example to help the reader understand the key aspects of power peak minimization.

The classic SALBP consists in assigning the tasks of a set $\mathcal{O}$ to the workstations of a set $\mathcal{M}$ of a paced, synchronous production line. Predecence constraints are defined that force each task $j \in \mathcal{O}$ to wait the end of all its direct predecessors before its processing can start: the notation $i \prec j$ indicates that $i$ is such a direct predecessor. Each task $j$ features a processing time $t_j$ which is constant and independent of workstations. The goal is usually to optimize the cycle time or the number of workstations, the other being given, in such a way that precedence constraints are fulfilled, tasks are not preempted and each workstation processes at most one task at a time all along the time horizon. It is worth noting that the classic SALBP disregards scheduling aspects, because once tasks are optimally assigned to workstations, they can be scheduled at any date along the cycle time. This does not change the solution value, nor it affects its feasibility, as long as precedence constraints among tasks on the same workstation are complied with. In the SALB3PM, similarly to what is done in the SALBP-F, both the number of available workstations $m = |\mathcal{M}|$ and the maximum allowed cycle time $c$ are given. Moreover, each task $j$ features a power consumption $W_j$, constant and independent of workstations. The goal becomes to find a feasible assignment of tasks to workstations s.t. the highest peak of the overall power consumption profile is minimized. This objective requires to integrate scheduling decisions in the SALB3PM, thus asking for dedicated decision variables. Most of all, the strong connection of this further decision layer with the other classical decisions make the SALB3PM harder than the SALBP.

Figure 1 illustrates the impact of power peak minimization by comparing two feasible solutions for a SALB3PM instance with cycle time $c = 18$, $m = 3$ workstations and $|\mathcal{O}| = 9$ tasks. The leftmost one is a generic solution that displays a very fluctuating overall power consumption profile. The rightmost one is an optimal solution, i.e. in which the maximum value of global power consumption over the time horizon is minimized: the overall consumption profile is much more smoothened and a power peak reduction of 36.6% is achieved.

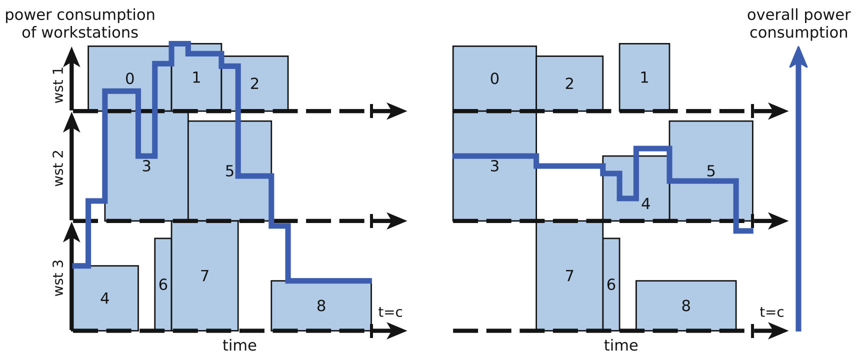


**Fig. 1.** A generic (left) and an optimal (right) solution of a SALB3PM instance with $c = 18$, $m = 3$, $|\mathcal{O}| = 9$. Dashed lines separate the schedule of workstations. Numbered boxes represent tasks: their width, height and position stand for associated processing times, power consumption values and starting times. A thick curve depicts the evolution of the overall power consumption profile.

## 4 An Integer Linear Program for the SALB3PM

In this section an Integer Linear Programming (ILP) model for the SALB3PM is presented. The model is *time-indexed*, i.e. its main feature is that the time horizon is subdivided in unit time slots and the variables describing the scheduling of tasks have a time index. This allows a detailed representation of the processing of tasks and hence of the cumulative power profile all along the time horizon.

Let $\mathcal{T} = \{0,...,c-1\}$ and $\mathcal{T}^i = \{0,...,c-t_i\}$ denote respectively the entire set of time slots, and the available time slots for the start of task $i$. The model has one integer nonnegative variable and two sets of binary variables:

- *power peak* variable $W_{\max}$, an upper bound on the power consumption peak;
- *assign* variables $X_{i,k}$, $i \in \mathcal{O}$, $k \in \mathcal{M}$, $X_{i,k} = 1 \Leftrightarrow$ task $i$ assigned to workstation $k$;
- *trigger* variables $S_{i,t}$, $i \in \mathcal{O}$, $t \in \mathcal{T}^i$, $S_{i,t} = 1 \Leftrightarrow$ processing of task $i$ starts at time slot $t$ of each cycle.

The proposed model is the following:

$$\min \quad W_{\max} \tag{1}$$

$$\text{s.t.} \quad \sum_{k\in\mathcal{M}} X_{j,k} = 1 \qquad \forall j \in \mathcal{O} \tag{2}$$

$$\sum_{j\in\mathcal{O}} t_j \cdot X_{j,k} \le c \qquad \forall k \in \mathcal{M} \tag{3}$$

$$X_{j,k} \le \sum_{h\in\mathcal{M}: h\le k} X_{i,h} \qquad \forall i,j \in \mathcal{O}: i \prec j, k \in \mathcal{M} \tag{4}$$

$$\sum_{t\in\mathcal{T}^j} S_{j,t} = 1 \qquad \forall j \in \mathcal{O} \tag{5}$$

$$S_{j,t} \le \sum_{\tau=0}^{t-t_i} S_{i,\tau} + 2 - X_{i,k} - X_{j,k} \qquad \forall i,j \in \mathcal{O}: i \prec j, k \in \mathcal{M}, t \in \mathcal{T}^j \tag{6}$$

$$X_{i,k} + X_{j,k} + \sum_{\tau=t-t_i+1}^{t} S_{i,\tau} + \sum_{\tau=t-t_j+1}^{t} S_{j,\tau} \le 3 \qquad \forall i,j \in \mathcal{O}, k \in \mathcal{M}, t \in \mathcal{T} \tag{7}$$

$$\sum_{j\in\mathcal{O}} W_j \cdot \left( \sum_{\tau=t-t_j+1}^{t} S_{j,\tau} \right) \le W_{\max} \qquad \forall t \in \mathcal{T} \tag{8}$$

$$X_{i,k},\ S_{i,t} \in \{0,1\},\ W_{\max} \in \mathbb{Z}_+$$

Constraints (2)–(4) are classical SALBP constraints. Each task $j$ is assigned to exactly one workstation $k$ by (2), and each $i \in \mathcal{O}$ s.t. $i \prec j$ is assigned to $k$ or one of the upstream workstations by precedence constraints (4). Tasks assigned to one workstation have the sum of their processing times bounded by $c$ due to (3).

Constraints (5)–(8) are specific to SALB3PM. Each task $j$ is processed at some date $t \in \mathcal{T}^j$ due to (5), which ensures its termination within given cycle time $c$. Constraints (6) add to (4) in enforcing precedence. If tasks $i$ and $j$, $i \prec j$, are assigned to the same workstation, then (6) (jointly with (5)) force $i$ to start at least $t_i$ time slots sooner than $j$. Otherwise (6) are redundant as the right hand side is greater or equal than one. Relations (7) impose to have at most one task at a time running on the same workstation at date $t$ of each cycle. Indeed, term $\sum_{\tau=t-t_i+1}^{t} S_{i,\tau}$ is 1 if task $i$ has started at a date $\tau \in \{t - t_i + 1, \ldots, t\}$, in which case it is still running at date $t$. Hence, (7) state that either both $i$ and $j$ are running at date $t$, which forces $X_{i,k} + X_{j,k} \le 1$, or both are assigned to $k \in \mathcal{M}$, i.e. $X_{i,k} + X_{j,k} = 2$ and at most one of the two can be running at date $t$.

Finally, (8) state that for each date $t$ the sum of the power consumption of the currently running tasks is bounded by $W_{\max}$. This is because the left hand side of (8) represents the overall power consumption at date $t$ of each cycle. Along with the objective function (1), this smooths the overall power consumption profile, as shown in Fig. 1.

## 5 Computational Experiments

In this section, the computational session conducted to assess the performance of the proposed ILP model is illustrated. The model is implemented in CPLEX 12.6 and solved by Branch&Bound (B&B). Tests are run on a Intel Core i7-5500U 2.40 Ghz machine with 15.55 Gb RAM. All instances are given a 3600 s time limit.

A testbed set of 19 SALB3PM instances is generated, inspired from 15 benchmark SALBP-1 datasets and 4 benchmark SALBP-2 datasets[1] and completed with task power consumption values $W_i$ randomly generated from the uniform distribution $U(5, 50)$. In the original datasets the number of tasks varies between 7 and 30, and either $c$ is given and $m$ is the computed optimal number of workstations, or $m$ is given and $c$ is the optimal cycle time. This guarantees the feasibility of the derived SALB3PM instances. From each SALB3PM instance, another one is obtained with cycle time augmented by 30% and rounded up, so as to stress the performances of the time-indexed model. To assess the power consumption improvement, a heuristic solution is generated by:

- solving (B&B) a reduced model (1)–(4) (i.e. removing scheduling constraints),
- sorting tasks on each workstation so as to comply with precedence constraints,
- schedule tasks at the earliest date, i.e. without idle times between them.

Table 1 reports the results for each instance. $W_{\max}$ is the optimal power peak value, while $T/(\%)$ is the computational time (in seconds) to compute it, or the optimality gap still to close at time limit. $W^H_{\max}$ is the value of the heuristic solution: the time to compute it is always less than 1s and thus neglected. Terms $\overline{W^H_{\max}}$, $\overline{W_{\max}}$, $\overline{T/(\%)}$ have the same meaning w.r.t longer cycle time $\bar{c} = \lceil 1.3 \cdot c \rceil$. Table 1 shows that in 23 instances out of 38 an optimal solution is achieved within time limit. In most cases only few seconds are needed, except in six cases which require more than 200 s. This is acceptable considering the strategic nature of the problem. For such instances, an average power peak gain of −19.8% is achieved w.r.t the heuristic solution (with $\frac{W_{\max}}{W^H_{\max}} < 1$ in 20 cases out of 23), in which scheduling decisions are greedy. In particular, the average gain is −22.5% for instances with high cycle time.

In 8 out of the remaining 15 instances, the B&B finds a feasible solution but the optimality gap is greater than 0 at time limit, even though less than 2.5% in five cases (6.31% on average). This is probably caused by the increased computation hardness, due to the growing number of tasks, and also the larger search space for instances with longer cycle time. Nevertheless, a considerable average power peak improvement of −27.1% is obtained w.r.t the heuristic solution.

In the remaining 7 instances, no feasible solution can be found. The heuristic solution can then be used as a warmstart for the B&B, as shown in Table 2.

In two cases, an average power peak improvement of −15.8% is achieved. By considering the overall behavior of the $\frac{W_{\max}}{W^H_{\max}}$ ratio, the optimality gap still to close at time limit is probably mostly due to the distance between $W^H_{\max}$ and the

[1] https://assembly-line-balancing.de/salbp/benchmark-data-sets-1993/.

**Table 1.** Computational results of the model alone.

| Instance | $\|\mathcal{O}\|$ | $m$ | $c$ | $W^H_{\max}$ | $W_{\max}$ | $T/(\%)$ | $\bar{c}$ | $\overline{W^H_{\max}}$ | $\overline{W_{\max}}$ | $\overline{T/(\%)}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| mertens-1 | 7 | 6 | 6 | 191 | 171 | 0.02 | 8 | 161 | 161 | 0.03 |
| mertens-2 | 7 | 2 | 18 | 77 | 57 | 0.18 | 24 | 87 | 48 | 0.27 |
| bowman-1 | 8 | 5 | 20 | 152 | 113 | 0.10 | 26 | 114 | 86 | 0.58 |
| jaeschke-1 | 9 | 8 | 6 | 249 | 249 | 0.02 | 8 | 178 | 178 | 0.08 |
| jaeschke-2 | 9 | 3 | 18 | 110 | 73 | 1.37 | 24 | 71 | 60 | 2.70 |
| jackson-1 | 11 | 8 | 7 | 217 | 188 | 0.05 | 10 | 146 | 121 | 0.52 |
| jackson-2 | 11 | 3 | 21 | 79 | 58 | 4.46 | 28 | 73 | 48 | 4.54 |
| mansoor-1 | 11 | 4 | 48 | 142 | 133 | 0.60 | 63 | 146 | 99 | 213.64 |
| mansoor-2 | 11 | 2 | 94 | 93 | 78 | 3.00 | 123 | 90 | 59 | 1305.11 |
| mitchell-1 | 21 | 8 | 14 | 241 | 211 | 11.97 | 19 | 210 | 149 | (1.36%) |
| mitchell-2 | 21 | 3 | 39 | 106 | 76 | 1383.80 | 51 | 116 | 62 | (10.71%) |
| roszieg-1 | 25 | 10 | 14 | 327 | 256 | 201.58 | 19 | 232 | 189 | (1.07%) |
| roszieg-2 | 25 | 4 | 32 | 144 | 119 | 878.39 | 42 | 147 | 88 | (3.53%) |
| heskiaoff-1 | 28 | 8 | 138 | 274 | – | – | 180 | 209 | – | – |
| heskiaoff-2 | 28 | 3 | 342 | 125 | – | – | 445 | 120 | – | – |
| buxey-1 | 29 | 14 | 25 | 468 | 395 | 3352.65 | 33 | 366 | 288 | (2.13%) |
| buxey-2 | 29 | 7 | 47 | 248 | – | – | 62 | 217 | 182 | (21.33%) |
| sawyer-1 | 30 | 14 | 25 | 389 | 326 | (1.56%) | 33 | 348 | 248 | (2.48%) |
| sawyer-2 | 30 | 7 | 47 | 202 | – | – | 62 | 191 | – | – |

**Table 2.** Computational results with warm start.

| Instance | $\|\mathcal{O}\|$ | $m$ | $c$ | $W^H_{\max}$ | $W_{\max}$ | $T/(\%)$ | $\bar{c}$ | $\overline{W^H_{\max}}$ | $\overline{W_{\max}}$ | $\overline{T/(\%)}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| heskiaoff-1 | 28 | 8 | 138 | 274 | 274 | (16.10%) | 180 | 209 | 209 | (15.47%) |
| heskiaoff-2 | 28 | 3 | 342 | 125 | 125 | (23.03%) | 445 | 120 | 120 | (52.40%) |
| buxey-2 | 29 | 7 | 47 | 248 | 223 | (12.63%) | 62 | 217 | – | – |
| sawyer-2 | 30 | 7 | 47 | 202 | 202 | (18.82%) | 62 | 191 | 150 | (16.28%) |

optimal value. This is promising in terms of further power peak gains that can be potentially obtained.

Finally, the results for the 9 instances for which an optimal solution is found with both $c$ and $\bar{c}$ show that the longer cycle time allows an average power peak gain of $-21.6\%$. This suggests that from an industrial point of view it may make sense to decrease production pace as the consequences in terms of power consumption may be considerable.

## 6 Conclusion and Research Perspectives

In this work, a new Assembly Line Balancing (ALB) problem, the Simple Assembly Line Balancing Problem with Power Peak Minimization (SALB3PM), is studied in which the overall power consumption peak is minimized. The scheduling aspects that must be taken into account make this problem harder than classical ALB problems. An Integer Linear Program is proposed and tested on benchmark instances completed with power features. Preliminary results show that considerable gains can be achieved in terms of power consumption, and thus that SALB3PM deserves attention from researchers. In particular, it seems promising to study the extent of the interaction between balancing and scheduling decisions. This could lead to decomposition-based efficient metaheuristic approaches to hopefully deal with real-world instances.

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# Modular Robot Software Framework for the Intelligent and Flexible Composition of Its Skills

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**Abstract.** Current trends such as mass customization necessitate an agile and transformable production. In this context, robotic technologies are seen as a key enabler. But, to date, industrial robots lack the flexibility to easily adapt to changing needs. Therefore, a modular skill-based software framework aiming for free configurability is presented here. A generic task control allows varying incoming tasks to be processed, based on the actual skills of the robot. In this way, the flexible composition of a robot's skills can be achieved, according to the actual situation.

**Keywords:** Autonomous robot · Configurability · Skills

## 1 Motivation

Customized products combined with the shortening and dynamization of product life cycles are challenging trends for the manufacturing industry [3]. To stay competitive, robotic technologies are seen as a key driver towards achieving an agile and transformable production [16]. Future robotic systems must be able to complete a wide variety of tasks at short intervals. Autonomous mobile robots in particular therefore demonstrate great potential [1]. However, this is contrary to the current situation. Today's robots lack the flexibility and reconfigurability to respond to changing needs. Great system complexity requires well trained experts to develop and operate those systems [8,16]. Promising to overcome these shortcomings is the skill paradigm [4,5,10,12,15,17–19]. A skill refers to a functionality or service a system offers. By first dividing the robots' functionalities into these skills, they can be freely orchestrated regarding the given task.

Within the scope of this paper, mobile robots should be enabled to autonomously take over varying production tasks, as coordinated and assigned by an superordinate planning system [6]. The tasks considered include commissioning diverse machine parts, pre-assembling these during transport or supporting workers during assembly. The focus of this paper lies on the skill-based


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software framework of the robots and addresses two main goals. First, the robot's skills should be freely configurable and easily adjustable to the changing requirements. Second, the robot should be flexible regarding the task handed over by intelligently composing its skills based on generic task control. The following section presents the related work. Then, the skill-based software framework will be introduced in detail and evaluated within two applications. Finally, a conclusion will be given.

## 2 Related Work

In reviewing related work [4,15,17–19] about the modeling of skills, hierarchical decomposition can be identified as a common key principle. Thereby, the primitives at the lowest level are the reoccurring sub-functions. Skills are composed of primitives and considered as reoccurring robot behaviors. Tasks refer to an ordered sequence of skills aiming to achieve a specific goal. Input and output parameters are used to permit the parametrization of skills [4,17]. The definition of preconditions and effects for individual skills allows for planning a skill sequence to achieve a given task [10,15]. A common state machine can be used to provide generic status information during the execution of skills [4].

Multiple approaches have been introduced for the application of the skill paradigm. Taking into account a whole production system, [12] introduces a holistic framework for the flexible orchestration of devices, based on their offered skills. In a similar context, [4] defines skills as solution-neutral and describes them in this way, semantically correlating to the tasks of a product assembly. Automated matchmaking thus becomes possible. These ideas correlate with the job the superordinate planning system should assume within this work.

With regard to industrial robots itself, skill-based approaches play a significant role in facilitating robot programming, e.g. in developing programming languages [18], skill-based programming systems [5] or combining these with programming by demonstration techniques [17]. [19] introduce a development platform to configure the robot skills by choosing from reusable software modules which are then deployed as apps. These approaches provide a good insight into how to make the robot software freely configurable or how to teach the robot new skills. Some generic task control is however needed in order to coordinate the function call of its skills according to varying tasks sent by a planning system.

[15] follows the trend of cognitive robotics and introduces SkiROS as a skill-based software architecture for robots, which allows them to autonomously plan and execute tasks based on their skills. [10] present a similar concept, while their focus is more on the information models used. Both approaches show the potentials of superordinate task management within the robot architecture. However, to date, these approaches are only applied to kitting tasks and there is a need to extend these to other production domains.

In summary, the initially stated requirements can not be fulfilled by the current state of the art. In order to be flexible regarding the tasks handed over, there is a need to encapsulate the software realizing a specific skill and provide a generic interface to use it. In addition, generic task management is needed, which works independently from the underlying skills. This is the prerequisite for allowing the easy composition of the robot's skills across the different domains of production.

## 3 Skill-Based Robot Software Framework

In order to enable robots to autonomously complete varying tasks, a skill-based software framework is presented (see also [6]). An overview is given in Fig. 1.

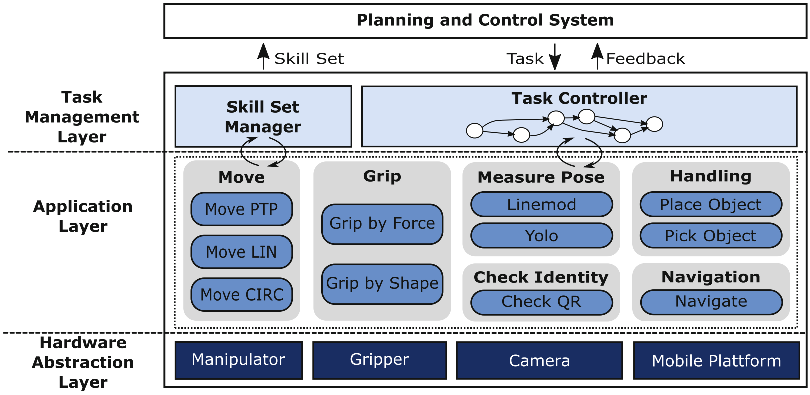


**Fig. 1.** Overview of the skill-based robot software framework

The modular robot software framework consists of three consecutive layers. At the lowest level, the hardware components of the overall system are integrated, with the aim of hardware abstraction. The application layer provides the skills that enable the robot to achieve tasks. It is expected that robots in the future will have to achieve a diverse range of tasks within short time cycles. Furthermore, there are almost unlimited possibilities for combining the skills in different ways. As a result, it is not possible to store all related knowledge permanently in the robot. Therefore, thematically related skills are combined in an app. Similarly to in the consumer sector, a robot's apps can be freely configured in terms of the current task, or can even be downloaded on a situation-specific basis. Tasks are handed over to and processed by the task management layer. The skill-set manager is responsible for drawing up a list of all the skills the robot offers. It passes this list to the planning and control system. Based on a semantically correlating description of skills and tasks, automated matchmaking as suggested by [4] or [12] can be performed. In this way, tasks to be completed get assigned to suitable and available robots. These are then handed over to and processed by the task controller of the individual robot, which subsequently coordinates the execution of its skills. The application layer is further explained in Sects. 3.1 and 3.2 and Sect. 3.3 describes the task management layer.

### 3.1 Modeling of Skills

Derived from the related work, *primitive skills* refer to the capabilities of a robot at the lowest level, which can not be further divided. *Composite skills* arise through the combination of primitive or lower-level composite skills and thus allow the modeling of complex robot behaviors on different hierarchy levels. As an example, by composing primitive skills like "move", "grip" and "measure pose", composite skills for "handling" can be achieved.

As well as modeling skills on different hierarchy levels, skills can be described on different levels of abstraction. Within this context, *abstract skills* describe the robot capabilities independently of the executing hardware and the underlying operating principles, whereas *specific* skills inherit from abstract skills and take these into account. [6] Thus, specific skills provide an opportunity to implement different building blocks for an abstract skill, which can be flexibly used depending on task-specific boundary conditions. For example, a gripper offers the primitive skill "grip"; by taking the operating principle into account, it can be separated between the two specific primitive skills "grip by force" and "grip by shape". Within this work an extended version of the skill taxonomy of [4] is used as a basis for the abstract primitive and composite skills.

### 3.2 Modularization of Algorithms into Apps and Strategic Applets

The skill-modeling gives a functional view of the robot capabilities. These given principles are further used to modularize the underlying software architecture of the robot by encapsulating it into apps or rather applets [6]. These consider the implementation view, build on the same structure and provide a generic interface containing a set of common control algorithms applied for all skills. An *applet* refers to the software implementation of a specific skill. An *app* is used as a generic construct to group a set of thematically-related applets into a software package, which together aim to perform a defined abstract skill.

Applying these concepts raises the central question of the robust and flexible programming of skill-building blocks at the outset when developing the robot's software architecture. By doing so, user-friendliness as well as constant extensibility of a multi-layer architecture are decisively influenced. In this respect, the conception of the architecture's lower levels already proves to be critical. For the realization of abstract skills as encapsulated apps, algorithms are first integrated into the system as independent functions. Of importance in this respect is the identification and definition of program sequences and interaction areas, which are representative for the algorithmic execution of functionalities offered by specific skills. Code fragments can be programmed or extracted from existing programs. Interfaces of separated functions are their prototypes and describe the data types of their return value. Depending on the semantic and functional nature of an abstract skill, several algorithms can be identified as its technical specification in the form of a specific skill. In order to guarantee a maximum degree of adaptability and the continuous modularization of the architecture, it makes sense to continue collecting such functions in classes according to the guidelines of object-oriented programming. In addition to its functional character, a class is also coherent regarding semantics. Ideally, each skill should create a class with strategically flexible algorithms available to it, thus giving the entire model an intuitive character. Generally, a skill-building block can then be implemented by creating the class object representing an abstract skill in combination with accessing one of its strategically specified skills in the form of a class method. The result of this concept can be transferred to the framework of apps and applets (see Fig. 2) and is exemplified based on a bin-picking task frequently used within commissioning.

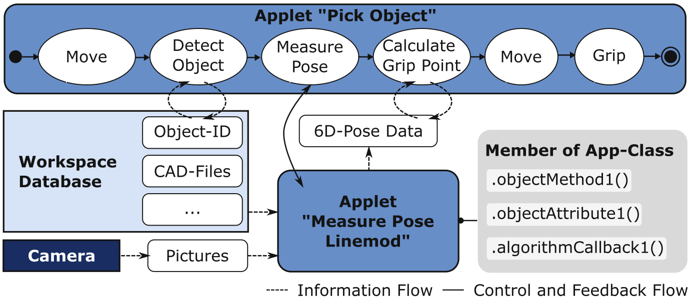


**Fig. 2.** Exemplary interaction of strategic applets within a skill-based system

In the presented work, ROS is used as implementation basis. Thus, the applet for the exemplary specific skill "measure pose with linemod algorithm" packages all software to run this process within ROS. In this way, the app provides the class-based collection of its strategic algorithms, which are then integrated within the applet. Strategy-based algorithms are similarly defined and used as can be seen in [7]. The app can further group a set of thematically-related applets, building on this same class into one software package. Applets are supposed to interact with all software and hardware resources in relevant system layers to adequately manipulate data. The call of the applet is done from the higher task controller or it can be further used to implement a higher-level composite skill. In this case it is integrated into an applet providing the scripted behavior of a picking skill. In both cases, the higher-lying calling entity handles the transfer of relevant messages via defined interfaces to the next applet.

### 3.3 Generic Task Control

In order to control the skills by the superordinate task controller, the idea is to include a standardized control interface to every applet. This is illustrated in the bottom part of Fig. 3 for the aforementioned applet to implement the composite skill "pick object". The control interface is defined by a state machine based on the PackML Interface State Model [11]. Similar to the concept introduced by [4], the applet's state machine describes its current execution status. The state machine furthermore introduces a set of control functions (marked italic in Fig. 3) that can be used to start, stop, pause or reset the applet. Expected, as well as faulty behavior can be monitored via the applet's feedback messages in the form of the current state within the PackML-based state machine.

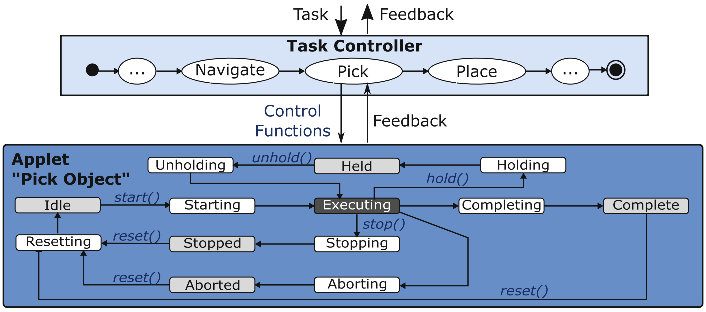


**Fig. 3.** Task controller interacting with an applet

The functionality that is provided by the application layer is used by the superordinate task management layer in order to perform given tasks. The task controller of the robot receives varying tasks from the superordinate planning and control system (see Fig. 3). Tasks have a complex, nested structure of sequential and parallel actions. Within the task controller, these are modeled as hierarchical finite state machines. The task controller dynamically builds these task state machines at runtime, by recursively iterating through the nested task structure and adding the actions as states to the state machine. Based on the generic control interface provided by each applet, the task controller is able to process the task independently of its structure and the actions it uses.

Within each state of the task state machine, the applet that offers the corresponding skill is addressed and controlled via the standardized generic control functions (see Fig. 3). Through the interface, the task controller is furthermore able to monitor the applet's execution. Faulty behavior of an applet can be detected and handled at task level. The task controller can additionally inform the planning and control system about the faulty behavior via status feedback.

## 4 Application Examples

**Modular, Skill-Based Bin Picking:** The methodology for the object-oriented modularization of skills is evaluated based on an existing bin-picking demonstrator. Figure 2 already showed a potential sequencing of specific primitive skills to achieve a composite picking skill. The system set-up is primarily concerned with recognition, 6D pose determination and robust picking of texture-less metallic machine elements from an associated industrial partner. In this way, the six primitive skills are processed as applets by a SMACH state machine [2]. As shown in Fig. 1, encapsulated, strategy-specific functions are aggregated in semantically coherent classes for apps, as their methods and several applets based on class methods were created for each app. The actionlib [9] provided by ROS is used in this case as the syntactic framework for the latter, resulting in an encapsulated and intuitive way of working when sequencing them within the composite skill. A first approach to implementing primitive skills with a focus on the lower layers of an architecture was successfully evaluated by the demonstrator.

**Flexible Task-Handling for Logistic Tasks:** The generic task controller for the automatic building and processing of tasks as well as the standardized applet control interface are evaluated on a simulated TurtleBot [14] equipped with an OpenManipulator [13]. The mobile manipulator implements multiple primitive and composite skills for performing logistic tasks. By making use of these skills, the robot is able to process tasks as sets of actions. Through the use of the generic task controller, these tasks do not need to be manually programmed within the robot's control software but can be passed to the robot in form of a nested JSON object. The task controller is able to automatically build a SMACH [2] state machine and control the required applets through the standardized control interface. Additionally, it is possible to halt a running task by sending hold commands to the task controller. When errors are detected within an applet's execution, the task controller gets passed the information about them and stops its execution as well. Further behaviors for error recovery need to be considered within the skill implementation, whereas the applet already provides the organizational structure. Feedback about the preemption or abortion of tasks also gets passed to the planning and control system.

## 5 Conclusion

In order to enable autonomous mobile robots to easily adapt to changing needs, and to flexibly complete varying tasks coordinated by an superordinate planning system, a modular skill-based software framework is presented. First, to reduce complexity, skills are hierarchically structured into primitive and composite skills and are modeled on different levels of abstraction. These concepts are used to encapsulate the robot's software according to the guidelines of object-oriented programming into independent building blocks, referred as apps and applets. The free configurability of the robot's skills is thus achieved. The PackML state model is introduced as a common interface to control and monitor the execution of the robot's skills. In this way, a generic task control able to process tasks independently of their content and structure is achieved. Thus, the proposed architecture fulfills the prerequisites for use within various production domains.

**Acknowledgments.** The results presented in this article were developed within the FORobotics (AZ-1225-16) research network. The authors would like to thank the Bavarian Research Foundation and all participating project partners for their funding and support of the project.

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# A Competence-Based Description of Employees in Reconfigurable Manufacturing Systems

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**Abstract.** The increasing demand for customer-specific, cost-effective products with shorter production times is shaping the industrial production environment. Therefore, both human workers and machines must react to these changes with greater flexibility and productivity. This paper shows a procedure to plan the employee ideally into the Reconfigurable Manufacturing Systems (RMS). The approach systematizes the competences of employees and enables an assessment of different expertise levels to finally realize a flexible integration of them into the constantly changing work environment. Therefore, the competencies of employees must be opposed with the needed skills so that the work processes can be executed adequate according to the product requirements. When this procedure is finally described digitally, companies will be able to realize a flexible workforce planning in the RMS, which is not possible so far.

**Keywords:** Human-centered reconfigurable manufacturing systems (RMS) · Competence-based classification · Human-machine-interaction

## 1 Introduction

Today's production environment is characterized by individual customer requirements, shorter product life cycles, increasing cost and time pressure [1]. RMS enable to cope with this high variance of customized products with variable work processes in a flexible work system. RMS are flexible, rapidly adaptable assembly systems regarding production capacity, functionality and system structure [2, 3]. Capacitive oversupply and a lack of capacity can thus be avoided [2]. Due to the variable manufacturing system, the workplaces and the work tasks change in a frequent manner for the employee [4]. In the context of this paper, a procedure for a competence-based integration of workers into a RMS is presented. The detailed digital description of human competences is part of the virtual representation ("Digital Twin") of workers, which can be used for an automated workforce scheduling.

Following the introduction, the paper is structured in four further sections. Section two gives an overview of the current state of research and the objectives we want to achieve. Afterwards, section three introduces the development of a model to describe the employees' competences to simplify personnel planning in RMS. Section four discusses possible application scenarios of the developed assessment including


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solutions to compensate competence gaps of worker. Finally, section five summarizes the paper and gives an outlook on further research contents.

## 2 Current State of Research and Research Goal

In this paragraph, five approaches for possible descriptions of machine skills and competences of human workers in a production environment are presented.

Reference [5] presents a taxonomy for the digital description of skills of automation devices in assembly. The aim is to optimize their comparison with the requirements of the work task. The assembly machinery offer their capabilities to the manufacturing system. Subsequently, other systems can search for required functions and use them to perform their working tasks. A functional analysis of both, the production process and the operating resources, leads to more flexibility in planning and application of resources. This allows an automated configuration and ad-hoc integration of equipment according to the plug & produce approach. The focus of this approach lies on the reconfiguration capability of assembly systems, for which reason the employee and his capabilities are not taken into account.

A more human-oriented way to digitally describe capabilities, but still not adaptable to the aim of the present project is considered by [6]. This approach uses an ontological representation to identify and configure team members for interdisciplinary teams in production networks based on competence profiles. They take into account competences such as problem solving, planning, technical, or language expertise as well as general and specific information of the individual team members i.e. their geographical location and phone number.

The method of [7] includes a comparison between employee qualifications and job requirements. The comparison focuses on changes caused by digitization and thus new challenges for the employee. The approach is prospective and provides companies with guidelines in the changing world of work. After applying the method, companies can derive qualification measures to prepare their employees for work in digital production.

A similar procedure was developed in the research project by [8]. The resulting procedure is used for strategic personnel development, especially in small and medium-sized enterprises (SMEs). In order to meet future challenges, SMEs can strategically align the competence profiles of their employees using the competence management tool developed. Professional, interpersonal, methodical and knowledge-based competences are the basic categories of the developed tool, into which the different tasks of the job description can be placed. The comparison of actual and target profiles on the basis of four different competence levels then shows the competence gaps that SMEs have to close. Since these approaches consider future changes in the digitized world of work, and do not take into account the requirements of an employee-matching to machine skills, it cannot be applied exactly to the conditions for employees in RMS.

A further human-centered approach is outlined by [9], in which individual capabilities of a human worker are described using a standardized taxonomy. The worker model contains two main aspects: individual human-related information and work-related capabilities. The latter contains the competences necessary for the concrete task execution, e.g. filling or joining by reforming. Three performance levels are distinguished for each competence: beginner, advanced and expert. Human-related information contains for example core capabilities or an individual fatigue level. The focus of this taxonomy is on the first conceptual presentation of a comparison between the abilities of humans and those of machines. However, the detailed level and a transferable description of human and machine capabilities are not yet sufficient for a precise matching.

In summary, it can be stated that there are already approaches that describe the employee and its competencies. However, among these there is no approach suitable for a digital description and thus an automatic planning and distribution of work tasks between men and machine. There is a lack of a standardized system for the optimal matching in the RMS. Such an approach is introduced in greater detail below.

## 3 Development of a Competence-Based Classification for Employees in Reconfigurable Manufacturing Systems

**Argumentation of the Positioning of the Approach.** As already described, RMS help to meet challenges such as short innovation cycles or products with many variants. By being able to react quickly and economically to sudden changes in market, RMS provide a remedy [10]. However, changes in the manufacturing system also affect other actors in the work system. The employee is a central component of it. If individual modules or functions i.e. in an assembly line change, it must be verified whether the employee is still able to fulfill his work task accordingly [4]. With this in mind, a procedure is required which simplifies the way to perform this verification.

As shown by [5], there are already attempts to describe machine skills to execute an automated resource planning. The aim of this article is to enable automated resource planning not only for production machines but also for employees in the work system. Therefore, a system has been developed which classifies, structures and assesses the competences of the worker in order to enable an easy and flexible personnel deployment planning.

The RMS is an operating resource and represents as such an element in the work system (see Fig. 1). According to [11], further elements of the work system are the human worker, the work piece, the work task, the workflow, the input and output as well as environmental influences. These elements interact with each other. For example, the work task is fulfilled through the interaction of people and resources.

The replacement of individual modules of RMS results in a change of the operating resource and thus in a change of a system element in the work system. Since this interacts with the human worker, the company must verify what this change means for him/her, and whether the human worker is still able to fulfill his or her task. The analysis of the working system and the interaction of its elements help not only to achieve an optimization of the entire system, but also to meet the human criteria of good work and valid legislation. For example, the Civil Law Code enshrines the employer's duty of care [12]. Ergonomic evaluation methods of work want to provide a damage-free work for humans and evaluate physical and anthropometric aspects and has to be realized when changes become effective at the work place. With RMS in the work system, however, the demands on people with regard to the required competences can also change, which are neglected in ergonomic evaluation methods. Thus, a method is needed to do so.

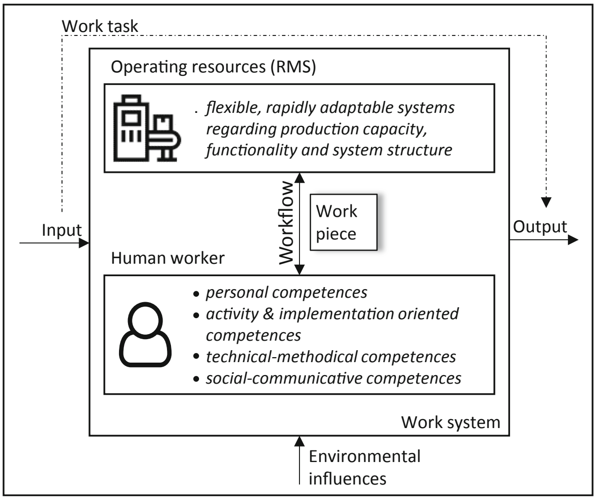


**Fig. 1.** Human and RMS in the work system

**Competence Modelling and Characterization Approach.** Humans in the working system can be described by the four types of competences [13, 14]. The employee needs *personal competences*, *activity- and implementation-oriented competences*, *technical-methodical competences* as well as *social-communicative competences* in order to be able to fulfill the work task with the aid of resources (see Fig. 1). Personal competences are skills to be wise and critical of oneself, to develop productive attitudes, values and ideals. Activity- and implementation-oriented competences are abilities to implement all knowledge, the results of social communication as well as personal values and ideals in a strong and active way as well as to integrate all other competences. Technical-methodical competences are abilities combined with technical and methodical knowledge, to creatively master even almost unsolvable problems. People with social-communicative competences are able to work together and interact with others, they can cooperate creatively and communicate [14].

These four types of competences represent the basic characterization of the systematics for the competence-based employee description in the RMS (see Fig. 2). The types of competences can be further differentiated. From the competence atlas according to [14], subcategories can be taken which are exemplarily shown in Fig. 2 (e.g. loyalty, execution readiness, communication skills, etc.).

If a company wants to match the changed requirements with the employee's competences, specific subcategories that are required at the given workplace can be chosen from the competence atlas. The technical-methodological competences of the employee are particularly important in this comparison, as they enable the employee to implement a work task operationally. Within the scope of this contribution, these will therefore be examined in focus and detail. In the context of the application field, the assembly, activities can be seen under the technical and methodical competences recording to German standards (VDI 2860, DIN 8593 and DIN 8580) [15]. These are joining, handling, checking, adjusting, and special operations and have also been included with their individual activity modules in the depicted system. Based on the system described, the changed requirements can now be compared with the competences of the employee.

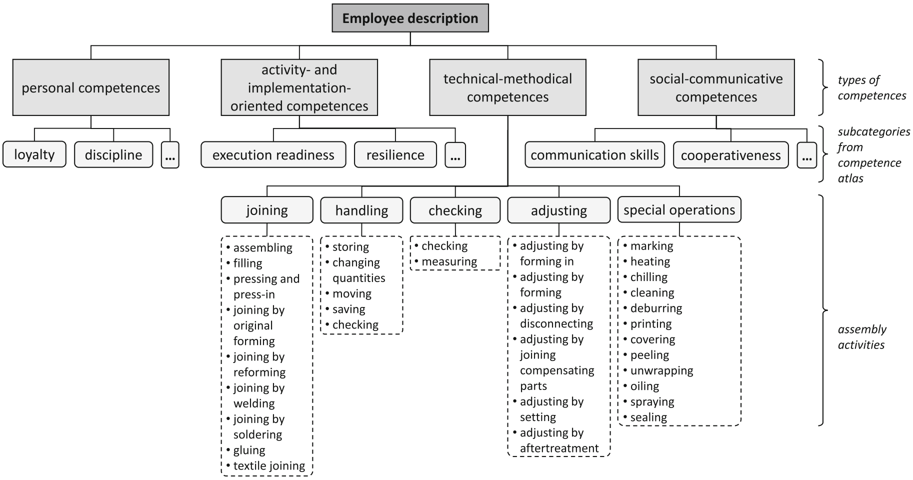


**Fig. 2.** Systematics for a competence-based employee description

**Comparison Between Available and Required Competences.** In order to enable the user to assess the level of expertise additionally, the system is to be supplemented by the expertise model according to [16]. In this model the qualitative development of competences is described in three stages:

*Stage A (competences are poorly developed).* At level A, the employees have basic knowledge with little application experience and are able to carry out specified tasks in a familiar learning and working situation with preparation.

*Stage B (distinctive competences).* Multiple experience in applying the knowledge in concrete professional situations, projects or processes is existing. The employees react to new, unforeseen situations with appropriate professionalism. They have differentiated knowledge and understand tasks and problems in their familiar working environment. They choose from a repertoire of possible actions to work on and solve tasks independently.

*Stage C (strong competences).* Employees have broad and in-depth specialist knowledge as well as diverse experience from various contexts. They are therefore able to anticipate problems completely self-organized, intuitively and find new solutions. They master the management of complex and new tasks and make valuable contributions to the further development of their organization, their field of work or discipline.

An evaluation of the requirements of the work system and the competences of the employee is depicted in Fig. 3. The grey dots present the given requirements according to the level of expertise in order to make them comparable by supplementing the competences of the employee, represented by the squares. The comparison reveals gaps that need to be closed to continue the deployment of the employee at the workplace.

Up to now, there has been no approach that enables flexible personnel deployment planning in RMS. The combination of the four types of competences, the assembly activities and the stages of expertise presented in this paper now enables an automated scheduling.

## 4 Possible Application Scenarios

The presented assessment (Fig. 3) shows a competence gap in assembling, where the employee experiences are poor and the requirements are high. In order to ensure that the work tasks are fulfilled in an appropriate quality, the company has to close the given gap. Below, three application scenarios of the given assessment with solution approaches to close the gap are presented:

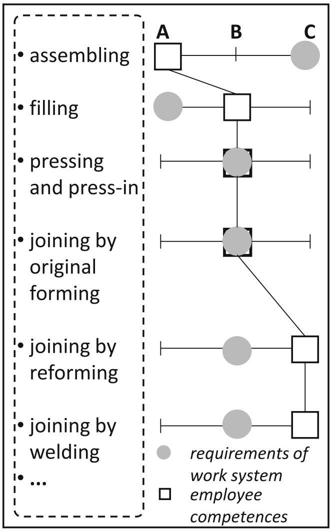


**Fig. 3.** Comparison of the work system requirements and the employee's competences

**Usage of an Individual Worker Information System.** In reconfigurable, flexible manufacturing systems, the worker has to adapt constantly to the changed work tasks, which significantly increases the complexity for the employees. According to [17], a generally valid presentation of worker information is not sufficient for a successful execution of a task. Consequently, the displayed information should be adapted to the individual experience of the worker and the production context. Therefore, an individual information system guides the employees through the working process at the best. By the usage of such a system, lower competences of the worker could easily be balanced out.

**Qualification Measures for Employees.** If the worker's competences do not match the skills required to perform the task, specific training measures can be used to provide selective employee qualification. On the job or off the job trainings would be suitable to educate the employee further. Additionally on the job trainings could bridge idle times, which is a further benefit for the company.

**Development of A Rotation Plan.** Another possibility to close the gap created would be a rotation plan. By establishing a competence matrix of all employees of a company a simple algorithm could reassign the employees to the work stations changed by the RMS. However, this would mean a high initial effort and is only practicable if the working environment and work organization allow a rotation. A balanced workload of the employees should also be taken into account, as well as the willingness of the employees to change stations frequently or flexibly.

To decide which of the three proposed solutions fits best, the needs of the employees as well as those of the company should be considered. If, for example, the employee is not willing to perform the work steps with an assistance system and is not familiar with the operation of such a system, the first scenario would not be recommendable. On the other hand, an assistance system could be too expensive for the company or the setup of such a system could be too time-consuming for the corresponding use case. The situation is similar with scenario two and three. In order to achieve a good and productive work system, it is always necessary to balance the economic aspects of a company with the availability, motivation and willingness of its employees.

## 5 Conclusion and Outlook

The presented assessment is an approach to a description of worker abilities. The combination of the four types of competences with the defined assembly activities and the three stages of expertise is a completely new approach and should lead in the long term to automated and flexible personnel deployment planning. In the coming years this assessment will be further developed at the Institute for Machine Tools and Industrial Management at the Technical University of Munich.

For the implementation of such an assessment, competences of the worker cannot be included on a one-off basis in the assessment, since the dynamic acquisition of competences must also be taken into account. In order to keep the maintenance effort of the assessment as low as possible, an automatic recording of the competence development would be conceivable. For example, competence development would be recorded by an individual error rate or by regular performance appraisals of the supervisor using a standardized, digital evaluation sheet.

In addition, it would be possible to integrate the presented assessment into the production cost planning by taking into account not only the conversion times of the plants, set-up costs and downtimes, but also the availability and competence level-dependent costs of the workers. An extension of the automated and optimized assembly planning of [18] would be possible.

Even if the creation of such an automated employee planning tool means a high initial effort for a company, it should not be neglected that without such a tool the flexibility trends in a digitized working environment will be difficult to meet. The developments in production lead to a constant flexibilization of work processes, therefore it is of great importance to also make the work organization more flexible in the future.

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# Product and Asset Life Cycle Management in Smart Factories of Industry 4.0

# Identification of the Inspection Specifications for Achieving Zero Defect Manufacturing

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**Abstract.** The contemporary manufacturing landscape is characterized by increased volatility shortened product life cycles and increased degree of product customization. Manufacturing companies are continuously facing the challenge of operating their manufacturing processes and systems in order to deliver the required production rates of high quality products, while minimizing the use of resources. They can achieve this with a concept named Zero Defect Manufacturing. This concept implies that inspection is performed to all the parts and therefore they can achieve zero defects. The problem is that inspection can be either time consuming process or a very expensive process. The goal of the current research work is a methodology for the identification of the acceptable inspection specification in order for the production system to stay efficient and at the same time produce non-defected products. In other words the outcome of this paper will be a set of maps that depicts which can be the acceptable inspection characteristics such as inspection time and inspection cost.

**Keywords:** Zero Defect Manufacturing · Inspection time · Inspection cost · Inspection specification · Defect detection

## 1 Introduction and State of the Art

The contemporary manufacturing landscape is characterized by increased volatility shortened product life cycles and increased degree of product customization. Further to that the required quality by the customers has been higher than ever and therefore, manufacturers in order to stay competitive should adapt to these changes and start adopting new strategies that will allow them to achieve higher product qualities keeping costs as low as possible and at the same time respecting the due dates. The minimization of cost is a major consideration for all manufacturing industries and this is directly related with the product's quality. In addition, the product's quality is directly related with the inspection policy that has been selected.

One of the strategies that can take into account and provide high quality parts at low costs is called Zero Defect Manufacturing (ZDM), which has as a goal of eliminating with various ways defected parts in the production, but it is not an easy task [1]. As described in [2, 3] there are four main strategies for implementing ZDM the Detect, Prevent, Predict and Repair of a defect. The most critical is the detection strategy


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because all the other strategies are relying on the data collected during the detection step.

It is common that in most of the manufacturing systems the quality testing of the product is performed at the end the process chain [4]. This is happening for separating the defective parts from the acceptable in order to treat them with different way. ZDM imposes that part inspection should happen in multiple stages [5] and not only at the end of the process chain.

The detection of a defect is a very important step of the manufacturing process [6]. However, there is no clear approach of what would be the acceptable specification of the inspection points, relatively to the total processing time and total product cost. Therefore, this paper aims to develop a methodology for defining what should be the acceptable inspection characteristics in order for the manufacturers to stay competitive and be able to achieve Zero Defect Manufacturing by inspecting all of the parts.

The majority of the literature deals with the development of effective and accurate inspection and monitoring technics without concerning the implications that may have to the actual production [5]. For that reason there is the need for integrated approaches to jointly optimize, at system level, maintenance, quality and production control strategies, in order to avoid local improvements that can bring minor, or even detrimental, effects at system level [7].

Genta et al. developed a method based on which he was able to predict the probability of defect occurrence relevant to each process step and that way they could plan an effective inspection [8]. Sarkar created an economic production quantity model where the process is deteriorated based on production of defective products. To avoid the higher cost of inspection, product inspection policy was performed instead of full inspection policy where the product inspection policy was not error free [9]. Mohammadi et al. developed a mathematical model for deteriorating process representing the expected total cost to obtain the optimal solution. The aim of this research was to determine the production period length and inspection policy such that the expected total cost is minimized [10]. In Sect. 2, the mathematical formulation of the current work is presented. Then in Sect. 3, the implementation of the proposed method to an industrial case is performed and finally in the conclusion section, the paper is summarized.

## 2 Proposed Methodology

Currently, there are numerous of different inspecting technologies with different characteristics each, and the implementation of inspection points on every manufacturing stage is not possible due to cost and time constrains. Therefore, manufacturers need a tool that could indicate what could be the acceptable combinations between inspection time and inspection cost based on the total processing time and total product cost. This methodology should be applied to the critical points for selecting the most appropriate inspection equipment in order to be able to inspect all the products and that way guaranty 100% defect free order.

The current methodology aims to assist manufacturers in the process of designing, re-designing, or adjusting manufacturing systems to new products in order to determine what inspection equipment they need. The method is quite simple but the outcome has a significant impact to the achievement of ZDM. Two measures were used for the initialization of the process, the Estimated Product Cost (EPC) and the Estimated Production Time (EPT), which includes all the costs and all the times for the manufacturing and inspecting the product, accordingly. Both measures consists the theoretical – nominal values of these product parameters and consider only the manufacturing of the product from start to finish without any inspection. Having those parameters, we define two ratios the Inspection Time Ratio (ITR) and the Inspection Cost Ratio (ICR) that are described by formulas (1) and (2). The ratio approach selected in order to provide a relative indicator that shows how much extra time or cost is needed for the inspection having as reference the nominal values.

$$ITR = \frac{Inspection\ Time}{EPT} \tag{1}$$

$$ICR = \frac{Ispection\ Cost}{EPC} \tag{2}$$

ITR and ICR take values between 0 and 1. ITR is an independent value whereas the ICR includes the calculated Inspection Time. The goal is to find all the sets of the two ratios that corresponds to acceptable inspection characteristics. Those sets will be used in order to create a map of the acceptable inspection characteristics in order to inspect all the products and that way achieve Zero Defect Manufacturing.

### 2.1 Performance Indicators Used for the Simulation

Three different PIs were used for the comparison of the different scenarios (SC): (a) the tardiness of the order (OT), (b) the quality of the solution (OQ), measuring how many defected parts were at the end and (c) the actual product cost (PC). The PC should not be mixed with the EPC. PC is the actual product cost as it was calculated after the simulation. Equations 3, 4 and 5 present the formulas that the KPIs are calculated. Those values were normalized and weighted and summed to one value which corresponds to the quality of the solution [11, 12].

$$OT = \max(DueDate - Makespan, 0) \tag{3}$$

$$PC = \sum RawMaterialsC + \sum OperationalC \tag{4}$$

$$OQ = \frac{TotalProductsMade - DefectedProducts}{TotalProductsMade} \tag{5}$$

## 3 Experimental Results

The use of the proposed method in an Industrial scenario will be described in this chapter. A dynamic scheduling tool was used for the simulation which is described in [3]. In addition, the product used for the simulations is composed out of 13 processes and the corresponding bill of processes (BoP) is shown in the right side of Table 1. The simulation was including only a part of the factory, and more specifically 10 machines, configured as “open shop” [13]. In addition, the simulation was performed for 3000 parts with a specific due date. In addition, the simulations were considering product inspection at the final manufacturing stage. The inspection parameters were defined according to the methodology presented in Sect. 2. The left side of Table 1 depicts the scenarios that were defined for the simulations with the inspection times and costs used for each one. In addition, the product under investigation has EPC = 341.2 € and EPT = 108.2 min. Having these values and using the formulas (1) and (2), we were able to calculate the corresponding Inspection times and Costs.

**Table 1.** Experiment inspection scenarios & product Bill of Processes (BoP)

| SC | ITR | ICR | Inspection Time (min) | Inspection cost (€) | Inspection machine cost (€/hour) |
|---|---|---|---|---|---|
| **1** | 0.1 | 0.1 | 10.82 | 34.12 | 189.2052 |
| **2** | 0.3 | 0.3 | 32.46 | 102.36 | 189.2052 |
| **3** | 0.5 | 0.5 | 54.1 | 170.6 | 189.2052 |
| **4** | 0.7 | 0.7 | 75.74 | 238.84 | 189.2052 |
| **5** | 0.1 | 0.3 | 10.82 | 102.36 | 567.6155 |
| **6** | 0.3 | 0.5 | 32.46 | 170.6 | 315.342 |
| **7** | 0.5 | 0.7 | 54.1 | 238.84 | 264.8872 |
| **8** | 0.7 | 0.1 | 75.74 | 34.12 | 27.02931 |
| **9** | 0.1 | 0.5 | 10.82 | 170.6 | 946.0259 |
| **10** | 0.3 | 0.7 | 32.46 | 238.84 | 441.4787 |
| **11** | 0.5 | 0.1 | 54.1 | 34.12 | 37.84104 |
| **12** | 0.7 | 0.3 | 75.74 | 102.36 | 81.08793 |
| **13** | 0.1 | 0.7 | 10.82 | 238.84 | 1324.436 |
| **14** | 0.3 | 0.1 | 32.46 | 34.12 | 63.06839 |
| **15** | 0.5 | 0.3 | 54.1 | 102.36 | 113.5231 |
| **16** | 0.7 | 0.5 | 75.74 | 170.6 | 135.1466 |

**Product BoP**

```
T901
:...T101
    :...T102
    :   :...T103
    :   :...T104
    :       :...T105
    :       :...T106
    :       :...T107
    :...T108
    :   :...T109
    :   :...T110
    :   :...T111
    :...T112
```

All the scenarios were compared among each other and with a benchmark scenario (“B”) in which inspection was performed every 100 parts, but the same number of defects were introduced during the simulation. Four different set of weights were used at the performance indicators (PI), in order to demonstrate the different requirements that each manufacturer has. The results from the simulations are illustrated in Fig. 1. It can be seen that in the three out of four weight sets the quality of the benchmark scenario is lower than 0.66, only in the last weight scenario that Order Quality is not that important (0.2) benchmark is close to the best with 9.52% relative difference from the best of the set.

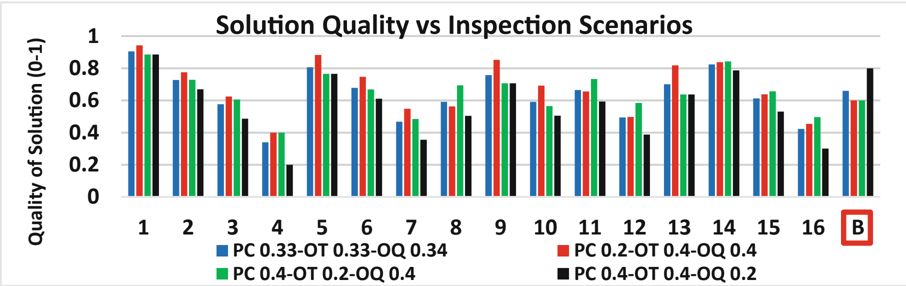


**Fig. 1.** Inspection scenarios and benchmark solutions quality

The next step is to use the results from the experiments, illustrated in Fig. 1 and create the maps for the acceptable inspection characteristics. For each weight set the 16 scenarios' values were compared with the benchmark and if they were above the benchmark then this value is acceptable and should be considered to the corresponding map. The benchmark scenario is the current situation on the shop floor and the current study aims to improve the performance of the system in terms of order quality but keeping production cost and makespan as low as possible.

Then all the revealed points were put in a common graph, Fig. 2 and the area that is below the marked line depicts the acceptable inspection combinations in terms of inspection time and inspection equipment operational cost. The weight scenario with the least possibilities is the scenario in which quality is not that important. This case is not presented in Fig. 2 because only one scenario was better than the benchmark test, scenario 1, which imposes very quick and low cost inspection device.

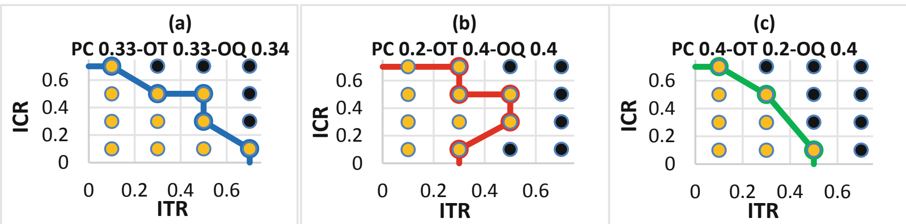


**Fig. 2.** Inspection specification map for different criteria weights

## 4 Conclusions and Future Work

This paper provides a method identifying the acceptable inspection parameters in order to select the appropriate inspection equipment and efficiently inspect all the produced parts and achieve ZDM. In addition, the results were split into four categories, each category was considering different weights to the PIs. It was observed and expected, that the inspection scenarios that had low inspection time and low inspection cost, were common points to three out of four maps. It is obvious that the cheaper and the faster the inspection point the better it is, but when it comes to inspection this combination is not always the case. Therefore, manufactures need methods like the above mentioned in order to be able to decide if an inspection point would be efficient or not.

Future work will focus on the study of multiple inspection point across the manufacturing of a product and simulating the entire shop floor. Further to that, the simulation of multiple product will be investigated as well as different shop floors set ups. In this industrial case, the shop floor was set up as an "open shop" configuration.

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# Risk Sources Affecting the Asset Management Decision-Making Process in Manufacturing: A Systematic Review of the Literature

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**Abstract.** Asset Management (AM) is promising for value creation from assets in the long term. A major concern to this end relates with the capabilities to achieve effective AM decision-making at every organisational level, i.e. operational, tactical, and strategical. Therefore, the goal of this research, grounded on a systematic literature review, is to identify which are the main sources of uncertainty that may influence the achievement of AM system related objectives and, as such, should be taken into consideration in a risk-informed decision-making process. Taking the manufacturing sector as a reference, the risk sources addressed by the extant literature are identified and mapped against a reference classification scheme. As a result, the research offers a comprehensive framework where risk sources, affecting the AM decision-making process, are systematically mapped. Information management is found to be the main risk source when making asset-related decisions.

**Keywords:** Risk management · Asset risk management · Risk sources · Asset Management · Manufacturing

## 1 Introduction

Asset Management (AM) as discipline and business process is recently at the centre of the scientific and industrial debate. In fact, AM has been climbing top management's priority list, having a special concern in physical assets [1], i.e. those assets that exist independently from any contract, as opposed to financial assets [2].

During its development, the AM system view promoted a holistic approach, leading to more attention to strategic, risk, safety and environment, as well as human factors [2–4]. Four founding principles are also remarked – i.e., lifecycle, system, risk, and asset-centric orientation – as levers to set an AM system within an industrial organisation [5]. While remarking the holistic approach, value creation has recently emerged as another essential concept to the purpose of AM. Indeed, AM embraces different kinds of actors that together aim at realising value by managing assets through coordination and in alignment with the organisational strategy [6]; accordingly, "effective


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control and governance of assets … is essential to realize value … to achieve the desired balance of cost, risk and performance" [6]. In order to achieve such a balanced cost, risk and performance, the focus on value in asset-related decisions is remarked by the most recent discussion on value-based AM [7–9].

Different application fields/sectors advocated the adoption of AM and, specifically, of an AM system. The establishment of AM as a business process was initially evident in the mid-90s in the oil and gas sector; later on, infrastructure and distributed network systems have progressively aimed to introduce AM in their core processes; manufacturing is, nowadays, still lagging behind the achievements in the other sectors, especially discrete manufacturing.

Notwithstanding the application sector, and the relative AM maturity within it, a common understanding is that a proper and efficient AM requires to set up an effective decision-making process, capable of supporting asset-related decisions through all the lifecycle phases of an asset [10]. In this perspective, risk management plays an important role in improving the decision-making process within AM [6]. Risk management has, in fact, a huge impact on the correct setup of a well-performing decision-making process [11]. However, within the AM field, asset-related decisions and decision-making are not particularly supported by practical guidelines [3, 4] in accordance with risk management. For this reason, the present work focuses on the relationships between the decision-making process within AM and the related risks. More specifically, the aim is the identification of possible risk sources affecting the decision-making process within AM, while particular attention is put on manufacturing companies, considering how the general concepts and principles of AM are currently implemented in this business context.

From a research perspective, this work fosters the importance of risk management, with the aim of enhancing its role in AM decision-making; from a practical perspective, the paper gives hints to asset managers about what risk sources should be considered for implementing a risk-informed decision-making process.

The paper is so structured: Sect. 2 describes the reference framework for AM risk sources, proposed as a background, and built by integrating the risk-orientation principle to the lifecycle-orientation; Sect. 3 deals with the systematic literature review methodology, and it describes how the framework is fulfilled based on the literature findings; Sect. 4 proposes the results of the literature review, then Sect. 5 states some conclusions and work limitations for future improvements.

## 2 Framework for Asset Management Risk Sources

This work assumes a reference framework for the analysis of the most impactful risk sources for the AM decision-making process. The framework is composed of two dimensions: asset-related decisions and operational risk sources (see Fig. 1).

The first dimension includes the asset-related decisions mapped against each lifecycle phase, see the bottom part of the scheme in Fig. 1. This dimension adopts an asset user perspective, so it does no include decisions as pricing, or maintenance service provision offering. The currently included decisions are related to evaluation of alternatives and suppliers, maintenance strategy definition, and budgeting for the BoL

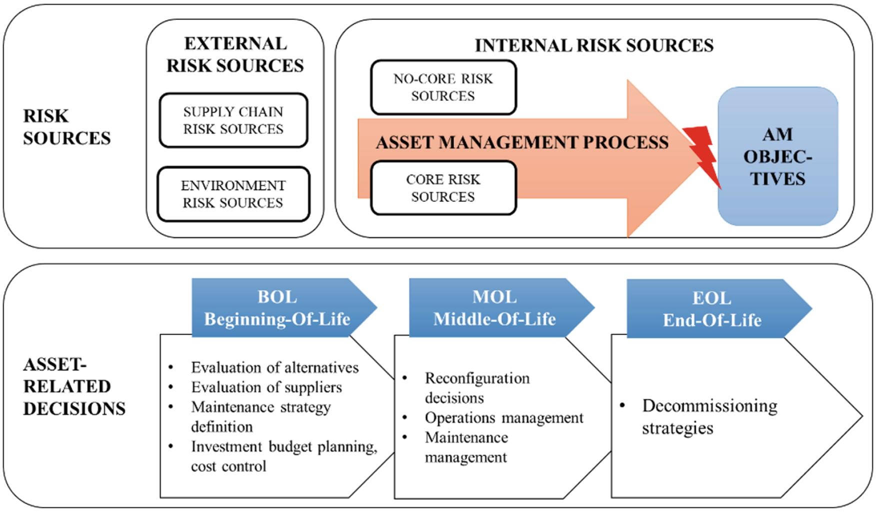


**Fig. 1.** Framework for Asset Management risk sources.

phase of the asset. The MoL phase is related to the operation of the asset, thus including operations and maintenance management decisions, and reconfiguration decisions to adapt the asset to everchanging production conditions. At the end of the asset lifecycle (EoL), the main decision is related to the selection of decommissioning strategies. For more insights into the asset-related decisions model, refer to [12].

The second dimension considers the operational risk model adopted to classify the risk sources and the respective risk categories, having as major concern the physical assets and their management process. The operational risk model adopted for the analysis is the one proposed by [13]: the risk model considers as a basic concept the definition of a risk source as “any entity or circumstance with the potential to generate uncertain conditions”; it is used as a reference to map risk sources found out from the systematic literature review.

Correspondingly, at the top of Fig. 1, the scheme of the operational risk model, as adopted in this research, is presented. Therein, the AM process is heading towards the AM objectives; however, the achievement of such objectives is affected by different risk sources that impact on the AM process. In particular, the impact of the different risk sources is identified as the variation in reaching the AM objectives.

Four different risk source categories are identified, which represent different types of risk sources, both internal and external to the company:

- *Core risk sources* belong to the internal risk category and are associated with the core processes of the company, which is a process that directly contributes to the value creation according to the company’s objectives. In the context of the present study, the AM process is the core process of interest.
- *No-core risk sources* belong to the internal risk sources and are associated with the no-core processes of the company. A no-core process is a process that is considered ancillary with respect to the core process and supports it in value creation. For

example, spare parts management is an ancillary process, relevant to support the AM process towards the generation of value from physical assets.

- *Supply chain risk sources* belong to external risk sources with respect to the AM decision-making process and are associated with the organisation in a broader view with respect to the core and no-core risk sources, which are internal. These risks stem from the interaction with suppliers. This may occur with the Original Equipment Manufacturers (OEMs) providing new assets, the OEMs/service providers supporting maintenance services, and the MRO (Maintenance Repair Operations) material suppliers.
- *Environment risk sources* belong to external risk sources and are associated with the environment surrounding the company and influencing the core process as well. Environment does not mean only natural events, but all the set of geographical, political, social, and cultural factors that could influence, as contextual factors, the core process. For example, new legal requirements or the lack of skilled workforce may influence the AM process.

The focus of this research work is on the second dimension of the framework (i.e. operational risk sources, the top part of the scheme of Fig. 1). A systematic literature review is applied to analyse scientific literature dealing with risk and AM in manufacturing, as described in Sect. 3. Then, Sect. 4 presents the mapping of risk sources against risk source categories.

## 3 Literature Review Methodology

A systematic literature review is carried out to explore risk within AM in manufacturing industries; in particular, the literature search is performed to look for the risk sources affecting the decision-making process.

The literature review is pursued looking at works present in databases as Web of Science (WoS), Scopus and Google Scholar. In particular, it is done considering the following features:

- adopting a comprehensive search in title, abstract and keywords;
- keywords used are *Asset Management* AND *Risk* AND *Manufacturing*;
- English documents are the only ones considered.

The literature search finds out 985 documents (16 in WoS, 189 in Scopus, and 780 in Google Scholar). After applying the elimination of all non-English written documents and filtering according to title and abstract, the final list is composed of 27 works. The bottleneck criterion is the one related to the screening phase because, even though manufacturing is introduced in the keywords, most of the documents, especially in Google Scholar, deal with risk and/or assets in the financial sector. Then, the final list of 27 documents is further screened through full paper readings to understand if each paper analyses some risk sources in the manufacturing sector.

Considering the above findings, it has to be noticed that the main limiting criterion of the literature review adopted so far is the confinement within the manufacturing sector: most of the documents treat risk within AM in infrastructure and distributed networks. Thus, even though the systematic literature review methodology is adopted to look in depth at the scientific documentation, the results are not completely satisfactory, since the number of papers after the last screening phase is small. To overcome this problem, additional literature is introduced to better feed the proposed framework: it comes from the background of AM in the scientific community, and it also considers the ISO 5500x body of standards, which gives some hints about risk in AM.

Thus, the risk sources found out in the scientific documents are classified according to the risk source categories therein discussed (Sect. 4). More specifically, the risk sources are derived by the analysis of the literature: the eligible papers clearly state the authors are addressing specific risks, even though usually they do not refer to specific decisions. As a consequence, with this information it is possible to complete one dimension of the framework, the one dealing with risk sources (top part of Fig. 1), mapping them against risk source categories, defined while going through the literature analysis.

## 4 Risk Sources Against Risk Source Categories

The framework of risk sources versus risk sources categories is fed as a result of the step of full paper reading using the 27 works selected from the systematic literature review. The analysis of the articles allows either to understand which kinds of risk sources are highlighted in the scientific literature, either to associate them with the relative risk source categories. The analysis is firstly done considering the eligible papers; then, this set is enlarged thanks to additional literature (highlight by an * in Table 1) that has grounded the basics of AM, such as the ISO 5500x body of standards. For the sake of transparency, if the risk source is not derived from the eligible documents, a * is put next to the risk source; instead, if the risk source is identified in both eligible and not eligible documents, a (*) is used. Thus, Table 1 proposes the results of this analysis.

The analysis of the risk identified in literature allows to classify them according to the framework proposed in Fig. 1 (column of Table 1), and to group them into risk sources (rows of Table 1), which could be:

- Equipment: risk source related to machines, components or systems that could fail or, somehow, affect the possibility to achieve the desired AM objectives;
- Information management: risk source associated with the way information is gathered and managed;
- Human factor: risk source connected with leadership, culture, motivation, behaviour and competence within the organisation;
- Organisational architecture: risk source related to the organisational structure;
- Supplier: risk source associated with the suppliers of the organisation that could, in some way, affect reaching AM objectives.

The main finding of this analysis is the importance of considering information management as the most impactful risk source on the AM process. However, the second place is taken by the human factor, underlining the need for knowing and understanding AM principles to correctly manage systems of assets in the long-term perspective.

**Table 1.** Classification of risk sources against risk source categories

| | Core risk sources | No-core risk sources | Supply chain risk sources | Environment risk sources |
|---|---|---|---|---|
| Equipment | [14] | [14, 15] | | |
| | Security | Security<br>Failure | | |
| Information management | [6, 16, 25–27]* | [7, 16, 17, 19, 26, 27]* | [19, 20] | [21, 22] |
| | Information tracking (*)<br>Information availability*<br>Data collection*<br>Data management* | Information tracking (*)<br>Data tracking (*)<br>Data security<br>Data collection*<br>Data management* | Data security<br>Information security | Information security<br>Data security<br>External hacking |
| Human factor | [6, 15, 23, 28]* | [18, 23, 28]* | | |
| | AM knowledge lacking (*)<br>Leadership*<br>Motivation*<br>Culture* | AM knowledge lacking<br>Maintenance knowledge lacking | | |
| Organisational architecture | [7, 24]* | | | |
| | Framework guideline stating AM objectives misalignment*<br>Responsibility allocation* | | | |
| Supplier | [6]* | | [27]* | |
| | Responsibility allocation* | | Maintenance activities outsourcing* | |

## 5 Conclusions

The present study focused on the analysis of risk sources to be taken into account within the decision-making processes supporting the implementation of AM in the manufacturing sector. The aim is to promote a risk-informed decision-making process tackling the lifecycle perspective of an asset, thus being aligned to the AM principles of risk- and lifecycle-orientation [5]. The main findings of the work are expected to bring a contribution both to researchers and to practitioners.

From a scientific perspective, the work fosters the importance of risk management in asset-related decisions. The main finding of the analysis is that information management covers a primary role as the most critical risk source in asset-related decisions. Furthermore, the culture of AM, identified by the knowledge ecosystem, seems to play an important role as a risk source, since the knowledge and capabilities not merely related to the technical aspects of AM, but also to the managerial ones, could promote and make effective and successful the decisions.

From a practical standpoint, the proposed framework (Table 1) will enhance the possibility of asset managers to correctly reflect on the decision drivers and the associated risks. This will allow them to take preventive actions in this regard.

Clearly, the present work is a starting point to bring forward new research work. In particular, the proposed classification should be completed, with the aim to map the risk sources against asset-related decisions in the lifecycle, as defined in the reference framework (Fig. 1). This additional analysis could make the proposed framework more valuable for both academia and industry since it creates a direct relationship between each risk source and each asset-related decision. In so doing, a more risk-informed AM decision-making process could be established, and the asset user will be aware of possible misbehaviour of this process.

Moreover, the research developed in this work and its results are limited to the needs and peculiarities of the AM in manufacturing. Another limitation of the review regards the explicit exclusion of maintenance as the scope of the literature review, even if it could be used as an exploratory field to enlarge the collection of research works that address the risk orientation as a precursor of AM [29]. These limitations may stimulate a wider scope of the systematic literature review in future works.

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# Conceptual Framework for a Data Model to Support Asset Management Decision-Making Process

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**Abstract.** Information and data management is nowadays a central issue to support the Asset Management (AM) decision-making process. Manufacturing companies have to take different decisions along the asset lifecycle and at different organisational levels, and, to this end, they require proper information and data management. In the literature, besides the crucial role played by information and data, there is evidence of existing gaps, especially related to information management and integration, and transformation of data into useful information. Thus, a conceptual framework is proposed to guide the definition of a data model to fulfil the previously identified gap. Generally, the framework aims at contributing to the improvement of the integration of information along the AM decision-making process. Specifically, it is intended to be aligned with the AM theory and, in particular, its fundamentals defined in the scientific literature and the ISO 5500x body of standards. Overall, thanks to the improvement of the information management and integration along with the AM decision-making, the expectation is to be capable of achieving more value-oriented decisions for the asset lifecycle.

**Keywords:** Data management · Information management · Asset Management · Decision framework · Manufacturing

## 1 Introduction

The deployment of the disruptive technologies developed and used during the Industry 4.0 era is changing the way organisations are looking to their assets. The black box has been opened through the extensive installation of sensors to gather raw data. Therefore, databases are created for the collection of data from different sources to realise centralised data storages, even unstructured (also called data lakes). Moreover, software tools for data analytics aimed at catching information behind the Big Data are growing in number and capabilities [1].

To acquire a leading role in this context, a successful digital transformation of the company is required and, to this end, capabilities are becoming central to manage information and data flows, recognise important data from waste (i.e. concept of Smart


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Data [2]), and analyse data to extract information properly (from “simple” mathematical artefacts to machine learning techniques [3]).

During this digital transformation, the way the assets are managed receives new stimuli to improve their management policy, relying on increased knowledge and information through data collection. However, this technological jump has not been painless, and sometimes, results are not guaranteed.

In Sect. 2, following an analysis of the most relevant works in this field performed, the main gaps encountered in the scientific literature are listed, with a special focus on physical assets within manufacturing systems. Then, in Sect. 3, a summary of the AM fundamentals is provided, before introducing the proposed conceptual framework, aimed at guiding data modelling to support AM decision-making. Finally, some concluding remarks and future researches are stated in Sect. 4.

## 2 Literature Review on Information and Data Management

The AM development, featuring an integrated approach along the asset lifecycle, is inherently geared towards sharing information and data between different databases, systems, and organisational functions, finally asking for an asset-centred orientation that relies on an effective asset data management [4]. A lot of work has been done so far in this direction, not only in AM [5] but also in maintenance [6], considered its natural precursor. However, two main extant gaps are recognised in the scientific literature when dealing with information and data for AM in manufacturing [7]:

- **Information management and integration:** consisting of the correct management and suitable integration of information in different asset control levels and between systems to support asset-related decisions [4, 8, 9];
- **Data to information transformation:** consisting of the suitable exploitation of the data to derive information (and then knowledge) from the system [10–12].

Overall, the information and data management results to be critical for a suitable AM system in manufacturing, especially when dealing with information integration. Different approaches are proposed to improve its body of knowledge while complying with AM fundamentals.

Among them, it is worth to notice the connection between AM and BIM (Building Information Modelling), which brought to the publication of the ISO 19650 (substituting the PAS 1192). Aligned with BIM, the asset information exchange is analysed in the ISO 15926, which took advantage from researches in the field of product data [13]; despite the focus on process plants, it is adaptable to manufacturing [5]. Also, maintenance has taken the endeavour to face information and data within the wider scope of AM [14]: meaningful examples may derive from what developed in data management [15], or E-maintenance [16, 17]. In this very field, an interesting framework to guide information and data management has been developed in [18] but enclosed within the scope of maintenance without looking at the AM theory, which is the aim of this work.

As demonstrated by the literature, most of the data models adherent in terms of scope to AM derive from the maintenance field. Those data models help in structuring the maintenance decision-making process, dealing with alert generation for abnormal conditions of the assets, maintenance strategy definition for the assets, including CBM (condition-based maintenance) programs. Nevertheless, a first attempt to move towards AM decision-making process is recognised in [19], which means enlarging the scope of decision-making along the asset lifecycle.

Moreover, data models based on object-oriented modelling and, as the next step, ontology, have been proven to be suitable to support problems related to information and data management, especially their integration along the lifecycle [20, 21].

This paper aims at contributing to this promising direction. To this end, as a first methodological step (see [22] for ontology development methodology), a conceptual framework to support data model development for AM decision-making is proposed in Sect. 3, after a brief overview on AM fundamentals defined in the literature.

## 3 Proposed Conceptual Framework

The proposed conceptual framework starts from the work done in [18], and it paves the way to widen the scope towards AM. This goal is reached by firstly analysing which AM fundamentals must be considered to build decision-making coherent with AM theory. These fundamentals are summarised in a recent work published in 2018 [23]:

1. Asset lifecycle stages (BoL - Beginning of Life, MoL - Middle of Life, and EoL - End of Life);
2. Asset control levels (strategic, tactical, operational);
3. AM principles (Lifecycle, System, Risk, Value orientation).

The underpinning goal of the conceptual framework is to enlarge the scope of the decision-making process (including decisions related to different areas such as capital investment, operations & maintenance, shutdown and outage, and others [24]): the decomposition into blocks of the proposed framework helps to reach this purpose.

The framework (in Fig. 1) has the aim of being a conceptual reference for the development of data models for the description of the AM decision-making processes.

On one side, the AM fundamentals are mapped considering the block in which they first appear (other blocks "receive" fundamentals due to cascade effect as well as information and data). In so doing, the conceptual framework aims at integrating these fundamental in the overall decision-making process, which starts from the asset (Physical description block) and ends up with the final decision (AM decision-making block).

On the other side, it promotes information integration, which happens at the block named Value-driven system analysis. This block is responsible for carrying out the analysis that supports the decision-making: information and data coming from different sources must be considered and integrated. Thus, the proposed conceptual framework wants to foster the need for a structured way to integrate information to better support the AM decision-making process.

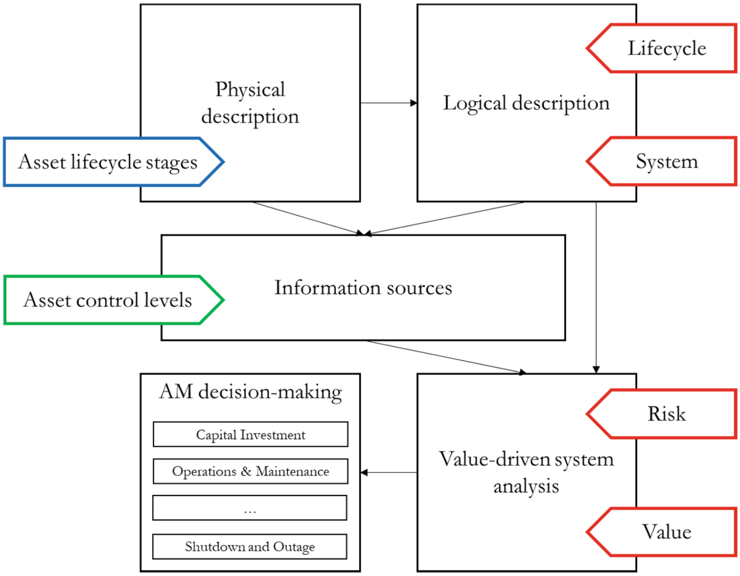


**Fig. 1.** Conceptual framework with a mapping of AM fundamentals.

### 3.1 Physical Description

The Physical description block is devoted to the physical representation of the asset. The asset model may derive from the conceptualisation/idealisation activity in BoL (whose information and data are gathered in CAx systems), or from an installed asset in MoL/EoL (whose information and data are gathered in systems like CMMS, Computerised Maintenance Management Systems, besides CAx systems). Thus, in this block, the asset lifecycle stages are introduced since the asset is currently in BoL/MoL/EoL stage; this differs from the Lifecycle orientation, as explained after.

### 3.2 Logical Description

The Logical description block aims at describing the function the asset must undertake; for example, in the maintenance context, this block describes how the asset works and how it fails. For this reason, this block enables modelling interdependencies and relationships between assets in the system (e.g. to logically represent the series or parallel configuration of two machines); so, it introduces the System orientation as AM principle. Moreover, the Lifecycle orientation is inserted here since *"AM process should incorporate long-term objectives and performances to drive decision-making"* [23], so the logical description enables the understanding of consequences of a decision. There is a difference between the asset lifecycle stages and the Lifecycle orientation: the former one only represents the stage in which the asset is (BoL, MoL, EoL), while the Lifecycle orientation represents how the decision is taken (driven by long-term objectives and asset, asset system, performance).

## 3.3 Information Sources

The Information sources block represents the layer between the physical and logical description of the system, and the value-driven system analysis and AM decision-making. It is intended to represent the IT ecosystem or landscape (also called industrial software stack [25]), collecting the software tools adopted to support company decision-making processes, and AM among them.

The allocation of each software tool to a specific asset control level is a prerequisite to implementing an optimal AM system (Fig. 2).

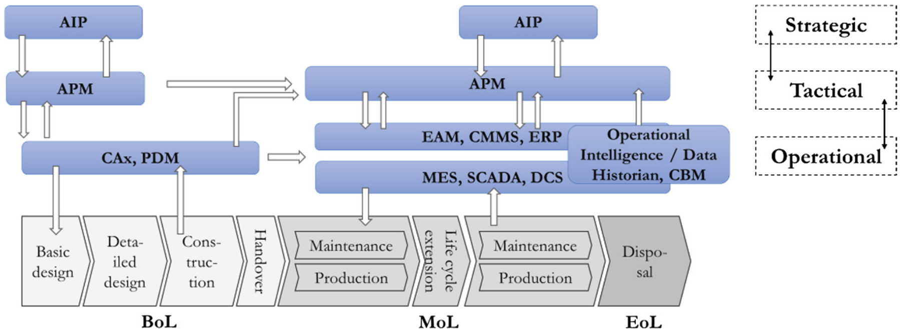


**Fig. 2.** IT ecosystem for AM decision-making (adapted by [26]).

Each software tool is so able to: (i) provide/gather information and data to/from software tools belonging to other asset control levels or within the same one; (ii) provide suitable information for the asset control level in which it is used to support the related decisions (e.g. asset health index for the development of strategies of asset replacement and maintenance, or Return On Investment for capital investment). This IT ecosystem has already been proven to be fundamental to implement a suitable strategy to manage the assets at best [27], especially to guide the analysis, as described in Subsect. 3.4.

## 3.4 Value-Driven System Analysis

The Value-driven system analysis block aims at supporting the AM decision-making process by developing suitable PIs (Performance Indicators), which must be adequate and aligned for the use in the final decision to be taken. The development of such PIs happens through an analysis that must comply with AM fundamentals previously cited, and it must also consider the three main drivers guiding the decision-making process: cost, performance and risk (aligned with [28]). The definition of appropriate value elements is a core activity at this step of the decision-making process because it allows performing analyses aligned with corporate objectives [29].

The Value-driven system analysis block is the one that collects inputs from all the other blocks and in which the information integration happens. As an example, refer to [18], where this block corresponds to the symptom analysis. Here, the health status of the machine is used to finally understand and analyse the symptom of a failure mode that is in evolution. The symptom analysis performed required the integration of information coming from information sources (monitoring variables), but also from the logical description (information about the failure mode, which could have a symptom). The integration of this information supports the symptom analysis that allows making a final maintenance decision.

Summarising, this block is the one responsible for information integration since all the analyses performed to sustain a final decision must rely not on one single information source, but different ones. Better structuring the connection between information sources and different analysis is valuable for an effective AM decision-making process.

### 3.5 AM Decision-Making

The enlargement of the scope towards the AM decision-making is represented by the last block that includes different asset-related decisions. The set of possible decisions to be considered within the scope of AM is large, but generally some classes of decisions could be recognised, from an asset user perspective [24, 30–32]: capital investment (evaluation of alternatives/suppliers, maintenance service contract selection, budget planning and cost control) in BoL; operations and maintenance (maintenance planning, operations planning, asset utilisation strategies), reconfiguration decision, and shutdown/turnaround/outage in MoL; reuse or rehabilitation strategy in EoL.

A suitable decision-making process enables these decisions, and they must rely on PIs developed in the previous block, i.e. Value-driven system analysis.

The correct integration of information in the previous analysis has a huge impact on the final asset-related decision.

## 4 Conclusions

The proposed conceptual framework claims to be a conceptual reference to develop data models, whose goals should be the integration of information to enable analysis on which decisions are taken. The framework serves as a guideline to enable a structured data modelling that could improve the AM decision-making process, including all the fundamentals. The framework is built looking at possible approaches to AM, in which maintenance plays a central role. Thus, starting from a framework developed for CBM programs, the proposed conceptual framework is built, whose decomposition into blocks helps in fulfilling and integrating AM fundamentals (asset control levels, asset lifecycle stages and AM principles), involving different decisions. Better structuring the relationship between different information sources and different analysis sustaining the decision is valuable to build a robust AM decision-making process. In so doing, thanks to the improvement of the information management and integration along with the AM decision-making, the expectation is to be capable of achieving more value-oriented decisions for the asset lifecycle.

Future research will be focused on the development of data models for the different decisions in AM to support all the decisions set, rather than only maintenance, with the final aim of creating a comprehensive data model that may support an ontology study.

As a side effect, it will also enable to formalise AM decision-making process, currently not yet fully described by extant reference or standard models.

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# Hybrid Approach Using Ontology-Supported Case-Based Reasoning and Machine Learning for Defect Rate Prediction

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**Abstract.** Manufacturers always strive to eliminate defects using different quality assurance tools and methods but some defect is often unavoidable. To compensate for defective products, surplus batches should be produced. However, surplus production is costly and it results in waste. In this paper, we propose an approach to predict defect rate and to set an appropriate amount of surplus production to replace defective products. This will result in reduced overproduction and underproduction costs. In the proposed work, the production order is represented ontologically. A formal ontology enables building clusters of similar production orders. A defect prediction model is developed for each cluster using Mixture Density Networks when a new order is received, the most similar production order, and its related cluster is retrieved. The prediction model of the retrieved cluster is then applied to the new production order. Accordingly, the optimal production amount is calculated based on defect rate, the overproduction cost and the underproduction cost. The proposed approach was validated based on a use case from the cosmetic packaging industry.

**Keywords:** Data analytics · Yield · Defect rate · Machine learning · Ontology

## 1 Introduction

Overproduction is one of the major sources of waste in manufacturing. Overproduction is excessive production of parts and products beyond the actual need. In lean literature, overproduction is known as the first type of waste, because it induces another major waste, which is inventory. One of the most common causes of overproduction is the expectation of defects. Typically, underproduction cost is much larger than overproduction cost, so to compensate for the number of defective items, manufacturers tend to produce more than the needed amount of a product. For example, if the order is for 95 units, and the process has a 5% defect rate, then the manufacturer would produce at least 100 units to cover the expected defect rate. The surplus production might increase even more: (1) if the manufacturing process has not yet reached a stable state, (2) production proceeds in small quantity batch production (3) failure to produce the required amount causes stoppage of subsequent processes.


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Kanban is a type of pull production system which is used to prevent overproduction in lean manufacturing [1]. In a Kanban system, a work can be started only when production approval card, called Kanban, is available [2]. However, the Kanban system assumes stable and repetitive production. Therefore, it is not suitable for fluctuating demand and product mix.

Cosmetic packaging is an example industry with fluctuating demand and product mix. For this reason, overproduction occurs frequently in the cosmetic packaging industry. Customer needs change rapidly, and therefore, product life continues to shrink. Frequent introduction of new products hinders stabilization of the manufacturing process, which often calls for production of small batches. Another complicating factor is the number of steps involved cosmetic packaging. To improve the aesthetics of the products, several processes are required. Therefore, overproduction is often propagated to several downstream processes. Therefore, more intelligent and data-driven methods are required to predict the defect rate accurately and, consequently, avoid overproduction.

The objective of this paper is to propose a systematic approach for defect rate prediction using ontology-supported case-based reasoning and machine learning (ML) techniques in cosmetic packaging industry. This paper is organized as follows. Section 2 provides a brief review of the related works. Section 3 introduces the concept of an ontology-supported case-based reasoning approach for defect rate prediction in cosmetic manufacturing enterprise. Finally, Sect. 4 provides the concluding remarks and identifies the future work.

## 2 Related Work

In this section, we provide a review of the proposed methods for predicting yield and number of defects in the manufacturing domain.

### 2.1 Yield Prediction

Yield refers to the percentage of non-defective product; i.e., the complementary measurement of defect rate. Yield prediction is widely used in semiconductor manufacturing to improve yield by providing early alert of nonconforming wafers, and thereby decreasing monetary losses. Semiconductor wafer yield is affected many factors, so traditional statistical analysis models do not work well to predict it [3].

Neural networks (NNs) have been used to predict yield. Tong et al. [4] proposed an NN-based approach, and also used fuzzy adaptive resonance theory to groups patterns into the appropriate number of clusters. Tong and Chao [5] used a general regression neural network (GRNN) because it can process both continuous and categorized output, and can be used if the linearity assumption is violated. Chen and Lin [6] proposed a fuzzy NN system, but it does not consider electrical parameters even though it is critical Wu and Zhang [7] considered electrical parameters along with key attributed parameters and physical parameters; the authors conducted statistical correlation analysis to identify electrical parameters. Lee and Ha [8] integrated a back-propagation network with case-based reasoning. The approach consists of four phases: learning relations between case variables and yield, weighting of features, extracting similar cases, and calculating the weighted averages of extracted yield. The paper was the first attempt to hybridize machine learning with case-based reasoning for yield prediction. Pak et al. [9] used a support-vector machine to predict yield; they also used an under-sampling method to eliminate imbalance from the data.

### 2.2 Defect Rate Prediction in Assembly Process

Various approaches of prediction have been proposed based on design characteristics of products, and on ergonomics. A Design for Assembly (DFA) technique allows a manufacturer to examine design alternatives in early design stage, to reduce assembly cost [10]. It is also used to evaluate the likelihood of mistake, and to identify potential failure [11]. The Hinckley model [12] is based on the idea that defect rate is positively correlated with assembly time and negatively correlated with the number of assembly operations. This model provides insight, but the real word is not that simple. Shibata [13] suggested a model that considers process and design factors, and Antani [14] considered human factors by developing a regression-based defect rate prediction model in automated and semi-automated assembly; this model was then validated in a manual automobile-assembly process [15].

Numerous prediction models that have been developed in Sect. 2.1 are highly suitable for implementation in large scale manufacturing. The most of small and medium engineering enterprises (SMEs) cannot afford the cost of introducing equipment with real-time sensors or installing sensors on every existing equipment. Therefore, it is hard to be implemented in small and medium engineering enterprises (SMEs). On the other hand, the prediction approaches in Sect. 2.2 is based on characteristics of product and process, do not require additional investment on equipment. Hence the approaches in Sect. 2.2 are relatively easy to apply. However, previous approaches cannot consider the cost of error, only focused on accuracy. To overcome these issues, this paper tried to consider expected cost based on the probability of defect rate is used to consider the expected cost.

## 3 The Proposed Framework for Defect Rate Prediction

The proposed framework is composed of 3 main phases as shown in Fig. 1. The first phase is the off-line phase of the framework when the clusters of existing work orders are created and their corresponding prediction model is developed. The second phase (the on-line phase) is related to predicting defect rate for new work orders. The third phase is a continuous phase where the actual and predicted defect rates are compared and the prediction models are further tuned and updated.

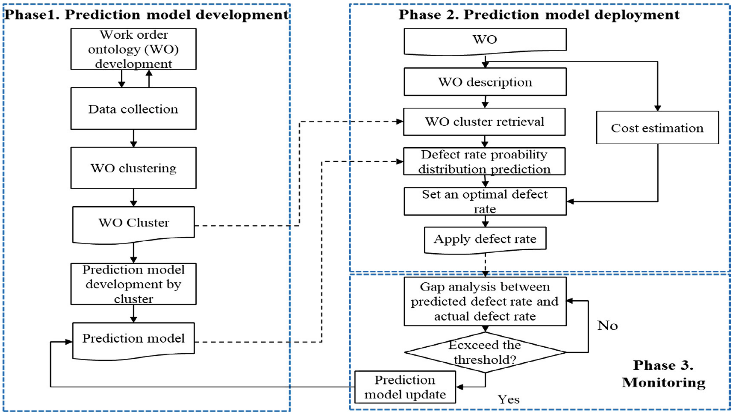


**Fig. 1.** The framework for defect rate prediction

## 3.1 Ontology Development

One innovative aspect of the proposed frame work is to use an ontological approach for representing the data related to previous production work orders. Ontology-based approach can be used to determine the similarity between production orders. When data is annotated by ontological entities, one can easily and accurately retrieve the most similar production orders in from the repository of the existing orders and reused their related defect rate prediction model. Also, ontology helps the users understand, communicate, and manage information effectively by standardizing the terminology used for production order description. Some examples of the key notions in production orders include *product*, *customer*, *production month*, *manufacturing process*, *production team*, and *production quantity*. Figure 2 shows the major classes and the relationship between the classes for the Work Order Ontology (WOO).

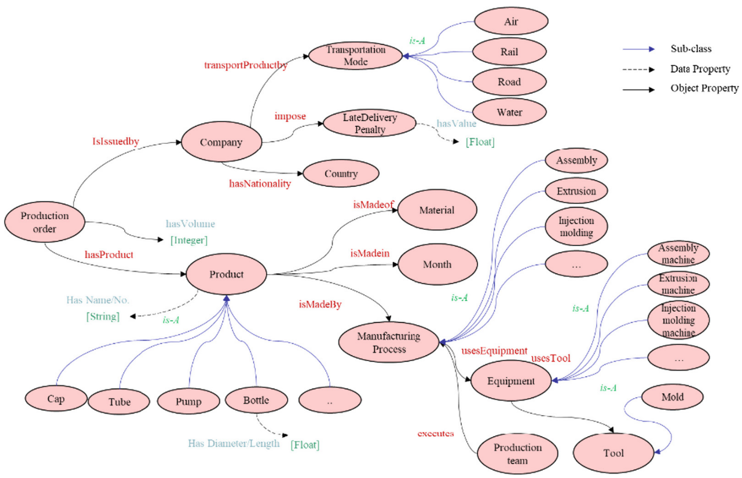


**Fig. 2.** Classes and relationships in the ontology

The workorder ontology is publicly available at https://github.com/corori/Ontology1.

### 3.2 Phase 1: Prediction Model Deployment

In this phase, the production orders, that are represented ontologically, are clustered based on their similarities. Next, historical data collection is conducted to be used in development of the prediction model for each cluster of production order. Sensitivity analysis and data wrangling are used to verify the relationship between various properties of the *production order* class and defect rate. For example, for some types of production order, the defect rate may decrease as production volume increases (Fig. 3).

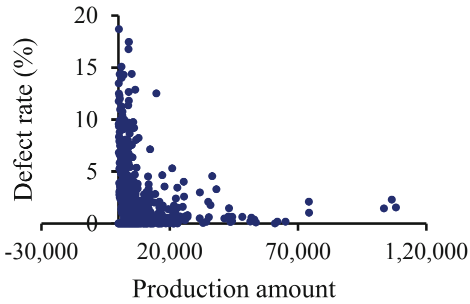


**Fig. 3.** Defect rate by production amount in coating process (bottle category)

The prediction models are developed for clusters of similar production order because similar production order shows similar trend of defect rate. For example, the defect rate trend of tube which is made by extrusion is totally different with bottle set which is made by assembly process. In the clustering step, the concepts are treated as features and properties are treated as feature value. Also, we should consider that even though the manufacturer produces the product with same production order properties, the defect rate is not a single point, but has a distribution in some cases (Fig. 4). For this type of problem, a Mixture Density Networks (MDN) is a suitable prediction algorithm. It can model general conditional probability densities and outputs the distribution [16]. Also, the distribution which is output of Mixture Density Network, can be used when the expected cost of defect rate is calculated.

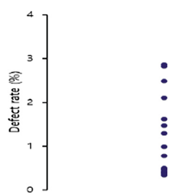


**Fig. 4.** Defect rate of specific bottle product which has same values of properties

### 3.3 Phase 2: Prediction Model Deployment

In this phase, the developed prediction model is deployed for use. When a new production order is received, the feature value of the production order is measured in WO description step. Then the most-similar production order is identified by calculating similarity between the new production order and all existing production orders. The similarity of the new production order to the stored production orders is determined by calculating the similarity between production order features. Three major methods can be used to determine the similarity between production orders: the edge-based method, the information-content-based method, and the feature-based method [17]. In the edge-based method, the path length between terms in an *is-a* taxonomy represents the similarity [18]. In the information-content-based method, the similarity of two production orders depends on the degree of informativeness of the superclass that includes both production orders [19]. The similarity is defined as

$$\text{Sim }(\mathrm{c}_1, \mathrm{c}_2) = \max_{c \in S(c_1 c_2)} [-\log p(c)], \tag{1}$$

where, $\mathrm{c}_1, \mathrm{c}_2$ are production orders, and $S(c_1 c_2)$ is the set of concepts that subsumes both production orders. The negative log likelihood is the *information content* of a production order $c$ according to information theory [20]. In the feature-based method, the similarity between production orders $\mathrm{C}_1$ and $\mathrm{C}_2$ is a function of their common and distinctive features [21]:

$$\text{Sim }(\mathrm{c}_1, \mathrm{c}_2) = \frac{n_{C_1 \cap C_2}}{n_{C_1 \cap C_2} + \mu n_{C_1 - C_2} + v n_{C_2 - C_1}}, \tag{2}$$

where $\mu, v \in \mathbb{R}$ are constants that are weighting factors, $n_{C_1 \cap C_2}$ represents the number of common features, and $n_{C_1 - C_2}$ and $n_{C_2 - C_1}$ are the numbers of distinctive features of $\mathrm{C}_1$ and $\mathrm{C}_2$ respectively.

Each of these methods has its strengths and weaknesses. The first and second similarity measure methods need a taxonomy [17]. In the cosmetic industry, such a taxonomy is not available for production order, so the third method is preferred. The most-similar production order can be retrieved by using the third method. Then the prediction model of the cluster which include the most similar production order is applied. The last step in phase 2 is to set an optimal defect rate that considers the cost. The expected cost of under production and overproduction is calculated as

$$\sum\nolimits_i p(Defect\ rate = i | z_i, x) \times unit\ \mathrm{cost}_{underproduction}(order - z_i), \tag{3}$$

$$\sum\nolimits_i p(Defect\ rate = i | z_i, x) \times unit\ \mathrm{cost}_{overproduction}(order - z_i), \tag{4}$$

where $x$ is the set features, $z_{\mathrm{i}}$ is the production amount when defect rate $i$ is applied. Underproduction cost includes a delivery-delay penalty, an additional transfer fee to meet the delivery deadline, the cost of additional production, and the cost of adjusting production planning. Overproduction cost includes additional production cost and inventory cost. Unit costs vary; examples of units are minimum lot size, production order, and date. The expected cost of each defect rate is the sum of the underproduction cost, overproduction cost and production cost. The optimal defect rate is the one that has the lowest expected cost. When this rate is determined, the production amount can be determined.

### 3.4 Phase3: Monitoring

Deployment is not the end of the phase. In many cases, the users of the model will the be manufacturing operators, and not the data analyst. For effective and efficient use of the model, it should be updated at appropriate times. Hence, a threshold is set such that if the difference between predicted defect rate and actual defect rate exceeds some threshold, the model should be re-trained.

## 4 Conclusion and Future Work

This paper proposes an approach to predict defect rate to minimize costs of underproduction and overproduction. Defects are unavoidable, so to compensate for expected defects, a manufacturer tends to produce more products than the quantity ordered. Overproduction wastes production resources and increases inventory cost. Underproduction causes delivery delay, and adds the cost of adjusting production planning; underproduction can even cause overproduction, because manufacturers must re-produce a minimum amount of production. We develop a method to predict defect rate by combining an ontology-supporting case-based reasoning approach with a machine-learning approach. Existing methods to predict defect rates have not considered the costs of underproduction and overproduction. The proposed approach has two main advantages: (1) it combines ontology-supporting case-based reasoning and machine learning to improve the accuracy of the prediction, and (2) it considers probability to minimize costs caused by both overproduction and underproduction. Although this approach is still conceptual at present, and must be developed and verified, it is an important step towards efficient production. Further study will include experiment, validation and verification of proposed approach.

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# Semantic Model-Driven PLM Data Interoperability: An Application for Aircraft Ground Functional Testing with Eco-Design Criteria

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**Abstract.** The latest developments in Model-Based Systems Engineering (MBSE) and Product Life-Cycle Management (PLM) are playing a role in the evolution of the aeronautical industry. Despite the reluctance of this domain to accept the introduction of technology leaps in the production process - mostly due to safety reasons - aircraft manufacturers are slowly moving to a new digital factory concept. The deployment of a PLM Tool for Aircraft Ground Functional testing with Eco-design criteria can be leveraged to improve both sustainability of the assembly line and efficiency of the Ground System Tests process end to end, however, heterogeneous data interoperability represents one of the major challenges in this framework. The ontology-based solution proposed in this work addresses this challenge, thus, shows how semantics can be exploited to streamline the data pipeline throughout a PLM digital platform.

**Keywords:** PLM · MSBE · Ontology · LCA · Eco-sustainability

## 1 Introduction

The future of the aeronautical industry is tied inevitably to the development of enabling technologies that make the advent of industry digitization possible. Technology advances like those on Model-Based Systems Engineering (MBSE) and Product Life-Cycle Management (PLM) tools and procedures are becoming more and more important in the industry and play a key role in the transformation on this sector toward a more efficient and sustainable activity [1]. Aircraft manufacturing has been traditionally reluctant to the introduction of technology leaps in the production process due to the complexity and the strict safety assurance requirements involving the aeronautical sector but also a tremendous bias against taking any sort of risks, and any innovation is a risk to some extent. Nevertheless, aircraft manufacturers are slowly moving to a new factory concept where data is the cornerstone and most precious asset of the company.


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In this transformation, many processes in the Ground System Tests (GST) station of the aircraft's assembly line present a relatively low grade of automatization, with a lot of room for improvement when it comes to digitization and PLM integration. The introduction of some of the aforementioned technologies in the modern assembly line can definitely impact the environmental sustainability of the whole process, however, data interoperability represents one of the major challenges.

## 2 Proposed Approach

The development of an ontological model to foster system semantic data interoperability within PLM framework for Aircraft Ground Functional testing with Eco-design criteria starts with the analysis of the functional requirements. To this aim, a IDEF0-based mapping of activities and information flows is carried out as a preliminary step.

IDEF0 is a method designed to model the decisions, actions, and activities of an organization or system. As a communication tool, IDEF0 enhances domain expert involvement and consensus decision-making through simplified graphical devices [2]. As an analysis tool, IDEF0 assists the modeler in identifying what functions are performed, what is needed to perform those functions, what the current system does right, and what the current system does wrong.

Despite the clear definition of system functions and requirements, data interoperability remains one of the big challenges when reengineering information systems. Data integration is a difficult task since data source can be heterogeneous in syntax, schema, or semantics. In order to achieve semantic interoperability through heterogeneous information systems, the meaning of the integrated data has to be understood – and shared – among those systems.

Data interexchange between the current software architecture is achieved through XSL transformations, however, as the XML transformation deals with the information interoperability at the syntactic level, ontological models can be leveraged to achieve semantic interoperability, therefore, empowering the current framework with smart data management capabilities. In particular, we can accomplish semantics-based data routing through a logic coded by SRWL rules, which analyses the information flow exchange requirements at different granularity levels and enriches each piece of information with shared, formal and reusable semantics (Fig. 1).

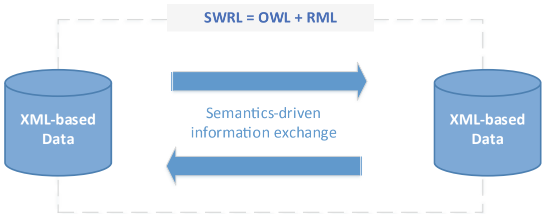


**Fig. 1.** Semantic interoperability through SWRL-based rules

The proposed approach is founded on recent outbreaks for Semantic Modelling, and Model-Driven Interoperability. More details about those two enabling technologies are presented in the next section.

## 2.1 Semantic Modelling

In the past two decades, the use of semantic structures, such as ontology models, aiming to enhance information systems has been proven to be very effective in the industrial domain. Ontology model development has already become an engineering discipline, Ontology Engineering, which refers to *"The set of activities that concern the ontology development process and the ontology life cycle, the methods and methodologies for building ontologies, and the tool suites and languages that support them*" [3]. The employment of ontology engineering tools in the area of industrial data and information modelling has opened the path for exploiting ontologies towards providing formal definitions of the elements and their types, properties and interrelationships. Therefore, the development an ontology-based solution for the management of domain information aims at fostering semantic interoperability between system engineering services, thus, encapsulating shop floor informational structure focusing mainly on factory sustainability, product design and planning, and interoperability.

The development of an ontology aims at raising the system inter-communications at a higher level of abstraction, thus, providing - on the one hand - a way to achieve so-called semantic interoperability capabilities while - on the other hand – fostering shared understanding and reuse of the model itself.

The DILECO OWL ontology is a Basic Formal Ontology (BFO) compliant ontology that partially reuses three more ontological models, namely: the Relation Ontology (RO), the Information Artifact Ontology (IAO), Ontology for Biomedical Investigations (OBI).

BFO serve as the Upper Ontology from which the domain-specific ontological model is developed (and aligned with). The Information Artifact Ontology (IAO) is an ontology of information entities (artifacts). An information artifact is, loosely, a dependent continuant or its bearer that is created as the result of one or more intentional processes. For examples, the English language, the contents of this document or a printout of it, and the temperature measurements from a weather balloon. The Ontology for Biomedical Investigations (OBI) is an ontology that provides terms with precisely defined meanings to describe all aspects of how investigations in the biological and medical domains are conducted. The OBO Relations Ontology (RO) is a collection of OWL relations (object properties) intended for use across a wide variety of biological ontologies, however, it has been proven to be applicable to other domains (Fig. 2).

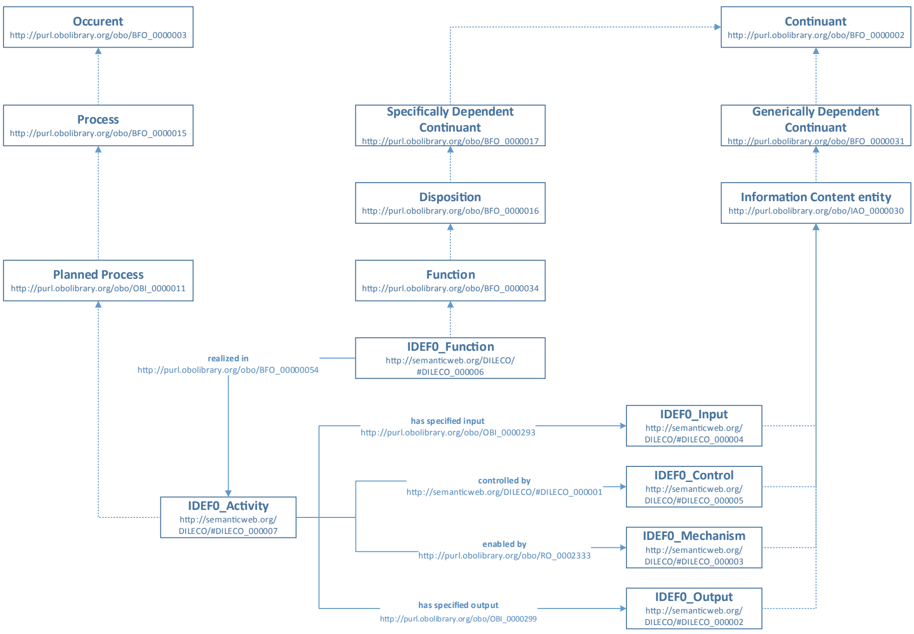


**Fig. 2.** DILECO ontology: upper tier

## 2.2 Model Driven Interoperability

Broadly speaking, the term "interoperability" should be perceived as the ability of separate systems – or artefacts – to work together. In spite of the fact that there has dependably been the need to accomplish interoperability between heterogeneous systems and notations, the obstacles encountered in overcoming their differences, the absence of consensus on the common standards to use and the deficiency of legitimate mechanisms and tools, have seriously hampered this task. In the last decade, the concept of Model Driven Interoperability (MDI) is increasingly gaining interest. MDI is a methodological framework, which aims to provide a conceptual support to achieve interoperable using ontologies and semantic annotations in enterprises. The requirements for the interoperability of semantics and knowledge have become increasingly important in Product Lifecycle Management (PLM), in the drive towards knowledge-driven decision support [4, 5] and knowledge-enabled ICT solution development.

According to state-of-the-art definitions, Model Driven Interoperability (MDI) approach is basically threefold:

- Model Driven Engineering (MDE) [6, 7] approach promotes the systematic use of models as primary engineering artefacts throughout the engineering lifecycle combined with both Domain-Specific Modelling Languages and transformation engines and generators.
- Interoperability [8] should be achieved at different levels, i.e. Business, Knowledge, Application and Data. The use of ontologies paves the way towards a formal and explicit model-driven transformation from enterprise level to code level [9].

## 3 Application Case

The present work introduces a number of innovations in the assembly line of an aircraft that makes a qualitative difference with respect to the current processes and methodologies for assembly and ground test processes. The solution proposed is a step forward in the degree of digitization of the current information steams, with a room for improvements like the Functional Testing.

Today, most of the operations in the assembly line involve the use of paper, like work orders, assembly instructions, diagrams, circuitry schematics, etc. In the case of troubleshooting tasks or in cases where expert assistance is required, people must be physically at the workplace to collaborate efficiently.

In this context, a core activity is represented by the *Semantic enhancement for integrating Engineering Design and LCA applications*, which aims at empowering the current framework with digital capabilities for cross-systems (Lifecycle Cost Analysis and Engineering Design) interoperability

The IDEF0 functional model regarding the aforementioned Activity (A22 - *Semantic enhancement for integrating Engineering Design and LCA applications*) defines the Inputs, Output, Controls and Mechanisms (also known as ICOMs) required to enable information exchange between the aforementioned applications, and therefore, to accomplish the computation of EcoEfficiency and Efficiency impact. The ontology in Fig. 3 illustrates the implementation of the DILECO OWL ontology on Protégé, which is a well-known free, open-source ontology editor and framework for building intelligent systems.

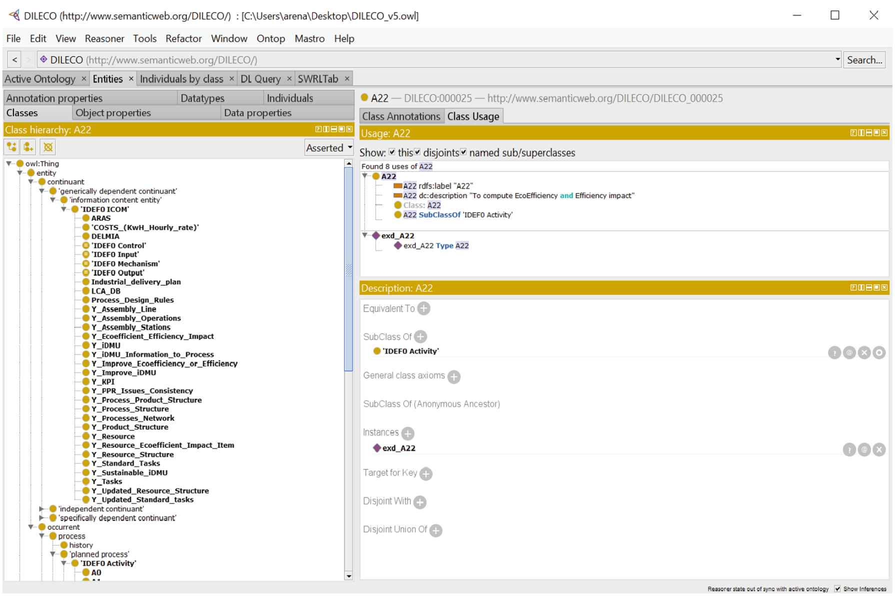


Fig. 3. Protégé development environment: An excerpt of the DILECO Ontology

Each of the ICOMs mentioned above characterizes an OWL class, which inheres the ICOM's name as its label (http://www.w3.org/2000/01/rdf-schema#label). Much the same applies to the relations among the ICOM's elements that characterize the interlinks between the activities and the inputs, outputs, mechanism, and controls. As the backbone of the semantic model is deployed – which is currently consisting of DILECO OWL Classes, Object Properties, and Data Properties – the logic through which we characterize the information flow is coded according to the SWRL language.

As shown in Fig. 4, the information inferred through the HermiT OWL reasoner is highlighted in yellow and derives from the analysis that such a reasoner carries out based on the SWRL rules (formal axioms). HermiT, indeed, is reasoner for ontologies written using the Web Ontology Language (OWL). Given an OWL file, HermiT can determine whether or not the ontology is consistent, identify subsumption relationships between classes, and much more.

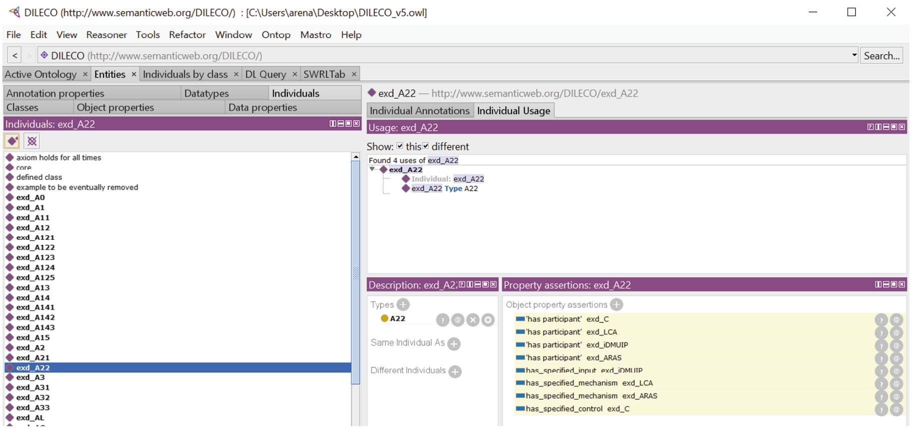


**Fig. 4.** Protégé: Inferred piece of information with HermiT reasoner

The logic defined within the DILECO OWL Ontology allows the system to infer that the Activity A22 *has a specific input* [DILECO:000188] that is the *iDMU Information to Process* [DILECO:000055], which *has an XML Data Structure* [DILECO:000810] labelled *iDMU Information to Process XMLDataStructure* [DILECO:000601], which is equivalent (OWL classes equivalency & XML attributes/OWL data properties equivalency) to the above-mentioned *Build Process*, whereas the prefix "DILECO" stands for:

*http://www.semanticweb.org/DILECO/DILECO_*

As an example, the last equivalence is achieved through the following SWRL rule:

*dileco:DILECO_000055(?a) ^ dileco:DILECO_000601(?b) ->*
*dileco:DILECO_000810(?a, ?b)*

As a result, the PLM digital platform can leverage on the proposed logic and the semantically-enriched information repositories to streamline the data pipeline.

## 4 Conclusions

This work has been supported by DILECO, a project funded from the Clean Sky 2 Joint Undertaking under the EU Horizon 2020 Research and Innovation programme (Grant Agreement No. 785367). DILECO project aims to develop and deploy PLM Tools for aircraft Ground Functional testing with Eco-design criteria. This technology will be a leap forward in Functional Testing and other tasks in the final assembly line with regard to lead time, recurring costs and also flexibility and transparency, contributing to the expected impacts set out in the work plan, under the relevant topic. The Future Aircraft Factory concept involves the integration among others of connected factory, intelligent automation, ergonomic work environment, optimum human-machine interfaces, zero defects and flexible manufacturing lines. The vision here presented is a more connected assembly line, introducing the digitization of ground-testing life cycle with Eco-design criteria.

The work presented documents the analysis of the domain-specific tools used to cope with the design of a so-called Sustainable Manufacturing Model and the investigation of the related requirements with the ultimate mission to develop an ontological model (called DILECO OWL ontology) that empowers the DILECO ecosystem with semantic interoperability capabilities. Such an analysis bounds per se the scope and granularity of the ontology, which has been therefore developed and tested with the use of state of the art tools for ontology design and development, such as Protégé editor, HermiT (java-based) reasoner, .NET-based script for data RDFization.

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# A Method for Converting Current Data to RDF in the Era of Industry 4.0

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**Abstract.** In the past two decades, the use of ontologies has been proven to be an effective tool for enriching existing information systems in the digital data modelling domain and exploiting those assets for semantic interoperability. With the rise of Industry 4.0, the data produced on assembly lines within factories is becoming particularly interesting to leverage precious information. However, adding semantics to data that already exists remains a challenging process. Most manufacturing assembly lines predate the outbreak of graph data, or have adopted other data format standards, and the data they produce is therefore difficult to automatically map to RDF. This has been a topic of research an ongoing technical issue for almost a decade, and if certain mapping approaches and mapping languages have been developed, they are difficult to use for an automatic, large-scale data conversion and are not standardized. In this research, a technical approach for converting existing data to semantics has been developed. This paper presents an overview of this approach, as well as two concrete tools that we have built based on it. The results of these tools are discussed as well as recommendations for future research.

**Keywords:** Ontology · Zero-defect manufacturing · Data integration · RDF · Semantics · JSON

## 1 Introduction

What might make Industry 4.0 a unique industrial revolution, is its capacity to rely on already existing infrastructures, just by interconnecting technologies. In that regard, the data produced by machines on assembly lines make for a particularly interesting case to investigate. Assembly lines in factories currently produce very large amounts of data, most of which is under-exploited, often simply stored to never be used again. At the same time, factories want to insure better interoperability between their services and tools. To do so, a more and more widespread approach is to add meaning to the data [1] through the use of semantics, or to be more precise, through the use of ontologies, allowing for data to be machine-understandable, and understood the same way across diverse systems of information [2–4]. The purpose of ontologies is to help mark-up data with meaningful metadata that will make it more easily interpretable. To formalize this new manner to structure data, a language named RDF (Resource Description


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Framework) [5] has been developed, which expresses data in the form of triples subject-predicate-object, and where URIs (Uniform Resource Identifier) symbolize the instances. URIs help identify a specific instance, and link it to its attributes, or to other instances. What RDF allows us to do, is to formalize our data as a graph. This is a very powerful way of storing unstructured data, and quickly retrieve the connections between data, unlike SQL (Structured Query Language) joints that are very difficult to express and expensive.

But this raises one big issue. Graph data is fairly new and has only been widely adopted in certain niches, such as the market of social networks. In the meanwhile, relational data has remained the bread and butter of most data management systems for the past 20 years. To exchange and communicate data between different systems, formats such as JSON (JavaScript Object Notation), which relies on a key-value pair paradigm, have become widely popular. Therefore, the data produced by assembly lines is mostly structured as tables, key-value pairs or trees, and comes in formats such as SQL databases, XML (Extensible Markup Language) files, Excel sheets or JSON streams. Some of these formats are difficult to convert into graph data because of their very structure, such as SQL, and others, like JSON, may only be easy to translate in certain cases, depending on how well the schema of the data matches with the ontology.

Therefore, some pre-processing is required to be able to leverage this data, which involves mapping the existing schema of the data to the ontologies we have designed, and then implement this mapping in a computer program that will achieve an ETL (Extract-Transform-Load) procedure to in order to handle the data accordingly. This raises several questions: how do we map an existing data schema to an ontology, and how do we formalize it? And once we have formalized this mapping, how do we implement it in a tool in order to automatically convert the data?

As we will see in the next section, methodologies to map non-graph data schemas to graph data schemas, and more specifically to RDF, is a very active field of research, and several recommendations, languages and tools have already been created to achieve this mapping. However, no standard has been issued yet, and some of these tools have limitations. This brings us to the second issue, which is the one we would like to address in this paper: How do we then use these methodologies to implement a tool that can automatically convert data? How can we "generalize" this tool so that it can be applied to different data formats, different data schemas, and different ontologies? Such a tool, or at least a general conversion algorithm, would make the life of software developers easier, which is a crucial step for the more widespread adoption of RDF and ontologies.

Therefore, the current research aims to present a general, easy to implement algorithm, that can automatically convert data to RDF without being dependent on the original data schema or the targeted ontology. Section 2 describes the state of the art in data mapping. Section 3 describes the approach that was proposed for this research, and the tools that have been used. Section 4 describes two applications of this approach and Sect. 5 discusses the findings and their implications.

## 2 State of the Art

Methodologies to convert non-graph data to graph data are still an ongoing field of research in the world of linked data and semantics, since the solutions to this issue could significantly increase the adoption of RDF. Mapping SQL data schemas to RDF has been a particular topic of focus, since most databases are relational. Even though the World Wide Web Consortium has issued no standard yet in that regard, it has issued a few recommendations. The most notable one deals with how to directly map SQL to RDF [6]. R2RML, a language for mapping SQL to RDF has also been issued and recommended by the Consortium [7].

Regarding on how to map JSON schemas with RDF, another language, JSON-LD (JavaScript Object Notation for Linked Data), has been created by members of the W3C [8] and has gained quite a lot of attention due to its simplicity of use and its practicality. RML, an extension of R2RML, can also be used to map JSON and other formats to RDF [9]. A language named GRDDL [10] has been developed quite early on during the development of the Semantic Web in order to map XML to RDF, but it is also possible to use it for the mapping of JSON to RDF. A language named XSPARQL has also been developed to query XML and RDF and to transform data from one format to the other [11].

As we can see, there are many methodologies and languages to map existing data schemas of all kinds of formats to ontologies. The questions then arise: how do we provide this mapping to a software tool, and how do we implement the conversion of the data? One way would be to simply use these methodologies as they are, and to explicitly implement the mapping in the code. There are several problems with this approach. First, explicitly hard-coding values in a program is bad practice in the world of software development, because every evolution of the data schemas will have to be implemented in the code as well. Also, the code wouldn't be reusable for different data schemas or different ontologies. Another issue is that in the case of assembly lines, the amounts of data to process and integrate are huge, and so are the ontologies we have to map them to. Explicitly coding the mapping therefore implies that each data will go through one test for each different field of the data schema, which is doable for small mappings, but would be a tedious work and come at a great cost of performance for really big ontologies and data schemas.

What we would like to achieve instead is to come up with a general conversion algorithm, one that would be able to automatically process the data based on a mapping we would have provided it, but that wouldn't need to be aware of the details of the ontology or of the original data schema, so that we would be able to feed it any mapping, or to adapt it to any data format in input. Something lightweight that could be easily implemented in different programming languages, which would have good performances regarding time and memory consumption, and that would be easy to understand and maintain for software developers.

## 3 Proposed Approach

As stated previously, the intent behind this paper is to present a general implementation to automatically convert non-graph data to RDF through a software tool, without having to know the data schema or the ontology in advance, so that it could work with any mapping. We have tried to develop tools based on this implementation to convert data coming from XML files and JSON streams into RDF. Our idea was to develop a technique for mapping that would rely on an approach similar to what is currently done with configuration parameters for software tools. Instead of hard-coding the values of the configuration parameters in the software, they are usually stored in a separate file, under the form of key-value pairs. When the code is running, the value is retrieved through the key called in the code. This allows for an easy way to modify the parameters of a desktop application or a web service (e.g. the access path to a database) when necessary, without going through the expensive path of a code evolution.

Our approach regarding the formalization of the mapping was very similar in that we decided to provide it as a JSON file that the code could parse to retrieve the corresponding ontology concept for each data schema field (Fig. 1). One file would be dedicated to classes and another to the properties, since the process for creating a new class instance is not the same as the one for creating the property of an instance. In the JSON files, the fields of the XML or JSON data schema would be handled as the keys, and would be paired to the URIs of the classes or properties relationships they correspond to in the ontology (Fig. 2).

In the code of the software tool, two functions will need to be implemented: one for the creation of a new instance of a class, and another for the creation of a property of this instance. The first function will create a new URI and create an RDF triple expressing of which class this URI is an instance of. This triple will consist of this new URI as a subject, "rdf:type" as a predicate to indicate the "is an instance of" relationship, and the URI of a class as an object. The second function will create a triple that will assign a new property of a certain value to a certain class instance. To do so, it will create a triple that consist of the URI of the instance, the URI of the relationship to the property, and the value of said property.

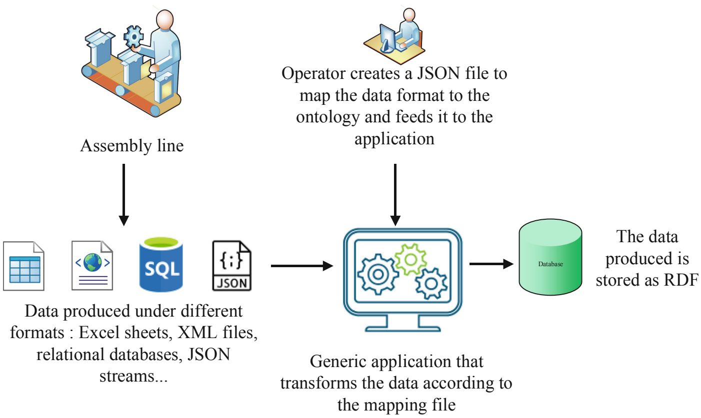


**Fig. 1.** General architecture of the proposed solution

```
"Process": "http://.../ontology/class_000501"
"AssemblyLine": "http://.../ontology/class_000502"
...
"has_id_process": "http://.../ontology/prpt_000701"
"has_ProcessName": "http://.../ontology/prpt_000702"
...
"hasAssemblyLine": "http://.../ontology/prpt_000801"
"hasStation": "http://.../ontology/prpt_000802"
…
...
```

```
<rdf:RDF xml:base="http://.../ontology/"
xmlns:ns0="http://.../ontology/"
xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#">
<ns0:class_000501
rdf:about="http://.../ontology/class_000501/ID=d93ba7">
        <ns0:prpt_000701>Id_Process_1</ns0:prpt_000701>
        <ns0:prpt_000702>Assembly Process 1</ns0:prpt_000702>
        <ns0:prpt_000801
        rdf:resource="http://.../ontology/class_000502/ID=610bd1" />
</ns0:class_000501>
…
…
</rdf:RDF>
```

**Fig. 2.** Mapping JSON file (left); RDF output file (right)

The next step is to create an algorithm using these functions. The first thing this algorithm will have to do is to parse the file or the stream it will receive in input. For each new object in the file, it will retrieve the JSON key or XML field that corresponds to this object, it will check if it corresponds to a class in the class mapping file, and if it is the case, create a new class instance. If the key or field corresponds instead to a property, the algorithm will retrieve the URI of the relationship in the property mapping file and link the URI of the object to the value in the file (Fig. 3). As we will see later in this paper, this approach works well granted that, in the case we are creating a property, we have a way to know which class instance it has to be linked to. This information is easy to retrieve depending on the original data schema, but it is also the only part of the algorithm that cannot be generalized.

## 4 Application Cases

### 4.1 Semantic Enhancement to Ease Aircraft Design and Lifecycle Cost Data Integration

The first software tool we have developed based on this approach was for a project aimed at digitalizing the life cycle ground testing of aircrafts. The purpose of the tool was to be able to feed it an XML file containing the data to be processed to output a Turtle[1] file containing the original data but descried using RDF instead of XML. Our approach was particularly well adapted to this case, since the original XML data schema consisted of objects matching the ontology classes, and attributes matching the ontology properties. Also, objects that had to be linked together were imbricated in each other, which made it easier to link one instance to the other algorithmically. The tool we created for this use-case was developed in C# with the framework .Net Core 2.1[2]. We created two JSON files: one that mapped the names of the XML objects to the corresponding ontology class URIs, and another that mapped the XML attributes to the corresponding property URIs. The structure of the algorithm is the following: while reading the XML file, for each new XML object, the algorithm would look-up the name

[1] A syntax and file format to express data in RDF. https://www.w3.org/TR/turtle/.

[2] Free, open-source framework from Microsoft. https://dotnet.microsoft.com/download.

of the object in the JSON file and retrieve the corresponding class URI, and would then create a new line in the Turtle file consisting of a triple for a new instance of a class. It would then read the attributes of this object, and for each attribute, lookup the corresponding property relationship URI in the JSON file to create a triple in the Turtle file comprised of the abovementioned class instance URI, the property relationship URI, and the value of the attribute in the XML sheet.

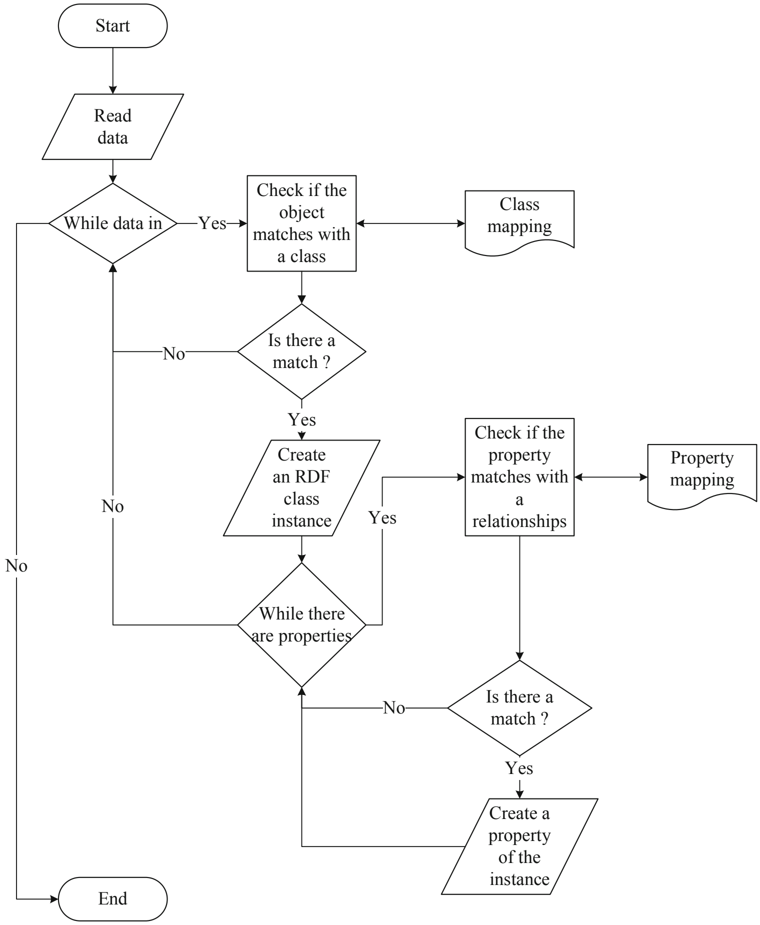


Fig. 3. Flowchart of the proposed algorithm

The only issue that needed to be solved was how to link instances together, when a property was referring to an instance and not just a literal. As stated earlier, the solution was easy due to the structure of the XML file. Whenever the algorithm was creating a new instance, it would save this instance URI, and when reading a new object and creating its new URI, it would link these two URIs together by looking up the property relationship corresponding to the new object name in the property mapping file. Then the algorithm would be able to create a new triple with the previous instance URI as the subject, the relationship URI as the predicate, and the new instance URI as the object.

## 4.2 Zero-Defect Manufacturing

Another ETL tool has been developed in the context of the Z-Factor project. This project aims at improving the quality and the productivity of the European manufacturing industries through five multi-stage production-based strategies. These include: the early detection of the defect, the prediction of the defect generation, the prevention of defect generation as well as its propagation in later stages of the production, the reworking/remanufacturing of the product and finally the management of these strategies through event modelling, KPI monitoring and real-time decision support.

In this case, the original format was a JSON stream, therefore consisting of key-value pairs, and the created RDF triples would have to be stored in a triple store powered by Apache Fuseki[3]. In order to save the triples to the triple store, we used a library named DotNetRDF[4]. Each JSON object corresponded to the instance of a class, and certain key-value pairs corresponded to a property of this object. Others could be ignored.

If the overall algorithm remained the same, this time, attention had to be given to the fact that different JSON objects within the stream could refer to the same instance, and therefore it would be necessary to be able to retrieve the URI of a previously created instance. Our solution to this issue was to use the ID of the object as the URI to the corresponding instance. This way, when reading a new object, we would not need to know if it already existed or look for its ID: just by concatenating the base URI of the ontology and the value of the "id" key-value pair, we would be sure to refer to the correct instance.

Another issue was that the key-value pairs could refer to literal properties but also to other class instances. One way to handle that would be to test beforehand if the key does exist in the class mapping instead of the properties mapping, or to create a separate file for properties that refer to an instance of another class rather than just a literal value. Then the algorithm could distinguish this case and create an instance of the adequate class and link it to the object instance. But this raises a few questions as well. In our case, this approach worked because the value stored in these key-value pairs was the id of the instance, which we could use to create a new URI. But what if several values in the JSON object are related to this instance and not the overall object? Then it will not be possible anymore to apply a general treatment to the key-value pairs, and it will be necessary to create specific treatments for specific fields.

[3] HTTP interface to RDF data, developed as a servlet. https://jena.apache.org/documentation/fuseki2/.

[4] .Net library for parsing, managing, querying and writing RDF. http://www.dotnetrdf.org/.

## 5 Conclusion

In this paper, a generic algorithm for the automatic conversion of different types of data into RDF has been presented, and it was demonstrated that it can contribute to quickly and easily building ETL processes for data that has to be transformed and described with RDF. The main contribution of this research is to propose a solution that doesn't require to hard-code the mapping, and that can be reusable for different data schemas and different ontologies, and that can be easily adapted to other data formats.

Nonetheless, as we have seen, this methodology does not function with every data schema in input. Ideally, for this generic treatment to be efficient, the data structure in entrance should follow the logic of the ontology, class instances and property value should be easily distinguishable. Also, the id of an object should be easily retrievable when referring to an already existing instance, in order to facilitate the work of developers. Otherwise, they will have to look for the instance in the already saved RDF triples, which would kill performance. These issues need to be addressed through future research and tools development.

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# Total Cost of Ownership Driven Methodology for Predictive Maintenance Implementation in Industrial Plants

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**Abstract.** This paper proposes a methodology to drive from a strategic point of view the implementation of a predictive maintenance policy within an industrial plant. The methodology integrates the evaluation of system performances, used to identify the critical components, with simulation and cost analysis. The goal is to evaluate predictive maintenance implementation scenarios based on alternative condition monitoring (CM) solutions, under the lenses of Total Cost of Ownership (TCO). This allows guiding the decision on where in the industrial system to install diagnostic solutions for monitoring of asset health, by keeping a systemic and life cycle-oriented perspective. Technical systemic performances are evaluated through Monte Carlo simulation based on the Reliability Block Diagram (RBD) model of the system. To validate the methodology, an application case study focused on a production line of a relevant Italian company in the food sector is presented.

**Keywords:** Predictive maintenance · Total Cost of Ownership · Condition monitoring · Decision-making

## 1 Introduction and State of the Art

This work presents a methodology aimed at supporting the implementation of predictive maintenance in industrial applications by providing a strategic guideline. The final aim of the methodology is to support industrial engineers in defining where in the industrial system to install technologies for collecting monitoring data and which type of solution to select. The concept of predictive maintenance, is widely analysed in the scientific literature and it is more and more recognized as a potential area for getting benefits for manufacturing companies thanks to the possibilities provided by the new technologies. However, in the literature some limitations for the development of industrial applications in the real world are highlighted, and they include:


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– lack of frameworks that can be used to guide decisions from a strategic point of view [1–4]. In fact, many authors introduce specific application cases of predictive maintenance implementation without providing general procedures that can be taken as a reference and generalized;
– lack of simulation approach [5, 6]. In fact, there is a lack of methodologies in the literature that exploit the possibility of implementing and analysing scenarios a priori through simulation, overcoming the problem of absence of historical data;
– lack of integration between economic evaluation and technical performance analysis for predictive maintenance implementation [6–9]. In fact, many authors have proposed an economic assessment only as simple review and feedback of performed maintenance activities to correct maintenance tasks without considering relationship between predictive maintenance and impact of Total Cost of Ownership (TCO).

Moreover, companies nowadays are facing a vast offer of solutions for predictive maintenance by technology providers and are expressing needs for having formal guidelines to understand where to address their investments.

The proposed methodology has the purpose of overcoming these criticalities with the aim to combine technical performance analysis with economic evaluation, representing a structured approach that supports the implementation of predictive maintenance activities in industrial applications. In the following Sect. 2 the main steps of the proposed methodology are described and in Sect. 3 an application case within the food sector is described.

## 2 Methodology Description

The complete iterative procedure is reported in Fig. 1, and is described in this section, step by step.

**Step 1 - Context definition.** The first step of the methodology consists in the clear identification of the context in which predictive maintenance activities should be introduced, defining the asset system (production plant) to be analysed and modelled. In this step it is important to clearly identify the type of production process involved; the reference objectives of the company and any industrial specific constraints (production capacity, budget, quality of products, performance indicators, layout configuration). All the elements defined in this step are key points for the guidelines definition in the elaboration of predictive maintenance approach in the industrial reality.

**Step 2 - Cost Breakdown Structure (CBS) and Targets definition.** The second step is aimed to build the cost model structure for the TCO of the reference asset system. In particular, the Cost Breakdown Structure (CBS) has to be defined at this step, including the relevant cost items along asset life-cycle [10, 11]. Moreover, criteria and required parameters to estimate each item must be identified. The defined TCO model will be used to evaluate alternative scenarios for predictive maintenance implementation. Selection of adequate target levels in terms of net present value of TCO or payback time are also defined at this step.

**Step 3 - System modelling.** This step consists in system modelling which has two aims. On one side, a Failure Mode and Effect and Criticalities Analysis (FMECA) must be implemented in order to identify the asset system components (machines and functional sub-groups) and provide information on asset failure modes/causes and effects. This activity enables getting information on asset components degradation and its detectability. On the other side, the use of Reliability Block Diagram (RBD) is addressed in order to model the entire system including the impact of each component failure at system level [12].

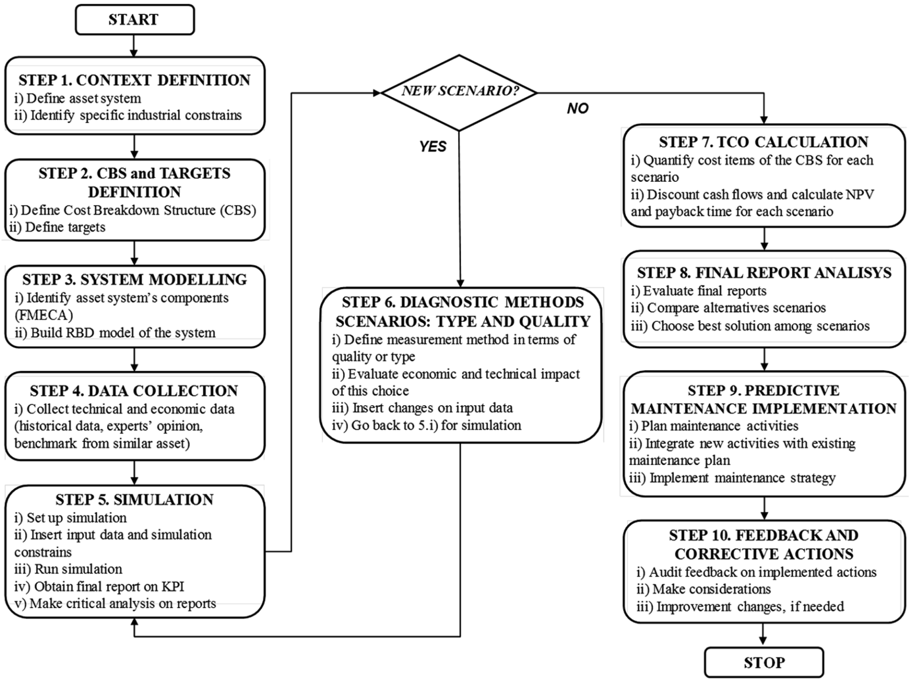


**Fig. 1.** Proposed iterative methodology.

**Step 4 - Data collection.** This step is dedicated to data collection. In particular, two types of input data should be considered, i.e. technical and economic data. Regarding the needed technical data to perform the performance analysis, for each component of the system, the probability density functions of TBF (time between failures) and TTR (time to repair) should be identified. Strategies to collect the data to define these distributions can refer to historical data register and fitting, in case collected data are available and reliable in terms of data quality, use of experts' opinion or pre-defined distributions/benchmark data from similar assets in case of no quality data of in case of no available data due to assets at their beginning of life stage (greenfield projects). Regarding the economic data, they are the ones needed to quantify the cost items in the CBS and to estimate the TCO of the asset. If they are not available, experts' opinion and benchmark data from similar asset/system could be used.

**Step 5 - Simulation**. Innovative step is the introduction of simulation to evaluate and compare several scenarios derived from different condition monitoring (CM) systems, exploiting Monte-Carlo technique, based on the RBD model of the plant. For each scenario, a set of independent histories that collect events on plant life as failures is obtained to generate samples from probability distributions, representing the expected future evolution of system status from initial to final time event [13]. The final result is a statistical estimate value of the performance of the complete system, expressed through a performance indicator such as Operational Availability, and of any of its sub-systems, under the specific simulated scenario conditions. This step is run for the case base scenario, enabling identified critical components within the system, and for any alternative scenarios defined in the following step, through and iterative procedure, enabling evaluating alternative CM solutions.

**Step 6 - Diagnostic methods: type and quality**. Based on criticality analysis of system components carried out in step 5, this step allows defining several scenarios (derived from different CM techniques on critical equipment) with the aim to select the best solution among proposed alternatives. This innovative step is directly connected to step 5 through a logical connector "New Scenario?", in order to regulate the generation of diagnostic methods scenarios, that bring modifications on system with respect to the AS-IS context already analysed in the previous step.

In particular, it enables to consider alternative types and installation locations of tools to monitor asset health and different expected level of quality of capability of the diagnosis and prognosis process. Moreover, it enables considering the economic impact of the solution. These elements are input for running again step 5 (simulation) for each alternative scenario and evaluating the impact of condition monitoring measurement systems on the system performance during its lifecycle.

**Step 7 - TCO calculation**. This step allows to evaluate each single scenario, pre-defined in the previous step, through TCO evaluation [14]. In this step, the CBS cost items are estimated (dependent/independent on the system technical performances) and cost flows discounted, quantifying the net present value for each scenario.

**Step 8 - Final reports analysis.** This step is based on the analysis of the results obtained from the estimation of the TCO in each scenario. In order to get to the final choice of the best alternative solution, an adequate documentation that summarizes main features of each conducted analysis should be provided through reports, diagrams and graphs based on both technical performance parameters and economic evaluation. The solution that ensures minimum TCO has to be selected while, if more than one solution satisfies this criterion and different scenarios have equal or similar TCO value, alternatives should be compared using other criteria, that have to be defined initially and that have a relevant meaning in performed analysis

**Step 9 - Predictive maintenance implementation.** This step refers to the planning and the implementation of the predictive maintenance activities based on the CM systems as chosen in the previous steps. Company should integrate CM systems with scheduling and planning of entire maintenance strategy. This step is relevant and not trivial because a correct integration between company strategy and defined maintenance activities, on critical machines in the production system, facilitates the exploitation of predictive approach, reducing costs and increasing efficiency of production.

**Step 10 - Feedback and corrective actions.** Last step identifies feedback and review on performed maintenance activities and corrective actions through two main sub-phases. The first one is based on audit result and comparison with pre-defined objectives to provide information about technical and economic impact of predictive maintenance activities on the system performances. The second one is based on improvements implementation, if needed, which allow correction of maintenance activities, based on achieved results. If company decides to make changes because it is necessary to correct maintenance tasks or to introduce new CM techniques, it is identified by "YES" path in the proposed methodology. Thus, it is necessary to come back and define a new scenario, that represent changes required by company. This step completes the entire proposed procedure and it represents the key to obtain a dynamic methodology oriented to continuous improvement.

## 3 Application Case

The proposed methodology is implemented in a numerical application carried out in collaboration with a relevant Italian food company with the aim to validate it. The case study is focused on an industrial plant, recently installed. The company expressed the need for a methodology that can be used to guide the definition of the maintenance policies for managing the plant and in particular, to focus the investments in predictive maintenance solutions. Through the methodology, the implementation of the first five steps, was done by the use of a Reliability Engineering software (R-MES ©) which supports Reliability Block Diagram modelling and Monte Carlo Simulation. The application is implemented only as a numerical experimentation thus, steps 9 and 10 are not included because they consist of practical activities only based on company cost-effective decisions and implement actions.

Based on the criticality analysis developed in phase 5, two scenarios were selected in step 6 to be compared and evaluated. The scenarios address the installation of different diagnostic systems for monitoring wear on different critical components within the system. Moreover, each scenario is analysed considering two levels of diagnostic capability quality:

a. *Best case:* it is based on the assumption of perfect functioning of installed CM system and relative achieved benefits on system availability:

$$\left(TBF_{assets} = TBF_{assest\,AS-IS\,scenario} \text{ and } TTR_{assets} = 0\right)$$

b. *Worst case*: it is based on the assumption that condition monitoring systems are not perfect in detecting failures and also, delays could affect restoration activities:

$$\left(TBF_{assets} < TBF_{assest\,AS-IS\,scenario} \text{ and } TTR_{assets} = 50\%\,TTR_{AS-IS\,scenario}\right)$$

Table 1 summarizes cost items as calculated in step 6 after running simulation (step 5) for each alternative scenario. It can be noticed that investment costs of scenario 2 are higher than investment cost of scenario 1 due to higher cost of adopted sensors. The time losses for installation of CM systems are identical while, the disposal costs in scenarios 2 are higher due to higher number of sensors installed. Energy consumption costs, associated to installed systems, in scenarios 2 are higher due to higher number of sensors, while production losses costs are reduced in scenario 2 due to higher overall system availability with respect to scenario 1. An important parameter considered is the availability of the production process since the introduction of sensors allows to reduce inefficiency associated to production losses.

**Table 1.** Summary of economic cost items for proposed scenarios.

| Cost item | Economic value | | | | Description |
|---|---|---|---|---|---|
| | Scenario 1a | Scenario 1b | Scenario 2a | Scenario 2b | |
| *Una-tantum costs* | | | | | |
| Investment cost | 28000 € (year t = 0) | 28000 € (year t = 0) | 32500 € (year t = 0) | 32500 € (year t = 0) | Acquisition of sensors and software |
| Cost due to plant downtime for installation | 28080 € (year t = 0) | 28080 € (year t = 0) | 28080 € (year t = 0) | 28080 € (year t = 0) | Production losses for CM systems |
| Disposal cost | 400 € (year t = 20) | 400 € (year t = 20) | 500 € (year t = 20) | 500 € (year t = 20) | Recovery or dismiss CM techniques |
| *Yearly costs* | | | | | |
| Energy consump. | 1200 €/year | 1200 €/year | 1500 €/year | 1500 €/year | Energy consumption by CM system |
| Production losses costs | −64228.32 €/year | −21864.96 €/year | −79260.48 €/year | −25964.64 €/year | Savings costs for availability increase |

The availability comparison between base case (A = 81.57%) and different proposed scenarios, as well as total annual equivalent cost (CTAE) and the payback time (discounting rate of 5%, as used by the company for investments evaluation) are assessed in Table 2.

**Table 2.** Summary of availability and TCO calculation for proposed scenarios.

| | Scenario 1a | Scenario 1b | Scenario 2a | Scenario 2b |
|---|---|---|---|---|
| Availability* | 83.45% | 82.21% | 83.89% | 82.33% |
| Δ Availability | +1.88 (2.25%) | +0.64 (1.5%) | +2.32 (2.77%) | +0.76 (0.92%) |
| Payback Time | <1 year | <2 years | <1 year | <2 years |
| CTAE | −58851.39 € | −16488.03 € | −73246.48 € | −19950.64 € |

*Availability is estimated through Monte Carlo simulation running 10.000 iterations

All scenarios provide an increment of system availability thus, all proposed solutions are cost-effective respect case base, even if each of them has a different impact on overall system availability. Payback time is less than 1 year in best condition while investment costs are recovered in 2 years in worst operating condition. Best solution is scenario 2 that provides a higher increment of technical system availability despite a higher investment due to higher investment cost. Moreover, scenario 2 shows the lowest TCO value representing best investment during entire plant lifecycle since it provides a high reduction of production losses costs.

## 4 Discussion and Conclusions

This work concerns the definition of an innovative methodology that provides support for investment and management decisions for predictive maintenance implementation in industrial plants. In detail, key strength points are:

- the definition of practical methodology to implement predictive maintenance activities through a significant integration between technical performance evaluation (RAM analysis) and economic assessment (TCO evaluation);
- the combination between RBD model with discrete events simulation based on Monte Carlo technique, through exploitation of R-MES software, for estimation of technical system performances along its lifecycle under different CM scenarios;
- the introduction of an innovative step for the generation of the alternative CM scenarios for evaluating the impact of different types of monitoring systems and quality of diagnostic capabilities, through simulation and TCO estimation;
- finally, the validation of proposed methodology within an important Italian food company.

The methodology was actually positively valued by the managers of the company which recognize, as its main potentialities the easiness of application, satisfying company requirements; the overcoming of the criticality associated to absence of historical data, through the introduction of the simulation phase and the possibility of exploiting several data collection strategy; and, the integration of TCO estimation as principal tool for the evaluation of generated scenarios, providing the possibility of considering whole plant life-cycle. After the application case implementation, the company decided to develop a pilot project to evaluate the investment in the solution provided by the proposed decision-making methodology.

Overall, the defined methodology represents a good decision-making support to identify critical components, on which predictive maintenance activities should be implemented. In fact, it allows to manage a better utilisation of resources because it avoids the installation of CM systems on machines and components, that in reality, are not the most critical ones.

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# Ontology-Based Resource Allocation for Internet of Things

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**Abstract.** The Internet of Things has revolutionized the lifestyle in all aspects. Considering the huge number of connected objects and the plethora of real-time services, edge computing approaches have emerged. Resource allocation is one of the most important challenges in the Internet of Things. Here edge computing allows the use of resources at the edge network, hence, filling the gap between cloud and end-devices. The network resource allocation should meet users' expectations and provide optimal use of resources. Today, most of the systems are moving toward a self-x concept, such as self-organizing. As a result, these systems must be aware of users' preferences and the current state of the IoT ecosystem in order to adapt themselves to the conditions. In this context, we benefit from the employment of semantic technologies as these enhance the current systems with information modeling and reasoning capabilities which effectively support the allocation of IoT network resources.

**Keywords:** Internet of Things · Edge computing · Context awareness · Resource allocation · Semantic technologies · Ontology

## 1 Introduction

Nowadays the Internet of Things (IoT) has dominated all aspects of our lives. As a result, objects are connected to the network and talk about each other. Around 18 billion connected objects are forecasted by 2022 related to the IoT [1]. There are a variety of applications (e.g., smart city, smart manufacturing, and video surveillance) provided in an IoT network. In this ecosystem, most of the service providers use the cloud data centers to process the huge volume data produced by objects and extract a value of it. However, this results in imposing a high load on the network and degrading the performance of the cloud. Meanwhile, because of the distance between the cloud and the source of data, the opportunity to act on data in real-time will be lost [2]. In order to solve these problems, a new distributed computing paradigm named fog computing [3] has emerged which aims at filling the gap between cloud and end-devices. Fog computing enables network objects to cooperate and make their resources available, in order to reach a goal, i.e. providing services.


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Regarding fog computing which aimed especially towards IoT, we consider an IoT network consists of three layers; cloud, fog, and end-devices. Fog layer includes distributed nodes such as routers, servers, and even mobile devices distributed between the end users and the cloud. In this context, we define the problem well-known as resource allocation as follows; given the IoT network and the IoT requests along with their requirements, find a mapping between requests and nodes at the network. The resulted nodes should execute tasks to reach the request's target and to satisfy the network performance and quality of services. Resource allocation is one of the most important challenges in the IoT context.

Fog computing is able to locally allocate edge devices (comprises end devices such as mobile phones, edge devices such as routers, and edge servers) to the IoT requests and prevent the transmission of huge amounts of raw data to the core network (including the core routers, regional servers, and cloud centers). In order to do this, it is important to consider some key features regarding IoT objects:

- Limited available nodes' resources (e.g., electrical energy, memory, and processing power).
- Network heterogeneity regards both nodes' capabilities and requests' requirements.
- Dynamic behavior of IoT networks; connections among nodes are created dynamically.
- A huge number of nodes deployed over an extensive area; network topology changes quickly.

All these features conclude to a dynamic network, where all nodes need to interoperate in order to allocate available resources in a distributed way. Most of the decisions should be taken autonomously to avoid centralized solutions. Therefore, resource management should be continuously addressed to dynamically adapt the system to changes in terms of IoT requests' requirements and network topology. This is the reason we need "context awareness". Context awareness can exploit all available context information in order to make better decisions regarding a constrained pool of network resources. Therefore, it can improve the performance of resource management algorithms for IoT ecosystems.

The term "context awareness" refers to the ability of computing systems to acquire and reason about the context information and subsequently adapt the corresponding applications accordingly [4]. In addition, context awareness is a foundation of all self-x properties including self-configuration, self-organization, self-optimization, self-healing, etc. [5, 6]. As a result, the IoT network would be able to exploit resources in an efficient and self-organizing way. Semantic technologies use formal semantics to facilitate context- awareness, and reasoning on IoT. They enhance the raw data and link the data in any domain in real life. Ontologies provide a sophisticated semantic mechanism for resource modeling and allow representing both hardware and software, physical and virtual resources along with the relationships between them and in a variety of granularities [7].

This paper focuses on the mentioned challenges in the IoT resource allocation and we propose to use context information to allocate IoT resources in an optimized way. To this end, this paper suggests to use ontologies to model our IoT network/requests.

Then we leverage semantic rules/query engines to drive inferences and find a suitable mapping between IoT requests and resources.
Some of the applications for our proposal include but not limited to:

- Autonomic and self-organizing IoT networks (e.g., automated manufacturing).
- Power/workload management in the IoT ecosystem.
- Monitoring the resources in the IoT network and detecting the likelihood of node failures and applying policies for remediation.
- Context-aware strategies for the future regarding long-term reasoning (extracting trends and patterns).

This paper is organized as follows. In Sect. 2, we look at some related work using ontologies in the IoT domain. Section 3 describes the proposed approach, based on the unification of the IoT and cloud ontologies and leveraging it for optimized resource allocation. Finally, Sect. 4 provides an overview of the benefits of the proposed approach and some indications for future research.

## 2 Related Works

In the context of this paper, we review cloud computing ontologies, IoT ontologies, and resource management in IoT as our related work literature survey.

Zhang et al. [8] propose a cloud computing ontology called CoCoOn to discover suitable infrastructure services for the user's needs. The CoCoOn ontology defines a set of properties to describe infrastructure services. The authors implement a recommendation system based on the CoCoOn ontology in which SQL queries are used to interrogate the ontology and discover services. Rekik et al. [9] propose CloudO, a comprehensive cloud service description that plays a basic role for the discovery and composition of cloud services. The proposed ontology spans functional and non-functional aspects of cloud services at the three layers of cloud models, namely Infrastructure as a Service (IaaS), platform as a Service (PaaS) and software as a Service (SaaS). The proposed ontology helps user to discover and select appropriate cloud services through user's queries.

IoT-O [10] ontology intends to cover two sets of requirements - Conceptual and Functional in an IoT ecosystem. The "conceptual" requirements are based on the description of devices, data, services and their lifecycle while, "functional" requirements are defined as the requirements that follow best practices define by the semantic community. The ontology provides concepts needed for representing a device and its functionality. It reuses some existing ontologies such as IoT-Lifecycle [11] and SSN [12] to define the concepts related to the IoT domain such as duty cycles and sensing capabilities.

Moustafa et al. [13] propose Continuum, a model of a context-aware middleware that can dynamically discover environment and self-adapt applications to the new contextual conditions. They address the issue of changing environment due to the mobility through a monitoring service that is capable of reasoning during the runtime. Koorapati et al. [7] consider an ecosystem consisting of IoT, Software-Defined Data Center (SDDC) and cloud. The authors present a resource modeling framework based on semantic technologies insisting how semantic technologies are applied in addressing some of the key challenges in managing such an ecosystem. Delicato et al. [14] describe the challenges related to resource management in IoT considering different number of tiers; only cloud, only IoT, and three tier composed of cloud, IoT and edge nodes. The authors highlight the advantages of ontologies for resource modeling and provide a useful insight of OpenIoT [15]. OpenIoT is a middleware framework whose semantic-based resource management architecture enables managing the whole life-cycle of IoT applications and services infrastructure.

To the best of our knowledge, this paper is the first research paper which deals with using ontologies to discover, model, select, and allocate resources in an IoT ecosystem consisting of IoT, fog and cloud layers.

## 3 Proposed Approach

An IoT ecosystem with three layers is illustrated in the Fig. 1 in which the bottom layer encompasses the things (the IoT devices/nodes/smart objects), the top layer includes the cloud nodes and an optional middle layer consists of fog nodes. IoT request (originate from any devices) are intended to be received by the closest (in terms of the distance between the IoT requester and fog nodes) fog nodes. Upon receiving a request, the receiver fog node locally generates an assignment between its received requests and the ecosystem, resource allocation. Regarding the assignment, the IoT tasks will be distributed and deployed on the intended resources and served users considering the quality of services.


**Fig. 1.** IoT ecosystem comprising three layers: cloud, fog, and end-device layer [2]

The lack of unification of heterogeneous cloud/fog service description makes resource discovery and selection very complex tasks for IoT users. To alleviate the complexity, it is necessary to have a unified service model integrating service descriptions obtained from heterogeneous sources. This paper proposes to combine two ontologies; IoT ontology (IoT-O) [10] and cloud ontology (CloudO) [9] in order to model the IoT ecosystem using a unified ontology named IoT-Fog-Cloud.

IoT-O is a modular IoT ontology aimed at describing connected devices and their relationship with their environment. The IoT-O is composed of several modules including sensing module, acting module, service module, lifecycle module, energy module. On the other hand, CloudO describes the concepts, features and relations of different services (and their classification) in the cloud computing paradigm. Therefore, we can use IoT-O to model a variety of heterogeneous devices such as sensors, actuators along with their attributes. To represent cloud and fog services we leverage CloudO. Since a fog node is a cloud (with weak capabilities) close to the users and can provide a variety of cloud services we can model it as a cloud node in the resulted ontology. As a result, the proposed ontology enables us to model different resources and requests at the IoT ecosystem. In the following we show how we can benefit IoT-Fog-Cloud to manage the IoT resources efficiently.

The main activities of a typical workflow for allocating resources in an IoT network are illustrated in Fig. 2 and consist of: resource discovery, resource modeling, resource selection, and resource allocation. The figure depicts a context life-cycle [16] and corresponding resource allocation tasks that are related to each cycle. There are other activities related to resource management such as resource monitoring, resource estimation, and resource remediation which can benefit from ontologies. However, these steps are not the focus of this research.

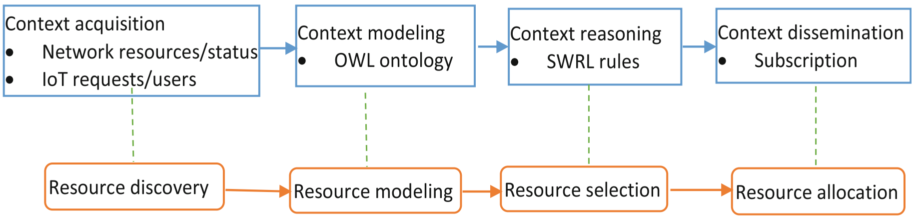


**Fig. 2.** Context life cycle and activities involved in resource allocation for IoT ecosystem.

At the first step, resource discovery, nodes acquire and share the concepts to attain essential information about the network. To do this, all nodes locally exchange their information with their neighbors to adapt to environmental changes. Also, upon receiving an IoT request, the receiver node can extract the requirements of the request. The second step, resource modeling, tends to represent the resources/requests in our IoT ecosystem. Using the IoT-Fog-Cloud ontology, we can define the entities, properties, and relationships that build up the resources/requests at the IoT ecosystem. The first two steps result the following models.

- IoT resources: cloud data centers, fog nodes, end-devices and the links between them along with their characteristics such as processing/storage capacity, load, energy, mobility status, sensing capabilities, link bandwidth/propagation delay (Network dynamic aspect). Domain/application (e.g., smart manufacturing, agriculture, health-care), peak time (Network static aspect).
- IoT requests: requests along with their characteristics such as requester and his/her mobility status, demands (processing power, storage, network), type (real-time or batch), priority, security level, deadline.

Third step, resource selection, considering modeled requests/resources and using reasoning techniques, decides about suitable resources to host the IoT requests regarding quality of services. To do this, we use Semantic Web Rule Language (SWRL) [17], a language for expressing semantic rules as well as logic. The rules infer new/intended knowledge about network/requests from our existing OWL knowledge base. Each node can investigate and consult the structured ontology throughout SWRL to find the optimized hosts for its received requests. Finally, at the resource allocation, nodes disseminate the concepts resulted from resource allocation step to their neighbors (e.g., remained nodes' capacity regarding new deployed tasks).

A typical resource allocation procedure from each node's view in our proposal is shown in Fig. 3. In order to make the procedure clearer and show how the proposed solution addresses the aforementioned challenges in IoT resource management consider a resource allocation scenario; a mobile node sends an IoT request to a fog node. The fog node extracts the requirements and properties of the request. The fog node already has a global view of the network through the IoT-Fog-Cloud ontology. Consulting the ontology and using SWRL rules, the fog node specifies the best node to host the request. In this specification the matching between the request and the host is checked such as the required sensing capabilities and bandwidth. After that, the fog node forwards the request to the selected host. Then, network nodes update their information about the underlying network regarding this hosting. In this procedure network nodes

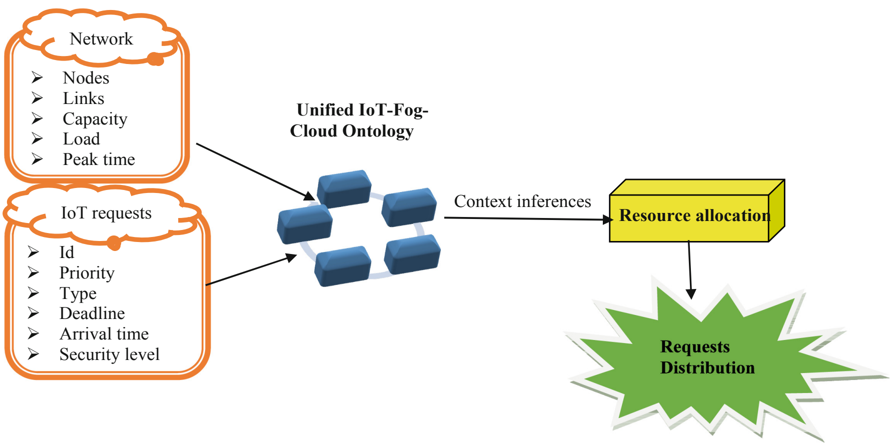


**Fig. 3.** Resource allocation work flow for each fog node in IoT ecosystem

constantly share their information and keep an up-to-date image on the network. As a result, by updating ontology, dynamic behavior of the network is well considered. In addition, by keeping the properties of the nodes and their resources and services, heterogeneity is addressed.

## 4 Conclusion

In this paper, the IoT resource allocation in a three layers IoT ecosystem composed of cloud, fog, and end-devices is introduced. Also, we showed how semantic technologies are applied in addressing some of the key challenges in the managing resources such an ecosystem. In addition, we have seen where the unification of the IoT and cloud ontologies helps the various lifecycle of managing resources and allocating them smartly.

In the future, using this unified ontology, smart resource management applications can be developed which can predicate the future status of the network (such as failing a node given that they are hitting the threshold, going out of the coverage of a special server because of the mobility), and the requests (such as increasing required sensing frequency and changing the priority or security level), and results in a self-organized and self-healing system. On the other hand, the same unified ontology along with SWRL rules can be used to develop smart application deployment algorithms to propose optimized deployments in terms of energy saving, load balancing and secure deployment by just expressing of how the IoT ecosystem is supposed to be and then getting to know if the deployment place is good enough to meet the preference.

We plan to modify the unified ontology and the inference rules so those poor fog nodes can quickly infer required results and act on-time on the basis of the received data. We also consider using the cloud's capability to extract long-term patterns from the IoT ontology and feed the results to the fog nodes and study the behavior.

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# Variety and Complexity Management in the Era of Industry 4.0

# Bringing Advanced Analytics to Manufacturing: A Systematic Mapping

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**Abstract.** Advanced analytics has the potential to redefine manufacturing. However, practical implementation is in its infancy. One reason is a lack of management tools that enable decision-makers to choose suitable techniques from advanced analytics for domain-specific problems in manufacturing. This paper uses a systematic mapping review in order to identify seven application areas to which analytics can add substantial value. Each area is then matched with suitable techniques from the field of advanced analytics. The resulting systematic map provides a novel management tool for the purpose of identifying promising analytics projects in manufacturing and thus facilitates decision-making.

**Keywords:** Smart manufacturing · AI applications · Advanced analytics · Systematic mapping review

## 1 Introduction

Advanced analytics offers new ways to improve and innovate manufacturing processes [5,10]. Steady progress in terms of computing power and storage capacity, as well as the rapid development of advanced algorithms, has equipped companies with unprecedented possibilities to generate knowledge and business value from large datasets [13,24]. In this way, analytics changes the basis of competition [10].

In order to thrive in today's competitive market environment, manufacturers can use advanced analytics to streamline complex operations while improving quality and reducing costs [22,25]. The manufacturing sector can benefit greatly from the use of advanced analytics, since data is abundantly available [16], providing a still largely untapped potential for process improvement and innovation. Manufacturing strategies, such as Industry 4.0 in Germany, Industrial Internet in the United States, and the Made in China 2025 initiative, recognize the strategic importance of utilizing data in order to enhance manufacturing competitiveness [21,22]. However, manufacturers are not exploiting the full potential of data and analytics. Recently, McKinsey speculated that less than 30 % of the potential has been captured so far [10].


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A main barrier that prevents manufacturers from harnessing the full potential of analytics is a lack of management tools that enable decision-makers to choose suitable techniques from advanced analytics for domain-specific problems in manufacturing. While research has brought forward various techniques capable of solving complex problems in manufacturing, little has been done to equip practitioners and decision-makers with the necessary management tools to implement these techniques on an operational level [7,23,25].

This paper uses a systematic mapping review in order to identify seven application areas to which analytics can add substantial value. Each area is then matched with suitable techniques from the field of advanced analytics. The resulting systematic map provides a novel management tool for the purpose of identifying promising analytics projects in manufacturing and thus facilitates decision-making. To the best of our knowledge, such a management tool, one that matches application areas in manufacturing with analytics, does not yet exist.

## 2 Background

Several authors have attempted to define the vague term "analytics" and yet there is no universally accepted definition. In this paper, we adopt the definition put forward by Davenport et al. [6, p. 7], characterizing analytics as "the extensive use of data, statistical and quantitative analysis, explanatory and predictive models, and fact-based management to drive decisions and actions." With the term "advanced analytics", we subsume methods originating from statistical learning, e.g., data mining techniques, as well as methods stemming from artificial intelligence research, in particular machine learning algorithms.

Previous work in the field of analytics applications for manufacturing has predominantly been limited to systematic literature reviews [3,4,9,12,18,19]. The available systematic literature reviews generally neglect to consistently systematize and link application areas with suitable analytics techniques in a structured and visually appealing way. A notable exception is Köksal et al. [12]. However, a drawback is the limited focus on quality improvement tasks, rather than considering additional important application areas such as production planning, product inspection, or machinery maintenance.

Flath and Stein [8] have developed an adapted data mining process model for manufacturing prediction tasks, proposing guidelines for modelling, feature engineering, and interpretation. However, similar to already existing generic process models, such as the cross-industry standard process for data mining (CRISP-DM), their work does not provide decision support for the selection of suitable analytics techniques.

Villanueva Zacarias et al. [23] propose a framework that automatically recommends suitable analytics techniques with respect to a domain-specific problem at hand. Similarly, Lechevalier et al. [14] present a framework for the semi-automatic generation of analytical models in manufacturing and a proof-of-concept prototype that allows practitioners to generate artificial neural networks for prediction tasks through a user interface. Both frameworks represent promising approaches tackling the problem of automated analytics technique configuration in the manufacturing domain. However, these concepts do not pursue the goal of identifying promising combinations of analytics and application areas in the first place. Therefore, both approaches are unsuitable for decision-making at the managerial level.

Table 1 stresses the research gap by reporting on related key literature. We explicitly searched for articles focusing on the fusion of both manufacturing application areas and analytics techniques. Evidently, existing solutions are either unsatisfactory or inadequate to facilitate the selection of suitable techniques from analytics for domain-specific problems in manufacturing. Although scholars have addressed the lack of decision support [7,25], no research has yet been devoted to comprehensively combining analytics with application areas in manufacturing.

**Table 1.** Selected key literature on analytics applications for manufacturing. Full circle indicates compliance with the respective criterion.

| Reference | Output | Mfg. | Analytics | Fusion |
|---|---|---|---|---|
| Pham and Afify [18] | Literature review | ◐ | ◐ | ○ |
| Harding et al. [9] | Literature review | ● | ○ | ○ |
| Choudhary et al. [4] | Literature review | ● | ◐ | ○ |
| Köksal et al. [12] | Literature review | ◐ | ◐ | ◐ |
| Cheng et al. [3] | Literature review | ◐ | ◐ | ○ |
| Sharp et al. [19] | Literature review | ● | ◐ | ○ |
| Flath and Stein [8] | Process model | ○ | ◐ | ○ |
| Villanueva Zacarias et al. [23] | Framework | ○ | ○ | ● |
| Lechevalier et al. [14] | Framework | ○ | ○ | ● |
| **This paper** | Systematic map | ● | ● | ● |

## 3 Methodology

We used a systematic mapping review, following the guidelines of Petersen et al. [17], in order to design a management tool that facilitates analytics selection in manufacturing. The goal of a systematic mapping review is to build a two-dimensional classification scheme, a map, to visually structure a research area. The analysis of results focuses on frequencies of publications for categories within the scheme, thereby creating a map which can easily help transfer knowledge to practitioners [17].

We chose Scopus to search for relevant literature, since it covers a broad, interdisciplinary field of research. The search was limited to journal articles written in English and published from 2008 until the end of 2018. This time frame of 11 years was regarded as sufficiently exhaustive, since research on analytics applications for manufacturing has only recently been addressed with growing interest [19,21,25]. Furthermore, discrete-part and assembly manufacturing that are classified into division 26–30 by the International Standard Industrial Classification (ISIC) were designated as the target domains of this work. Manufacturing companies operating in these high-tech sectors (e.g., automotive, aerospace, machinery, and electronics) are profoundly affected by digital transformation processes [15] and are, therefore, ideally suited to the adoption of analytics. However, some of the mentioned application areas also exist in continuous manufacturing processes, such as oil refining and chemicals.

Our literature search was split into two parts in order to obtain relevant research articles. The first search[1] identified seven major application areas in manufacturing to which analytics can add substantial value, namely demand forecasting, job scheduling, product inspection, process diagnostics and prediction, machine parameter optimization, diagnostic maintenance, and predictive maintenance. The second search queried each identified application area independently using appropriate keywords.[2] From the entire corpus of 1,853 articles, 81 articles that reported a successful application of at least one machine learning method were considered in order to build the final systematic map. These 81 articles were selected according to their average number of citations per year in order to include widely appreciated research articles. A stop criterion limited the number of articles per application area to 15 (or fewer if articles were cited less than three times on average per year). The reading and selection process was solely conducted by the lead author of this paper.

We only considered analytics techniques applied for the final regression, classification, or optimization task, in order to facilitate an easy interpretation of the systematic map. This is a reasonable approach, since the way data is preprocessed primarily depends on the final technique applied [1]. We agree with [25] that a promising approach to select a suitable machine learning algorithm is to look for problems of similar nature. Therefore, we are convinced that the frequency of published articles can be used as a valid proxy for the purpose of identifying suitable machine learning techniques for a specific application area.

## 4 Results

In the following, the main results of our research are presented. First, the identified application areas to which analytics can add substantial value are described

[1] `TITLE (manufacturing OR ‘‘smart production’’) AND TITLE (data OR ai OR analytics OR learning OR artificial) AND TITLE-ABS-KEY (application).`

[2] For instance, articles regarding machine parameter optimization were queried with: `TITLE-ABS-KEY (‘‘data mining’’ OR analytics OR learning OR ‘‘artificial intelligence’’ OR ‘‘neural network’’) AND TITLE-ABS-KEY (manufacturing) AND TITLE-ABS-KEY (process OR product) AND TITLE-ABS-KEY (‘‘parameter optimisation’’ OR ‘‘parameter optimization’’ OR ‘‘parameter design’’ OR ‘‘process parameter’’).`

and pooled into three main groups, namely *plan*, *make*, and *maintain*. Afterwards, the map resulting from the systematic mapping review is presented.

### 4.1 Application Areas of Analytics in Manufacturing

**Plan.** *Demand forecasting* and *job scheduling* are elements of the production planning processes of a manufacturing facility. Demand forecasting mostly uses historical time-series to predict future demand. Especially in large supply chains, demand forecasting can lead to a mitigated bullwhip effect [2]. Job scheduling applies optimization techniques in order to derive the actual production plan while making a trade-off between the impact of early or late completion of a task.

**Make.** *Product inspection*, *process diagnostics and prediction*, and *machine parameter optimization* aim at optimizing manufacturing processes with regard to quality, time, and costs. Product inspection can use image data in order to analyze product states, for instance the surface quality of steel, and classifies items into scrap or good parts. Process diagnostics and prediction are two major quality improvement and control activities. Whereas process diagnostics primarily determines variables that significantly affect quality, process prediction models the relationships between input variables and output quality characteristics. Furthermore, process prediction is usually a preliminary step undertaken in order to optimize manufacturing machinery input parameters. Thus, it is closely linked to machine parameter optimization, which yields optimal machinery parameters with respect to a target quality measure, such as surface roughness, for instance. Adjusting technological processes in relation to these parameters can result in improved productivity and product quality, as well as reduced costs [21].

**Maintain.** *Diagnostic* and *predictive maintenance* are two application areas that strongly build on each other [20], aiming to reduce downtime of manufacturing machinery and tool equipment. A new maintenance paradigm, condition-based maintenance, has gained considerable attention in recent years [19]. Condition-based maintenance utilizes online condition variables to detect, identify, and forecast potentially detrimental fault conditions. Current condition-based plans, designated as diagnostic maintenance, assess the current state of the system in real-time and perform maintenance when a triggering event occurs, such as the growth of a fault frequency beyond a particular threshold. However, a major drawback of diagnostic maintenance is that it cannot anticipate a breakdown well ahead of time. To overcome this, predictive maintenance looks at the current and past states of the system, as well as its expected future operational load, to predict how much remaining useful life a system has [19]. This temporal information advantage helps maintenance engineers to proactively order important spare parts that might not be immediately available.

## 4.2 Systematic Map

The resulting systematic map is shown in Fig. 1. The vertical axis presents all seven application areas, while the horizontal axis reports on techniques from advanced analytics that are classified in a two-level taxonomy.

Number of articles Low High

| | | Discriminative learning | | | Generative learning | Prescriptive |
|---|---|---|---|---|---|---|
| | | Structured data | Image data | Sequence data | Probabilistic | Optimization |
| | | e.g., support vector machine, dense neural networks | e.g., convolutional neural networks | e.g., autoregressive models, recurrent neural networks | e.g., Bayesian networks, hidden Markov models | e.g., genetic algorithm, particle swarm optimization |
| Plan | Demand forecasting | 7 | 0 | 4 | 0 | 0 |
| Plan | Job scheduling | 1 | 0 | 0 | 0 | 14 |
| Make | Product inspection | 3 | 4 | 0 | 0 | 0 |
| Make | Process diagnostics and prediction | 16 | 0 | 0 | 2 | 0 |
| Make | Machine parameter optimization | 0 | 0 | 0 | 0 | 12 |
| Maintain | Diagnostic maintenance | 12 | 2 | 0 | 0 | 0 |
| Maintain | Predictive maintenance | 10 | 0 | 2 | 2 | 0 |

**Fig. 1.** Systematic mapping of techniques from advanced analytics (horizontal axis) to seven application areas in manufacturing (vertical axis). Color intensities represent the relative frequency of proposed analytics techniques with respect to an application area. The sum of the matrix is greater than 81 (number of reviewed articles) because some articles compared multiple analytics techniques.

Since most analytics techniques applied in manufacturing are of a supervised nature [25], we chose to differentiates between discriminative learning, generative learning, and prescriptive techniques on a first level [1,11]. On the second level, discriminative learning techniques are further subdivided into structured, image, and sequence data-based models to allow for a more granular interpretation of the map. Examples of the most commonly encountered techniques are given below. For each application area, color intensities represent the relative frequency of proposed analytics techniques.

Empirical evidence from 81 reviewed journal articles shows that optimization techniques have thus far been applied in the areas of job scheduling and machine parameter optimization. Discriminative analytics techniques based on image data, e.g., convolutional neural networks, have become the primary tool for automated product inspection. Discriminative analytics techniques that rely on structured data are mainly used for demand forecasting, quality diagnostics and prediction, as well as diagnostic and predictive maintenance.

## 5 Conclusion

Advanced analytics is expected to have a significant impact on manufacturing. However, practical implementation is still in its early stages. One reason is that decision-makers have lacked management tools to choose suitable techniques from advanced analytics for domain-specific problems in manufacturing.

This paper applied a systematic mapping review to identify seven application areas to which analytics can add substantial value. Each area was then matched with suitable techniques from the field of advanced analytics. The resulting systematic map provides a novel management tool to identify promising analytics projects in manufacturing and thus facilitates decision-making.

Furthermore, the presented systematic map organizes interdisciplinary knowledge in a structured manner to serve as a means for common understanding in analytics projects. This is particularly helpful in order to bridge the gap between domain-specific manufacturing contexts and general-purpose analytics practices. In this way, collaboration between different stakeholders, e.g., domain experts and data analysts, can become a less complex and time-consuming task.

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# Impact of Modeling Production Knowledge for a Data Based Prediction of Transition Times

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**Abstract.** An increasing demand for customer-specific products is a major challenge for manufacturing companies. In many cases, companies attempt to satisfy this demand by increasing the number of product variants. In those companies, cost-oriented production processes have to be transformed into flexible workshop or island production structures in order to be able to produce this variety. This leads to an increasing complexity of production and subsequently planning. In order to reliably meet due dates, it is necessary to improve the quality of planning. This paper presents an approach for predicting transition times, the times between two production steps, by employing machine learning methods. In particular, the influence of the modelling of production knowledge of experienced employees on the prediction quality compared to a pure optimization of the methods' parameters is investigated.

**Keywords:** Production planning · Machine learning · Transition times

## 1 Introduction

A trend of an increasing demand for customer-specific products can be observed [1, 2]. The increasing number of variants forces many companies to transform their former cost-oriented flow production structures into flexible workshop or island production structures [3]. Typically, in the latter ones lead times (LT), logistics efforts and costs tend to increase, while the delivery reliability tends to worsen [4]. Today, most companies' highest logistical target is a high logistical performance and especially a high delivery reliability [3]. In times of an ever increasing globalization, a high logistical performance is crucial for a strong competitiveness, as markets all over the world have changed mostly from sellers' to buyers' markets [4]. In those, a high planning reliability plays a central role in achieving a high logistical performance [5].

In principle, companies can positively influence the delivery reliability by measures such as additional shifts, employee overtimes, short-term outsourcing or targeted overcapacities. However, those measures come at high costs. Those costs are a challenge for companies, especially for those in high-wage countries. An approach for


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acting more proactively and achieving a high delivery reliability is a more accurate prediction of order LT. Those LT consist mainly of transition times (TT), the times between two processing steps, which consist of waiting times before and after processing steps and transport times. TT scatter in general widely, which is why companies struggle to predict TT properly [6]. This paper aims at analyzing the impact of modeling and using production knowledge on the accuracy of TT prediction compared to a pure optimization of a prediction model's parameters using only raw feedback data. The research question is how much the prediction accuracy is influenced by these two tasks.

In the following section the challenges and consequences of a more accurate prediction are discussed briefly. In section three the state of the art of TT prediction is presented. Section four presents the conceptual design on the developed approach of an accurate TT prediction. In section five, the impact of modelling production knowledge of experienced employees is investigated and compared to a pure optimization of parameters being used in a machine learning (ML) method. Section six summarizes the findings and gives an outlook on future research.

## 2 Challenges and Consequences of an Accurate Transition Time Prediction

An accurate prediction of TT is a challenging and uncertain task [7]. Production planers often attempt to cope with this uncertainty by allocating time buffers in the manufacturing process. This leads to a phenomenon called vicious cycle of production planning that was already described in the 1970s. Allocating time buffers leads to an earlier release of orders. Assuming orders are not finished substantially earlier, an increasing work load at work stations leads to longer waiting queues. Caused by this, orders need even longer than planned and the LT scatter more widely [8]. Instead of allocating time buffers, the right approach would be to predict LT order-specifically. By this, LT scattering decreases while process and planning reliability increases. However, current planning systems do not support a more accurate prediction of TT [9]. Thus, companies often use static estimations of TT. On the other hand, research shows that a more accurate prediction of TT is possible [4].

Yet, there are difficult obstacles to overcome when predicting TT. In general, a profound and error-free database is a prerequisite for a robust and accurate prediction [2]. However, companies often do not possess such a database. Often they have a high degree of missing or erroneous data [10] and/or they do not have a large amount of non-redundant feedback data. As TT are related to orders in general and processing steps in particular, there is a limitation in the number of data entries per attribute by the number of orders or processing steps. Each attribute represents a data source, such as sensors, feedback data or master data. Generating more data points per order or processing steps would only lead to a more redundant data set that does not bring substantial benefits. An additional challenge is the data representation. Production data is characterized by a high heterogeneity in type, structure, semantics, organization and granularity, which is difficult to handle for most ML methods [11].

Besides the mentioned challenges, research states that it is important to model human expertise and especially production knowledge for a transformation of raw data into useful data [12, 13]. Thus, in section four, an approach for modeling this production knowledge into a data based prediction of order-specific TT is presented. In section five, the approach is applied both with and without production knowledge to a data set containing real feedback data of a producing company from the machine equipment industry. By doing so, the impact of modeling production knowledge is investigated and compared to a pure parameter optimization of a ML method.

## 3 State of the Art of the Prediction of Transition Times

In the following, eight papers are presented that have been identified as the most relevant ones in a semi-structured literature review with a total of 75 analyzed papers. In [6] LT estimations based on two different decision tree algorithms are compared for different basic job shop production configurations. It is found that feature selection has a significant impact on the prediction accuracy. At best, a deviation as high as 18% between predicted and actual LT is achieved. In [4] an approach of LT prediction in a tool shop based on real industry data is presented. In [14] both a feature selection for and prediction of cycle times in a simulation model of a use case from the semiconductor industry is described. In [15] a short term prediction model for LT in a semiconductor factory is proposed. In [16] three deep neural networks are compared for predicting order completion times. In [2] the use of a multivariate linear model, a non-linear random forest and a support vector machine algorithm is analyzed, all using real feedback data from a flow-shop production in the optics industry. In [17] LT in a semiconductor factory are predicted for three process steps by applying eleven different prediction algorithms. In [18] cycle times of wafer lots in a company from the semiconductor industry are predicted when releasing orders into production.

Analyzing the presented papers in detail, certain improvement measures can be derived. First of all, all papers focus on the prediction of LT that do not only contain highly scattering TT but also processing times. As processing times are often dependent on technological influencing factors whereas TT often depend on organizational factors, a separate analysis of both is recommended. In some of the papers significant reductions of the inspection areas have been made. For instance, in [16] only 12 workstations are considered, while in [6] only 6 workstations are considered. With the inspection area being to small, it can be explained, why in some cases selected features do not change their importance for the accuracy of LT prediction with respect to different production configurations. In general, a high usage of simulation data can be observed (in five of the twelve papers). Simulation data has in principle a high quality in terms of fewer instances of missing data or outliers. This characteristic is favorable for data analysis methods but real world applications are different. In four papers, use cases from the semiconductor industry are selected. As per [18], semiconductor factories are among the most digitized ones. With prediction accuracy is highly dependent on the number of training data, it is obvious, that an application in different industries is challenging. Lastly, it can be observed that e.g. in [14] feedback data from production is used for the prediction of LT, which is not known a priori, i.e. at the time when predicting LT. Hence, the accuracy of such a model decreases, when removing such features that were identified as relevant for prediction. In the following section, an approach is presented that addresses the mentioned challenges and weaknesses.

## 4 Conceptual Design of an Approach for an Accurate Prediction of Transition Times

Essential for any data analysis is the quality of the underlying data set [19]. Especially the feedback data of highly differentiated and complex processes of medium-sized machine equipment companies pose a challenge for predicting TT. As a result, this approach focuses on generating a high quality and informative data set.

In research, two approaches have shown to be effective methods for increasing data quality (see also section three): *Feature selection* and *feature engineering* [20–22]. Features are the attributes which characterize a specific data set [23]. In the process of *feature selection*, an analyst selects the features to decrease the total number of features which improves modeling accuracy [14, 22]. In *feature engineering,* a data scientist combines preexisting features or creates new features from scratch. Thus, *feature engineering* enables the opportunity to enrich a data set with knowledge from production experts, increasing the accuracy of TT predictions beyond the level of raw data sets. This task is especially challenging regarding the necessity of understanding the underlying production system as well as the available data set. Neither a data scientist nor a production expert can easily provide both.

Due to a potential extensive effort of generating a significant benefit from *feature engineering*, a systematic approach is fundamental [24]. This challenge has been addressed by several researchers, but mostly with high level and general concepts. In principle, a data scientist should begin by selecting obvious features such as dates and durations, and then continue to generate individual features such as LT or percentiles of a feature [20]. [24] suggest a three-phase method consisting of *exploring* the data, *extracting* relevant features and *evaluating* the engineered features. However, both approaches offer very few concrete actions and instead focus on the ability of a data scientist to understand the underlying system. The presented approach is based on previous work with the extension to include production experts into the process [25].

For *feature selection*, the most common method uses and ranks the set of features according to their relevance. The wrapper method accomplishes that by employing the learning algorithm and returning the features' impact on the prediction accuracy [26]. Having generated the high-quality data set, the learning model's performance can significantly be improved by optimizing its hyperparameters. Those are parameters of modeling algorithms that can be tuned to optimize the fit of a model to a data set [23].

Considering the steps above, we applied and evaluated the impacts of *feature engineering, feature selection* and *hyperparameter optimization* on a set of production data of a German medium-sized manufacturing company as follows.

## 5 Investigating the Impact of Modeling Production Knowledge for Usage in ML Methods

Validating the thesis of creating a significant benefit by enriching production data with additional production knowledge, the used raw set of production data consisted of real production information of approx. one year taken from a company's MES. Features included for analysis were e.g. the number of orders per day, number of operations per order, planned dates for starting and finishing the order, number of parts per order and estimated processing times by the processing production planner. Summing up, the data set contained 25 features and 100.000 data entries. In this, total LT accounts for 458,000 h, of which TT has a share of 78%. The used features are all known a priori.

In a first step, we designed a case-based approach to infuse additional knowledge into the data. Then, basic analysis on the data set was conducted, promptly identifying two findings. First, the TT per processing step varied with the time left until the order was completed. Second, the workload of the factory had a significant effect on the TT. By extracting daily data of all processed orders, new features were created accumulating the processing times of orders outstanding (i.e. calculating the workload of that day). Beyond that, the production expert stated that the work schedule (i.e. planned downtimes) causes a great portion of the TT. With this knowledge, the created feature eliminates planned downtimes such as weekends or nights for machines not operating at these times. This led to a decrease of TT to 44% of LT. After implementing all engineered features, the data set included about 90 features.

In the process of generating an optimal data set, we applied some basic *data preparation* methods to clean the data of missing and incorrect entries. In accordance to [27], instances with missing values were ignored, if their total appearances summed up to less than one percent of total instances and the median was inserted in residual cases. However, for some specific features missing values were interpreted as nulls, if missing values are allowed in the first place, e.g. additional processing times or priority.

Following, the wrapper method iteratively computed TT predictions adding a new feature each iteration to find the most influential ones. As seen in Fig. 1, the steps indicate a severe improvement when specific features were added to the model. Shown is the mean absolute error (MAE) of the TT predictions in working days that decreases over the number of features included into the model. Out of the best 25 features, we engineered 14 through expert knowledge. Among the most influential features are e.g. the time prediction by the production planner or the order-specific amount of time left to finish the complete order.

For modeling, we used python as programming language including its ML library. In particular, the scikit Regression Tree was used to perform the TT predictions [28]. Optimizing its performance, the following hyperparameters were adjusted: Decision tree depth, minimum number of samples to be at a leaf node and minimum number of samples required to split a node. To evaluate the engineered features in comparison to the raw data set, four scenarios were analyzed. The scenarios I and II use only the raw data, while III and IV use the enriched data set. While I and III have default hyperparameters, in II and IV those hyperparameters were optimized.

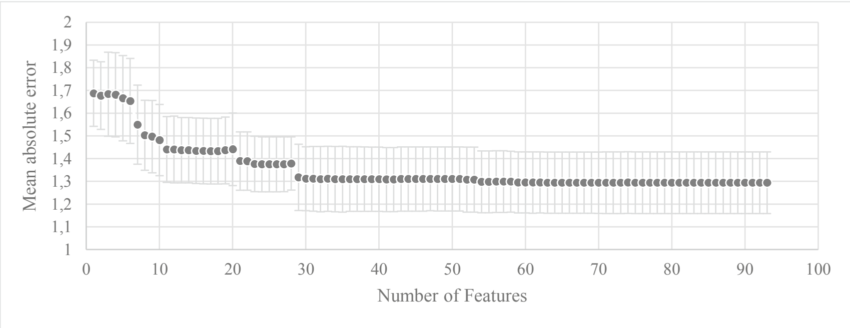


**Fig. 1.** Results showing the prediction error per number of used features

As seen in Fig. 2, the TT prediction error is lowest for the data set that includes optimized hyperparameters as well as selected and engineered features. It reaches a 14.6% lower MAE than the data set without engineered features and thus shows a significant improvement. The effect of optimizing the hyperparameters is explicitly high for the decision tree due to its tendency of overfitting and therefore shows a great improvement of about 25% for the raw data set and 18% for the enriched data set. One can assume that engineering features helps the fitting of the model by providing more informative features, which leads to a lower need for optimization. This could prove important in cases of high amount of data, in which an evaluation, such as this, would need too much time to compute.

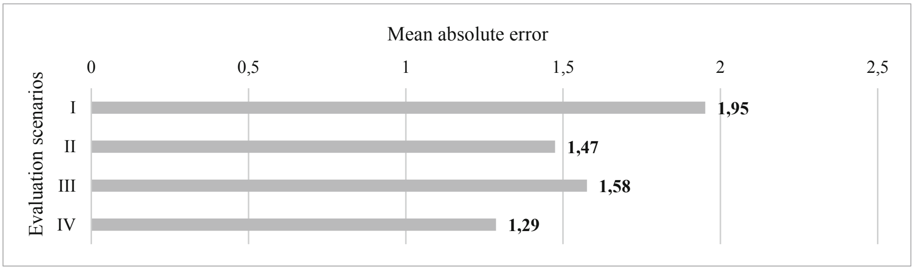


**Fig. 2.** Mean absolute error of transition time predictions in working days

## 6 Summary and Outlook

In this paper, the importance of a more accurate prediction of TT, that represent the time between production process steps, has been discussed. By using more accurate TT, logistical performance can significantly be approved by simultaneously reducing costs. Based on a CRISP-DM based approach for a order-specific prediction if TT, a validation with real production feedback data took place. Modeling production knowledge in combination with optimizing a ML method's hyperparameters decreased prediction errors by 44%.

In the future, a profound evaluation is planned on what type of production knowledge can improve the prediction accuracy even further and how that knowledge can be modeled for a use in ML methods. One concrete example will be to evaluate the impact of modeling order sequence corrections at machines. At last, the integration in a company's planning process needs to be conceptualized, including a control loop for a self-learning development of the prediction model in order to maintain a high prediction accuracy. A major challenge for this control loop is to deal with the fact that production managers will actively influence the TT based on the predicted length.

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# Reconfigurable Manufacturing: A Classification of Elements Enabling Convertibility and Scalability

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**Abstract.** Reconfigurable manufacturing, providing capacity and functionality on demand, is an ever more important factor of competitiveness in volatile, unpredictable, and rapidly changing markets. In this regard, scalability and convertibility are considered particularly relevant characteristics, as they directly reduce reconfiguration effort and enhance system responsiveness. However, in previous research, scalability and convertibility have predominately been addressed conceptually on a high level of abstraction with only limited consideration of how specific manufacturing elements can enhance and realize them. Therefore, the objective of this paper is first to identify and classify elements enabling scalability and convertibility in order to bring reconfigurability-related concepts closer to the world of practitioners. Moreover, as a result, the paper concretizes scalability and convertibility and provides a foundation for future empirical research on reconfigurability.

**Keywords:** Reconfigurable manufacturing · Reconfigurability · Changeable manufacturing · Scalability · Convertibility

## 1 Introduction

Reconfigurability of manufacturing systems has been studied since the late 90's as a key to competitiveness in scenarios characterized by unpredictability of markets [1]. In addition, emerging intelligent manufacturing technologies promise to enable and enhance reconfigurability [1, 2]. However, despite these promising potentials, the wide implementation of manufacturing solutions realizing the reconfigurability characteristics still appears rather limited in industry [2, 3]. It is widely recognized that the core characteristics of reconfigurability are: modularity, integrability, diagnosability, scalability, convertibility and customization. Among them, scalability and convertibility are considered essential characteristics [4, 5]. Scalability, i.e. the ability to make rapid and efficient incremental changes of capacity [6], and convertibility, i.e. the ability to conduct quick changeover between existing products and adaptability to future


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products [7], represent key reconfigurability characteristics, as they directly contribute to the goal of the reconfigurable systems, which is providing exactly the capacity and functionality needed when needed [8]. Moreover, scalability and convertibility directly reduce reconfiguration effort and enhance system responsiveness [9, 10], as well as "bridge" between the remaining characteristics since they are enabled by modularity, integrability and diagnosability and, in turn, enable customization and thus reconfigurability itself [11, 12].

Therefore, in this paper, scalability and convertibility are considered as primary characteristics in order to realize the advantages of reconfigurability in manufacturing firms. However, in previous research, these characteristics have predominately been addressed on rather abstract levels with only limited consideration of the manufacturing elements that enhance these characteristics, their inherent relations, and how they can actually be realized in manufacturing [13–15]. In this regard, reconfigurability is increasingly being promoted as a multi-dimensional and complex capability that can be designed and implemented specifically for different manufacturing contexts, by exploiting relationships between core characteristics and/or enablers [13, 14] at multiple manufacturing levels [16, 17]. Therefore, in order to support practitioners in realizing the potentials of reconfigurability and design appropriate manufacturing solutions that realize reconfigurability, it is important to consider not only structural aspects that enable scalability and convertibility but also their manufacturing levels of realization. Accordingly, the aim of this paper is to bring reconfigurability-related concepts closer to the world of practitioners and create the foundation for future field-based investigations on the topic, leading to the following research question: *Which manufacturing elements enable scalability and convertibility as relevant characteristics of reconfigurability in manufacturing?*

In addressing this research question, "elements" enabling scalability and convertibility are defined as concrete constituents of such characteristics. Moreover, focus is limited to the factory and lower manufacturing levels, where previous research on manufacturing "elements", "enablers" or "assessment criteria" (enabling specific characteristics of reconfigurability and/or enabling reconfigurability as a capability in itself [3, 18–20]) has been considered. For this purpose, criteria have been defined for analyzing previous research and ensure coverage of reconfigurability as a multi-dimensional capability and in turn create a basis for future research based on case studies. The remainder of the paper is structured as follows: Sect. 2 presents criteria for identifying and classifying enabling elements, Sect. 3 provides the results and Sect. 4 presents conclusions and outlines future development of this research.

## 2 Classification Criteria for Elements Enabling Scalability and Convertibility

This section presents the criteria applied for classification of different elements identified in previous research. These have been introduced in order to cover relevant aspects related to scalability and convertibility from a multi-dimensional perspective. The criteria are described as follows:

- **Manufacturing level of reference:** from a hierarchical systems view, reconfigurability can be developed on different manufacturing levels [21]. Moreover, reconfigurability on lower manufacturing levels positively influences reconfigurability on higher manufacturing levels [16, 22, 23]. Thus, elements influencing scalability and convertibility should be identified in regard to multiple levels. Specifically, this paper focuses on levels within the factory: (i) workstation (**WL**), (ii) system (**SL**), and (iii) factory (**FL**).
- **Effects on either short-term or long-term reconfigurations:** as a multi-dimensional capability, reconfigurability has characteristics acting in the Configuration Period (CP) and others acting in the Reconfiguration Period (RP) [11]. CP is the period for decisions on structural aspects (i.e. the design) of systems, whereas RP is the period for decisions on system changes (i.e. related to the operations). Scalability and convertibility are characteristics acting during the RP [11], thus their enabling elements support reconfigurations with either short or long-term time horizon. Short-term time horizon reconfigurations **(ST)** cover e.g. solving disruptions and quality problems, exploiting flexible production resources or changing from one existing variant to another (i.e. changes within workstations, leading to brief changeovers without any further investment in production resources) [24]. Long-term time horizon reconfigurations **(LT)** are associated with changes of structural aspects at either workstation, system and factory levels, in order to change production capacity and functionality [25].
- **Classification in physical and managerial elements:** depending on manufacturing levels, the nature of elements influencing scalability and convertibility may be different. As observed by many authors, reconfigurability at lower levels is generally associated with physical and "hard" elements, while reconfigurability on higher levels is generally associated with more managerial, logical, and "soft" elements [6, 10, 16, 21]. Physical elements **(PE)** can be either technical systems of the factory (i.e. operational resources and processes) and spatial aspects (i.e. floor and ground areas) [17]. Managerial elements **(ME)** refer to logical elements, operational rules, organizational policies, and IT support for the management of technical systems [10, 17], e.g. rules established for re-planning production resources in order to accomplish market changes [6].

In the following, nine elements have been identified and classified according to these criteria. In this regard, relevant literature was located from authors' previous systematic literature searches on reconfigurability, which collectively have used a broad spectrum of key words e.g. "reconfigurability", "reconfigurable manufacturing system", "changeable manufacturing", etc. in relevant databases e.g. Web of Science and Scopus, as well as through additional snow-ball search processes. Papers referring to: (i) "changeability", often used to denote to the capability of manufacturing systems to adapt to any changes independently on the manufacturing level of reference [4, 26]; (ii) "flexibility", often used at workstation and system levels [6]; and (iii) "transformability" often used at factory level [3, 4] have been reviewed as well.

## 3 Research Results: Elements Enabling Scalability and Convertibility

This section presents the elements enabling scalability and convertibility identified in the literature review. Figure 1 synthesizes the classification of these elements according to the aforementioned criteria through the color-coded labels visualized for each element. The figure shows that scalability and convertibility are enabled by a combination of nine manufacturing elements, which are comparatively less abstract than scalability and convertibility. These nine elements are enabled by a combination of other aspects that are, in turn, more concrete than the previous ones. For brevity, these have not been included in detail here. Even if not detailed, such aspects have been immersed and exemplified in the following description of the nine elements. As observable in the following descriptions of the nine elements, elements and aspects are positioned in Fig. 1 progressively enlarging, from left to right, the focus from WL, to SL and then to the entire FL.

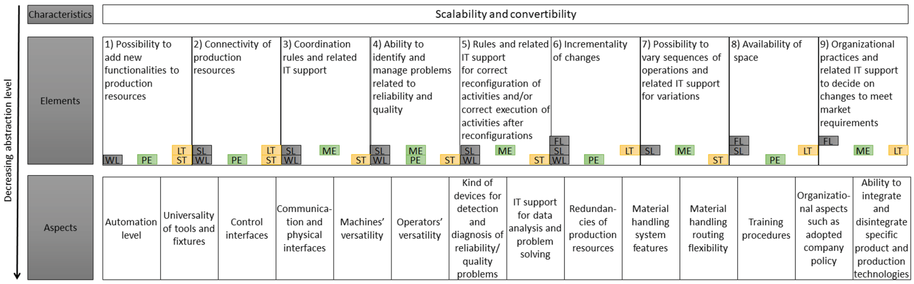


**Fig. 1.** Elements enabling scalability and convertibility and their classifications.

(1) Possibility to add new functionalities to production resources: this element has been located at WL and classified as PE. Indeed, operators and machines should be provided or designed (in case of machines) in a way that allows future conversions to new requirements. Specifically, manual workstations rely on operators' versatile skills [7, 17]. Conversely, to facilitate future conversions of highly automated workstations with complex and partitioned architectures, machines' control interfaces should be designed for easy integration to newly introduced tools/machines [13]. Universality of tools and fixtures adopted at the workstation would facilitate their employment for varying requirements and tasks [13]. In general, the possibility to add new functionalities to production resources may allow ST scalability and convertibility (e.g. by recurring to operators' versatility) or even LT reconfigurations (e.g. exploiting machines interfaces allowing integration to newly introduced tools/machines).

(2) Connectivity of production resources: this element has been classified as PE and defined at WL and SL. Indeed, as it allows information exchanges, from the perspective of supporting information systems, it should be defined and supported at every individual manufacturing level [27]. Information may simplify the

adaption of operators and/or machines to eventual new requirements in terms of implemented functionalities [20, 28]. Connectivity may certainly simplify ST reconfigurations (e.g. interactive screens and information boards connected to a central information system might guide operators in executing a certain variety of tasks [29]); conversely LT reconfigurations should be enabled by additional aspects allowing structural changes of the workstation (e.g. the integrability of machines interfaces).

(3) Coordination rules and related IT support [19]: these elements may be defined at both WL and SL. Rules are ME even if the possibility to benefit of the IT support is also related to the connectivity of production resources. Both rules and IT support are enablers of scalability and convertibility only if, during the CP, these are designed with a RP perspective: in this case, they would be oriented at speeding up the adaptation to change by improving production resources synchronization during reconfigurations, thus allowing more frequent reconfigurations [30, 31].

(4) Ability to identify and manage problems related to reliability and/or to production quality: this element may be defined at both WL and SL. It includes both PE, such as devices for detection and diagnosis of reliability/quality-related problems [18, 20], and ME such as problem-solving methodologies and related IT support [32]. PE should be defined especially at WL and ME should be defined (and supported by adequate information systems) especially at SL. Moreover, the exploitation of modern digital technologies promise to improve such ability [2, 33]. It enables better scalability and convertibility at WL and SL by allowing the reduction of ramp-up periods after reconfiguration [30].

(5) Rules and related IT support ensuring the correct reconfiguration of production/assembly activities and/or the correct execution of activities after reconfigurations: these elements may be defined at both WL and SL. These are ME, even if the possibility to benefit of the IT support also presupposes the presence of PE. Both rules and IT support are enablers of scalability and convertibility only if, during the CP, these are designed with a RP perspective. In this case, they would be oriented at avoiding problems related to human mistakes during reconfigurations and/or after reconfigurations, thus allowing more frequent reconfigurations by contributing to the reduction of reconfiguration ramp-up times [30]. At WL these might be mechanisms to detect the usage of right tool and right components for a certain task (poka yoke) [20].

(6) Incrementality of changes: at each level (i.e. WL, SL and FL) converting and/or adapting production capacity through as small as possible changes means higher convertibility and/or scalability [34]. Intuitively, the incrementality of changes achieved at WL, strongly influences the incrementality of changes at SL and in turn at FL. As detailed below, many aspects of this element should be properly designed during the CP, these may enable, especially at higher manufacturing levels, LT scalability and convertibility by reducing the effort required for reconfigurations [34]. At WL, an influencing aspect is the versatility of operators and integrability of machines' control interfaces, which favor implementing incremental changes of workstations without implying substantial changes of workstations themselves [13]. At SL, the universality of workstations may allow accomplishing incremental changes, for example the possibility to share and or swap functional units among

stations. [3, 18, 20]. Moreover, features of the material handling system, such as the level of automation of its devices and the possible movements of these systems, impact on the incrementality of changes too [20]. At FL, incrementality of changes can be seen as technical "upgradeability" of the factory [2]. It depends on the ability to integrate and disintegrate specific product and production technologies [17]. Finally, by analogy with SL, the level of automation of warehouse systems may affect factory reconfigurability. Thus, generally this element supports LT reconfigurations.

(7) Possibility to vary sequences of operations and related IT support: this element may be defined at SL as a ME, however it also depends on PE, such as the presence of functional redundancies of workstations/functional units [19] and specific features of the material handling system [6, 20]. Examples related to this element are opportunities and decisions on machines relocation [35] and material handling redirections [35]. Even in this case, the possibility to benefit of the IT support is related to the connectivity of production resources at WL. It enables ST scalability and convertibility. Indeed, the number of feasible routes of all part types and the availability of this information for decisions on system operational changes positively impacts on changes in production capacity and functionality [6]. In turn, this aspect depends on the versatility of operators' skills and/or the integrability of machines' control interfaces [20].

(8) Availability of space (this is mainly influencing scalability rather than convertibility): the utilization of space at SL and FL potentially allows increasing the number of resources in case of need [20]. Thus, this element enables LT reconfigurations.

(9) Organizational practices and related IT support to decide on changes on the operations to meet market requirements: such ME at FL enables LT reconfigurations. These are: labor reassignment [35] and training procedures (such as cross training and continuous improvement of operators skills; outsourcing and subcontracting possibilities [6]; exploitation of different processing plans available for making a product [7]; possibility to act on shifts and flexible labor time [7]. For example, the possibility to change shifts and number of resources involved [6, 20] is a ME that has to be defined at FL during the CP and, once defined, it allows implementing LT-oriented changes of production capacity and functionality at either WL and SL. It should depend on organizational aspects such as adopted company policy.

## 4 Conclusions and Further Research

The aim of the research presented in this paper was to bring reconfigurability-related concepts closer to the world of practitioners. Accordingly, nine manufacturing elements enabling scalability and convertibility have been identified from previous research and classified according to criteria defined with the aim of exploring the multi-dimensional aspects of reconfigurability, i.e. manufacturing level, time-span of reconfiguration effect, and as being either managerial or physical. These nine elements contribute with a concretization of abstract concepts of scalability and convertibility and bring these reconfigurability-concepts closer to practice. Future research should aim at further enhancing the theoretical classification through feedback and examples gathered directly in field. Moreover, cases should allow understanding how such elements can increase convertibility and scalability. Specifically, since empirically-founded or case-based research on reconfigurability is rather scarce, future research should aim at investigating e.g. elements of scalability and convertibility in practice in regard to their inherent relations, reinforcing effects, different types of applications, and resulting performance outcomes.

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# Industry 4.0 in SMEs: A Sectorial Analysis

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**Abstract.** The diffusion of Industry 4.0 within companies depends on their size. The resources and processes of large companies are more structured, so they are likely to deploy 4.0 technologies more quickly than SMEs. In order to prevent these SMEs from becoming victims of this industrial revolution, it is essential to fully understand the organizational, human and technological challenges of Industry 4.0. This article presents a review of the barriers and problems that a 4.0 investment can create for small and medium-sized businesses depending on their sector. Our analysis proposes a synthesis matrix with the effects of industry 4.0 in the different sectors of SMEs. This matrix presents the impacts, opportunities and risks of each of the main technologies of industry 4.0. Based on process innovations such as training plans or customer proximity, SMEs seem to have adopted their own Industry 4.0 concepts according to their sectors of activity.

**Keywords:** Industry 4.0 · Small and medium-sized enterprises · Sectorial analysis

## 1 Introduction

SMEs are independent companies with a limited number of employees. This number varies according to the national files of the different countries. The most common standard is 250 employees with a total turnover not exceeding EUR 50 million [1], in particular in the European Union. The United States considers SMEs to include all companies with less than 500 employees (OECD). In France, for example, small, medium and micro enterprises represent nearly 48.5% of jobs [2].

The world has experienced 3 major industrial revolutions. Today, a fourth revolution is taking shape: Industry 4.0. Its roots are at the dawn of the third millennium with the emergence of the Internet. This revolution does not stem from a new energy source but from the potential of a new technological phenomenon: digitalization. The survival of SMEs therefore depends largely on their ability to respond to these new industrial challenges.

In the manufacturing industry, which accounts for the largest share of industrial production, about 10% of firms are currently making intensive efforts to integrate


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Industry 4.0 [3]. There is a significant relationship between company size and Industry 4.0 implementation [3]. Large companies are much more advanced in integrating information technology systems into their production facilities. Various surveys [3] have reached similar conclusions, demonstrating that only 13% of small and medium-sized enterprises in the manufacturing industry have already integrated 4.0 into their facilities and systems; 17.5% have committed to it and developed their first concrete implementation plans; just under 40% are reviewing them; and about 25% of SMEs have not yet considered integrating this new industry [3].

The aim of this study is to understand where SMEs stand in the face of this digitalization of society. The great strength of small and medium-sized enterprises lies in the adaptability and reactivity of the market [4]. Is it possible that digital only benefits companies with more than 500 employees? What types of SMEs benefit from Industry 4.0, and to what extent? Why is it more complicated for SMEs to adapt to this new technology? Why don't they visualize its adaptation? What are SMEs using to integrate Industry 4.0? In order to try to address all these questions, it is essential to understand whether small and medium-sized enterprises have the necessary skills and knowledge to carry out this process independently or whether they need a specialized integrator. The idea of an apprenticeship plan offers the possibility to support companies in this process [5], as industrial companies trying to implement Industry 4.0 face a number of challenges and constraints.

The question for SMEs is: When is the right time to integrate these technologies? Many actors in the fields of science, politics and economics feel the need to actively support the digitalization process. Nevertheless, SMEs lack the resources to invest in research and development activities, they struggle to manage complex IT solutions and lack the expertise to integrate new technologies [6].

## 2 Analytical Framework

### 2.1 Diagnostic and Framework of the General Market

It should be noted that there are two types of SMEs: the goods and the services sectors. The figures in this section include all SMEs selling market goods, i.e. all tangible and intangible products (goods and services). In order to better focus our study, it is important to define an analytical framework. Let is start by defining the challenges of the SME market in relation to Industry 4.0.

SMEs are the backbone of economies and guarantee the good health of the European economy. In response to trends in globalization and international interconnectivity, SMEs are selling more products and services to foreign markets, while competitiveness continues to increase. In recent years, the trend towards automation and data exchange in manufacturing has become increasingly important for today's companies [7]. This trend has a number of implications for workers, ranging from technological changes to social effects. The definitions of the term Industry 4.0 are diverse and extremely varied, but essentially describe an integrated network of digitized and web-based machines and products [8]. In this article, we will use the following definition: Industry 4.0 is the integration of digital systems to control physical systems. It is therefore characterized by the integration of digital technologies into the global manufacturing process.

According to [9], SMEs employ the majority of the workforce in services for private individuals, commercial crafts (bakery, delicatessen, pastry), and specialized scientific and technical activities (including liberal professions). Similarly, in construction, other than a dozen large companies, three-quarters of all employees are employed by SMEs. We have therefore decided to select the 3 most important sectors in terms of number of employees by sector of activity and category of company based on 2015 figures according to [9]:

- Commerce, transport, accommodation and catering (1)
- Industry (2).
- Specific activities, scientific, technological activity. Services, administration (3).

With regards to the ranking used previously, we noted that industry action 4.0 is more easily identifiable and quantifiable in SMEs producing services. The technologies of 4.0 are terrific at providing the means to connect with customers or partners by setting up autonomous processes [6]. Digital technology, data study and the connection between customer and production unit have given birth to a factory generation: Smart Factor [7]. This phase of business transformation is characterized by the digitalization of companies at the heart of their industrial strategy and processes.

### 2.2 Measuring Digitalization in Companies

Digitalization is becoming a major issue on a global level and we are seeing it on both an industrial and political level. It is not insignificant to note that several countries today consider digitalization via Industry 4.0 to be strategic [10]. To fill the lack of resources for SMEs to invest in research and development activities [6], several governments, particularly in Europe, have made financial aid available to develop alternative solutions in 4.0 (European Parliament-2016). In France, for example, aid for industrial SMEs was approved in 2017. This allows up to 40% of digital and digital investments to be deducted from their taxable profits (French Government-2017). According to Eurostat (2016), the French government is ranked first in the implementation of education and training policies for Industry 4.0 compared to its European neighbors (UK, Germany, Italy).

### 2.3 The Great Impact in Value of Industry 4.0

To conclude this part of the analytical framework, we would like to highlight a study published by the World Economic Forum, which shows the impact of digitalization in terms of cumulative value. In the different sectors we have chosen to isolate, we note that the impact of digitalization plays an important role. These results show the impact of digitalization in terms of cumulative value for the years 2016 to 2025 (The future of trade - The impact of digitalization: Cumulative value of digitalization to industries, 2018). Based on the results of this study, we find that the sector most affected by far is the one directly affecting the final consumer. The accumulated value of digitization is nearly US$5,000 trillion, which corresponds mainly to the digitization of services dedicated to consumers such as shops, transport, accommodation and restaurants.

## 3 Types of SMEs Versus Industry 4.0

The OECD conducted a study on automation risk by job type, so it seemed appropriate to us to isolate the top 9 high-risk occupations in this study. The study highlights that 14% of jobs in the 32 countries studied are highly vulnerable to 4.0 technologies, i.e. they have at least a 70% chance of being automated. We therefore believe that these 9 sectors are the companies' targets for implementing 4.0. This confirms the research work of Ruessmann (2015) [11] (Fig. 1).

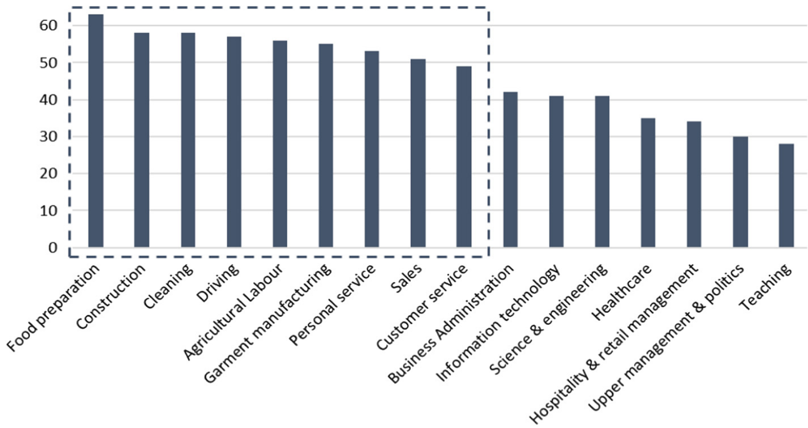


**Fig. 1.** Automation risk by job type (%)

Thanks to the study carried out by the OECD, we proceeded to cross-check information between the main axes of Industry 4.0 defined by [11] and [12], with trades at risk in terms of employability in the context of the integration of Industry 4.0.

The matrix synthesis (Table 1) therefore presents this cross-reference of information. We found an important difference in the development of the different axes of Industry 4.0 in the applicability of the job sectors that the OECD agreed had a high risk of automation. The table below shows, for each of the industry sectors, a summary of the articles that have studied the jobs at risk, including risks and potential depending on the case and the applicability.

**Table 1.** Synthesis matrix of effects of industry 4.0 in SMEs sectors

| Axes | Sector | Findings | Ref. |
|---|---|---|---|
| Big data | Food preparation | Uses of big data, looking specifically at how these techniques and technologies govern our ability to imagine food worlds | [13] |
| | Agricultural labour | Agricultural remote sensing data, as general remote sensing data, have all the characteristics of big data | [14] |
| | Sales | The forecasting of sales in the supply chain could be enhanced by customer analytics based on big data and associated technologies | [15] |
| | Customer service | The intelligent customer relationship network usually uses the customer's equipment's movement trajectory data, customer platform operating data, customer network base stations, and other content as customer behaviour data | [16] |
| Autonomous robots | Food preparation | Food processing plants are using automation solutions, which are cost effective for higher production volume as compared to the conventional processes | [17] |
| | Construction | The resulting relative poses uncertainty between the mobile robot and its workpiece would likely exceed that permitted by the construction process, thereby preventing the robot from performing work reliably | [18] |
| | Agricultural labour | Automatons are more economically feasible than conventional systems because the former perform tasks faster, improve productivity by working more hours and reduce the amount of herbicides required, among other benefits | [19] |
| | Cleaning | The development of a robotic system designed to clean the outer surface of elliptic tapered structures such as Dubai airport concourse | [20] |
| Simulation | Food preparation | The use of agent-based simulation has increased in agri-food supply chains (ASC) research in recent years | [21] |
| | Agricultural labour | Multi agent systems are a good way to understand a complex system by implementing simple and easy-to-understand local interaction rules | [22] |
| | Sales | Sales and operations planning is a challenging issue to improve customer satisfaction and control production costs solutions. Based on simulation, it can be easily tuned to reach optimization and best fit the industrial context while incorporating specific characteristics | [23] |

(*continued*)

**Table 1.** (*continued*)

| Axes | Sector | Findings | Ref. |
|---|---|---|---|
| | Customer service | For better customer satisfaction, order processing service simulations such as design customization need to analyse customer behaviour and evaluate product lead-time | [24] |
| Augmented reality | Customer service | The study of [24] highlights the influence that recent technological advances in virtual reality can have on the customer experience | [25] |
| Additive manufacturing | Food preparation | Three-dimensional printing systems that accept both food ingredients and printing materials are known as 3D food printers | [26] |
| | Construction | Reduce labour costs, reduce material waste and create custom complexes of geometries that are difficult to achieve with conventional techniques | [27] |
| Cyber security | Driving | Safety is a fundamental concern in modern vehicle systems. This technology is vulnerable to hacking and malware, making it important for cyber security to analyse potential attacks and their impact on the safety of vehicle users | [28] |
| Systems integration | Construction | Architecture, engineering, construction and facilities management are applying. These integration technologies enable the collaborative use of information throughout the product and project life cycle, and allow for greater integration of people, processes and business systems, sharing information more effectively | [29] |
| Internet of things | Driving | Connected cars are becoming a common sight on our roads. We will see innovation occur much faster than ever thought possible as the ubiquity of fast networks collides with the availability of high-powered software | [30] |
| | Customer service | Changed the relationship between traditional customer networks, and traditional information dissemination has been affected. Smart environment accelerates changes in customer behaviour | [31] |

Based on the information provided by the synthesis matrix, we compared the different sectors according to the presence of various 4.0 technologies and obtained the radar shown in Fig. 2. It can be noted that the “construction” and “customer service” sectors are those that show the greatest presence in terms of the installation of technologies. On the other end of the scale, the cleaning and sales sectors have implemented these technologies in a lesser way.

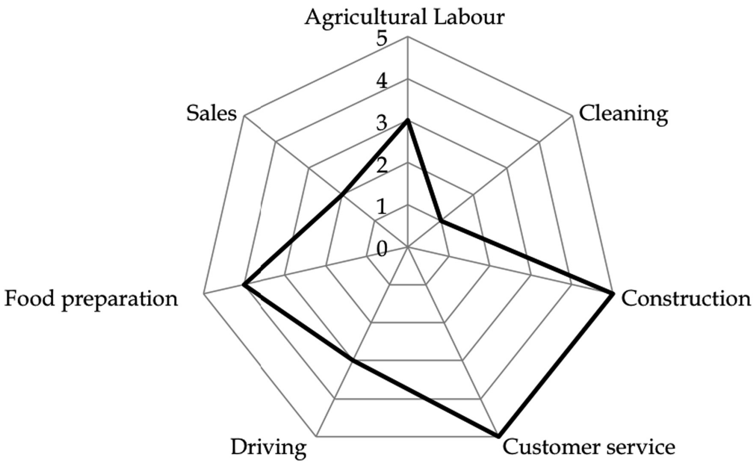


**Fig. 2.** Presence of 4.0 technologies by sector

## 4 Conclusion and Perspectives

This paper discussed the implementation of Industry 4.0 in SMEs. After exploring the foundations of Industry 4.0 and the existing literature relating this subject to SMEs, it was found that there is a significant relationship between the size of a company and the implementation of Industry 4.0. Large companies are much more advanced in integrating information technology systems into their production facilities. For SMEs, it is more difficult due to the investments required and the challenges that come with integrating 4.0. However, to compensate for lack of funds, governments have released many financial aids. In addition, the application of 4.0 in SMEs is characterized by the integration of new internal processes such as the reorganization of flows to increase flexibility and training. Training employees to master these new technologies is a major challenge for both companies and governments.

In response to this observation, we conducted a literature review to determine which sectors were the most important in terms of number of employees, namely: (i) Trade, Transport and Accommodation; (ii) Industry; and (iii) Services and Administration (3). In order to establish a link with digitalization, we highlighted the most important sector in terms of investment in digitalization: the service sector. The service sector is very important from an economic point of view and is also the sector that has invested the most in digitalization.

Compared to previous studies on the implementation of Industry 4.0, this article provides a synthesis matrix based on scientific sources, which includes the different industrial sectors and the different technologies that are used in each of them. This matrix allowed a cross-analysis between the sectors most vulnerable to change and the type of digitalization with high potential already in place. Our synthesis of the reviewed works allowed us to identify the SMEs sectors with highest levels of 4.0 implementation, which are: “construction”, “customer service” and “food preparation”.

Industry 4.0 offers real opportunities to increase flexibility and simplify operational management. SMEs can clearly benefit from 4.0 if they establish a solid training and financing plan. The investments are significant, but the effects are quickly visible and allow significant savings in terms of cost. Developing 4.0 operating systems will make manufacturing systems more flexible and allow for better product customization by creating a close relationship with their customers. Finally, to deepen and complete our study, it seems relevant to us to make a comparison between Industry 4.0, SMEs and employability because we still have little backward step on the creation and/or destruction of jobs with regard to these new technologies.

Our literature review has some limitations. First, it is a qualitative study that does not quantify the impact that may or may not generate the presence of SMEs within the industry. Based on available information, it seeks to generate a summary of the current state of the development of the different technologies, but this does not rule out the possibility that companies may be found in sectors that were not considered in this study. Future research should focus on investigating the most attractive technologies to implement depending on the sector. This should include what investments should be made according to sector and what economic impact including any of these technologies would have on a company.

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# Reconfigurable Manufacturing: A Case-Study of Reconfigurability Potentials in the Manufacturing of Capital Goods

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**Abstract.** The capital goods industry supplies highly volatile marketplaces with products customized to increase product performance and reduce operating costs. Consequently, an order winning criteria for capital goods manufacturers is to quickly and effectively reconfigure supply and manufacturing systems to suit ever changing product and volume requirements within short time frames. In order to clarify such potentials of reconfigurability, this paper presents a case study on reconfigurability potentials in a large capital goods company. The framework applied for this relates reconfigurability drivers with different production levels and purposes. The findings suggest that local content and sub-contracting requirements are main drivers for the potential application of reconfigurability on network level, being reinforced by reconfigurability on system and equipment level. Thus, the paper extends previous research on reconfigurability and addresses potentials beyond shop floor level in a multi-dimensional approach.

**Keywords:** Reconfigurable Manufacturing · Configuration · Case study

## 1 Introduction

Today's global manufacturing environment is characterized by several trends that challenge traditional manufacturing concepts and entail development of new changeable and reconfigurable concepts which at the same time are efficient and responsive [5]. For instance, in high-value manufacturing, a stage-wise postponement of committing order specifications is often required by the customer due to uncertain requirements, rapidly shifting local regulations, frequent new product offerings, and increased local content requirements [13]. Such conditions are particularly challenging in the capital goods industry, where engineer-to-order (ETO) products are sold through highly competitive tendering schemes and postponement of order specifications has a profound impact on multiple levels of the supply chain and manufacturing system [4]. Thus, capital goods manufacturers must be able to rapidly react and reconfigure supply


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and manufacturing systems with the aim of producing multiple customized product variants. Moreover, such companies must be scalable in terms of adjusting capacities for different variants, for new products, and for changing order sizes [12].

Thus, in capital goods manufacturing, the scope and rapidness of changes that need to be handled cost-efficiently is generally increasing. For this purpose, product modularization and configuration has been widely addressed, providing various methods and tools for creating configuration models, making these models available to the market through a configuration system, and establishing configuration tasks to specify the final product configuration [11]. However, improved responsiveness and efficiency for manufacturing and suppling increasing product variety and customizations, made available through the configuration system, is likewise needed. In regard to this, the Reconfigurable Manufacturing System (RMS) was introduced in the 1990's along with the concept of reconfigurability being an engineering technology providing less costly and quicker response to unpredictable market changes [9]. Reconfigurability is a system's ability to change its structure and resources rapidly and cost-efficiently, in order to possess exactly the capacity and functionality needed, exactly when needed [8]. To achieve reconfigurability, a system must have the following enablers; modularity, integrability, customization, scalability, convertibility, automatability, mobility and diagnosability [2]. To harvest the benefits of reconfigurability, it is crucial to realize these enablers on multiple productions levels spanning from equipment and workstations at individual manufacturing sites, to complete factories and global supply networks [7]. This is particularly evident in the capital good industry, where supplying products requires a complex interrelated network of assembly and production. However, previous research on reconfigurability has mostly focused on its potentials and applications on shop floor level in settings with medium to high manufacturing volume and with limited consideration of the complete manufacturing network as well coverage of manufacturing settings relying on ETO principles [1, 3]. Thus, the objective of this paper is to establish an overview of potentials for reconfigurability on multiple production levels and their relationship towards reconfigurability drivers and purposes, using a case study from the capital goods industry as the empirical foundation.

The remainder of the paper is structured as follows: Sect. 2 present the research methodology, while Sect. 3 presents the findings from the case study in accordance with the applied framework for reconfigurability potential assessment. Section 4 conclusively summarizes the results and provides future research directions.

## 2 Research Methodology

In order to investigate potentials for reconfigurability across multiple production levels, the research presented in this paper applies an explorative case study in a company manufacturing capital goods for the energy sector. The company has a yearly revenue of 10,1 bnEUR, has 24.648 employees and is a market leader with a global reach of 43 countries and a manufacturing footprint of 73 factories in 24 countries. The case study research method can be described as the study of past or current phenomenon drawn from multiple sources of evidence, for example interviews, observations and archives [10] and is well suited when the researched phenomenon needs to understood in its context, and where exploration of concepts and variables may be needed [14]. Thus, the case study presented here consists of semi-structured interviews with 12 central employees covering 8 meetings with approximately 60 min duration. The interviewees include vice presidents, production engineering specialists, factory managers and global industrial senior specialists in modularization and supply chain management. Two of the interviews were further combined with factory visits and half day work-shops. Each interview began with a background introduction to the concept of reconfigurability, followed by 3 primary questions; (1) Which, if any, reconfigurability initiatives exists in the company? (2) What are the potentials for reconfigurability in the company? (3) Who are the stakeholders for reconfigurability in the company? Extensive field notes were taken during the interviews and factory visits, which were afterwards coded and categorized in "drivers" and "potentials". Each driver was further grouped based on impact similarities. The potentials were categorized based on whether they would benefit change in manufacturing of different variants, change in manufacturing of different volumes or change due to the introduction of new products. As the last step, the drivers and the grouped potentials were assessed and consolidated to one or more production levels. This relational overview was finally shared with the involved stakeholders for the sake of validation and to receive feedback and make final adjustments.

# 3 Case Study Findings: Potentials of Reconfigurability

## 3.1 Manufacturing Reconfigurability Drivers

In the case study, 27 drivers of reconfigurability were discovered and consolidated into 5 main categories, see Fig. 1.

| Strict market entry regulations | Diversity in supply cost structure | Requirements for local supply | Improved capabilities of sub suppliers | Scope increases for deliverables | Lifecycle priority | Costs reduction initiatives | Improved product performance | Shorter time to market | Shorter lead time | Changing customer requirements | Rapid introduction of new technologies | Competitive industry | Vulnerable to substitutes | Short product lifecycles | Uncertain demand and volume | Uncertainty in product mix | Uncertain product requirements | Divers and local logistic regulations | Divers saturation levels | Frequent and late change to product specification by the customer | Divers demand timing | Increased product variety | High buyer power | Local regulations and requirements | Higher risk endurance by companies | Repowering of installation fleet |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Local content and sub-contracting requirements | | | | High competition on customer ROI | | | | Frequent introduction of new products | | | | | | | Uncertain and divers demand | | | | | | | Requirements for non-offered products | | | | |

**Fig. 1.** Reconfigurability drivers and their categorization.

The company operates in an environment where strict regulations for entering local markets exist and local suppliers are emerging and improving capabilities to match or exceed the quality of the dominating manufactures. Therefore, a continuous need to reduce lifecycle costs and manufacturing costs exists, in order to improve return on investment (ROI) for the customer without compromising product performance.

Furthermore, the company encounters high needs for frequently adapting the supply system to new product introductions and rapidly shifting and uncertain product specifications, amplified by shorter time to market, shorter lead time, vulnerability towards substitutes and local divers logistic and installations requirements. Lastly, an important driver is the supply system's ability to support the sales and production of products not yet designed, ETO products, as well as reinstating phased out products in manufacturing to repower existing products or create new deliveries in sales projects.

### 3.2 Production Levels and Reconfigurability Objectives

In order to classify and analyze potentials of reconfigurability triggered by the drivers, a hierarchy of production levels is adopted from ElMaraghy and Wiendahl [6]. The relationship between each production level and the product structure is depicted for the case company in Fig. 2.

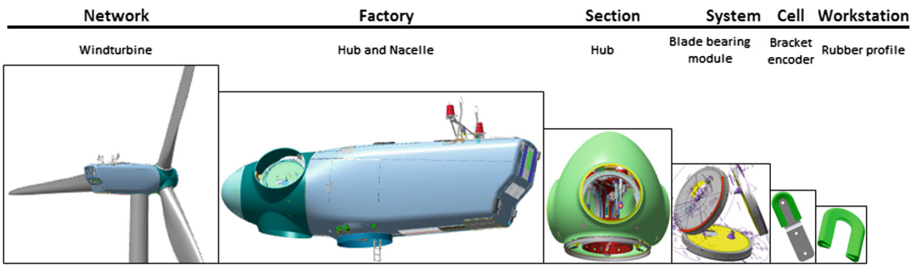


**Fig. 2.** Relationship between production levels and product structure.

The lowest level contains the workstations. Workstations apply one or multiple manufacturing techniques on a workpiece to transform it into a part element. The next level is a grouping of manufacturing resources into cells, consisting of multiple workstations that transforms multiple part elements into a single assembly part. On the system level, different variants of product modules/building blocks are manufactured from a collection of cells. The bracket from the cell level in Fig. 2 is part of the blade bearing module's BoM at the system level. Combining different product modules at the section level creates complete products ready to be shipped. In the case company, factories produce multiple products, which are either assembled and shipped or shipped separately and assembled at the construction site. The last level is the network level, which consists of interconnected factories producing different products. At the network level, products from multiple factories e.g. blades, tower and controls are shipped to the construction site and assembled to form the complete wind turbine. The drivers for reconfigurability impose changes to the supply system on all production levels. The potentials for accommodating these changes through reconfigurability depends on the purpose of the change, the reconfigurability driver and the production level. This research therefore applies the reconfigurability objectives suggested by Tracht and Hogreve [12] to further focus reconfigurability potentials and their objectives. The objectives are: (1) Variant: Reconfigure the supply system from currently suppling one kind of variant to suppling different ones, (2) Capacity: Reconfigure the capacity of the supply system to either increase or decrease supply volume, and (3) Product: Reconfigure the supply system to adapt the supply of new products.

### 3.3 Potentials of Reconfigurability Considering Multiple Levels and Objectives

The potentials for implementing reconfigurability identified in the case company are mapped with drivers, objectives and the six production levels described in the previous subsections, see Table 1. On the left-hand side, the 3 objectives for reconfigurability (V = variant, C = capacity, P = product) are represented for each of the 5 drivers. The combinations of drivers and objectives are mapped with reconfigurability potentials for each production level, represented at the top. The table should be explored by reading the potentials in combination with its drivers and objectives at different production levels. For example; the increase of local content requirements drives the company to reconfigure the supply system at the network level so that local supply chains are enabled to supply localized markets with multiple product variants from local suppliers.

**Table 1.** Empirical findings of potentials for reconfigurability.

| | | Network | Factory | Section | System | Cell | Workstation |
|---|---|---|---|---|---|---|---|
| Local content and sub-contracting requirements | V | - Supplying localized markets with multiple variants from local suppliers | - Reusing technology and operational approaches across multiple products | - Increase mobility through the factory in a box concept | - Enable division of work for specialized local suppliers | | |
| | C | - Enabling suppliers to produce near the customer<br>- Rapidly establish and expand local capacity<br>- Scale and adapt distribution of product variants<br>- Share capacity between manufacturing hubs thereby chasing local demands and reducing inventory | | - Decrease capacity loss though linking diagnostic capabilities with sub suppliers and manufacturing systems by means of harvesting local manufacturing data through a common manufacturing platform | | | |
| | P | - Entering new markets faster by establishing local configurable supply chains | - Confine impacts of manufacturing implementation of local product variants | - Adapt to different local cost structures | | - Faster implementation and ramp-up of local suppliers<br>- Sharing manufacturing setup with other industries thereby increasing the use of qualified suppliers | - Improve utilization of local capabilities due to standardization of manufacturing techniques<br>- Adapt manufacturing equipment to local regulations |

(*continued*)

**Table 1.** (*continued*)

| | | Network | Factory | Section | System | Cell | Workstation |
|---|---|---|---|---|---|---|---|
| High competition on customer ROI | V | - Reduce costs by establishing industry standards across competitors thereby enabling sub-suppliers to benefit from producing similar components | | - Increase mobility through the factory in a box concept | - Enabling the division of highly process oriented manufacturing into a more cost-efficient assembly sequence | | |
| | C | - Improve portfolio profits by adapting capacity to the most cost-efficient supply for each sale project | - Reduce transport cost by producing smaller assemblies which fit within a standard container | | | - Establish automatability to reach optimal balance between manual vs. automated manufacturing processes<br>- Automating standard parts of operations<br>- Faster training of personnel due to division of labor<br>- Standardized manufacturing resource interfaces | |
| | P | - Reduce costs by establishing supply chain interface management and reuse relevant parts of existing setup | - Faster maturity of margins due to faster and less expensive ramp-up | - Enable optimization of production setup without compromising future product design and performance | - Designing for economies-of-scale for relevant parts of the product | | |
| Frequent introduction of new products | V | | - Manufacturing resources can be configured to manage product families with different weight and space requirements | | | | |
| | C | - Portfolio approach to incremental implementation of new products in production | - Configurable and scalable buildings/facilities for space and weight adaptation | | | | |
| | P | - Reduce time to market by reusing distribution setups between factories and customers by having a global lead factory concept | - Faster integration of new products in brown-field manufacturing<br>- Reduction of cost for certification and testing | - Reuse of testing equipment functionalities and rapid prototyping<br>- Reuse of manufacturing resources<br>- Control and alignment of change in product modules with the manufacturing setup | | - Faster and more flexible rearrangement of workstations<br>- Reduction in time for changing the manufacturing layout for new products | - Reuse and smaller adjustments to equipment architectures for lifecycle cost reductions<br>- Increase equipment lifetime by modularizing the replenishment of spare parts |
| Demand uncertainty and diversity | V | - Increase supply responsiveness independently of product mix | - Reduce transportation costs when implementing large manufacturing equipment shipped from lead factory | - Better exploitation of space in manufacturing and storage areas | - Responsive production planning due to standardization<br>- Modular relationship between product properties and manufacturing functionalities | - Information configuration e.g. documents, routings, work instructions etc. | - Faster change-over between operations |
| | C | - Faster scaling of supply network capacities and capacity on demand | - Scaling of capacity according to demand thereby reducing product inventory and increasing profit | | - Easier line balancing when shifting between variants and rearrangement of workstations to even-out takt-time for bottlenecks | | |
| | P | | | - Adaption to new and old technology introductions in manufacturing | | | |

(*continued*)

**Table 1.** (*continued*)

| | | Network | Factory | Section | System | Cell | Workstation |
|---|---|---|---|---|---|---|---|
| Requirements for non-offered products | V | - Reuse of manufactured ETO parts across multiple product variant | | | - Parameterized manufacturing to optimize product performance for specific customer sites | - Integrate additive manufacturing with reconfigurable manufacturing thereby increasing ETO manufacturing capabilities | |
| | C | | | - Reduce capacity consumption of ETO products | - Enabling production of phased out product variants | | - Adaptable flexibility to cope with ETO design while maintaining the benefits of mass production for standard products |
| | P | - Long term manufacturing design based on product roadmap<br>- Faster alignment between ETO and standard manufacturing across products | | - Minimize information needed to prepare and design manufacturing setups and equipment | | | |

It should be noted, that the results in Table 1 solely present initial explorations of reconfigurability potentials gathered during the interviews and thus do not address how these can be realized or achieved in detail through specific reconfigurable solutions. In the following, the potentials are described in detail.

**Local Content and Sub-contracting Requirements**

On the network, factory and system level, the reconfigurability potentials are focused on the mobility of manufacturing resources and the fast establishment of local supply chains, with the purpose of producing closer to the customer and reduce inventory by moving capacity among manufacturing hubs and suppliers. A further focus is the potential of diversifying the design of manufacturing setups depending of local cost structures. For example, in some countries it is more profitable to employ manual labor instead of automated machines. On the system, cell and workstation level, the potentials are dedicated to an easier division of work between local suppliers and standardization of manufacturing techniques across industries to increase the use and scope of local suppliers and reduce ramp-up time for local supply.

**High Competition on Customer ROI**

The company has initiated a network and factory level initiative across competitors to standardize both product and manufacturing design, thereby reducing cost for suppliers producing sub-components. The mobility and integrability enabled by reconfigurability will further empower the company to produce a more diverse range of variants at each factory, thereby reducing the cost for the entire portfolio of sales projects and a more rapid maturity of margins due to planning production where it is most cost-efficient compare to the demand. At the section and system level, the main potential is to divide the process-heavy manufacturing steps into more cost-efficient assembly operations and further ensure economies-of-scale benefits for standardized components without compromising product design and performance.

**Frequent Introduction of New Products**
When introducing new products into the supply system, the emphasis is given on practical issues for capital goods, namely their extraordinary requirements for space and weight. These requirements apply from the network to the system level, as the components at these levels are large enough to cause challenges. These challenges can be diminished by designing modularized, scalable, configurable buildings, equipment, distribution tools and testing facilities on an incremental factory by factory basis.

**Demand Uncertainty and Diversity**
When changing between products in manufacturing, the potentials are mainly related to the enabling of the supply network to deliver capacity on demand and thereby become responsive independent of which products are sold. On the factory and section level, the focus is again on the size and weight requirements of the products. At these levels, cost reduction is sought by modularizing large transport and manufacturing equipment, which further enables a more optimized exploration of space when changing from one variant to another or moving the product between manufacturing cells. On the cell level, the great potentials of reconfigurability is within information configuration and planning. The mobility of resources in the manufacturing system enables the rearrangement of workstations and easier line balancing when changing between variants.

**Requirements for Non-offered Products**
Non-offered products can be both previously produced products, ETO products and products still in the development phase. Reconfigurability is challenged by this driver because of its dedication to the offered product program. The most significant potentials are adaptive flexibility on cell and work station level by the means of integrating additive manufacturing techniques (e.g. 3D printing) together with reconfigurability to keep mass efficiency for standard products, but with the ability to add additive resources with the purpose of further customization. On the network and factory level, the company can benefit from reconfigurability by aligning manufacturing and product development roadmaps, thereby preparing long term ETO product demand together with increased efficiency.

## 4 Conclusion and Future Research

The objective of this paper was to establish an overview of potentials for reconfigurability on multiple production levels and their relationship towards reconfigurability drivers and purposes, using a case study from the capital goods industry as empirical foundation. The multi-level approach enables a contribution to the body of literature by presenting a consolidated assessment of potentials for the entire supply system, which appears particularly suited in large enterprises and capital goods companies. The case study shows that reconfigurability should be regarded on all production levels to fully realize the potentials within each driver for manufacturing changes. The potentials are mostly triggered by the drivers for *local content and sub-contracting* requirements, as well as *customer ROI* and *demand uncertainties and diversity*. Both potentials and drivers are consistent with current knowledge but are now further empirically investigated and structured across all production levels and additionally related to manufacturing change objectives. The structural relationships are represented in a matrix format and categorized for its implication of applying reconfigurability. The drivers are argued to be general applicable across the capital good industry, whereas the potentials are case specific for companies supplying large products through global supply networks, and where ROI for the customer is the main order winner.

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# A DSM Clustering Method for Product and Service Modularization

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**Abstract.** Many manufacturers are in the process of evolving from mass production to mass customization to cope with the increasing diversity of customer requirements. This induces an increasing complexity resulting from the high variety offered to customers. This problem is heightened by integrating product and service within the same offering. Modularity is considered as a driver for reducing complexity while increasing offered variety of products and services. This paper addresses the question of how to modularize products and/or services considering different criteria from the designers and domain experts. To this end, a Design Structure Matrix (DSM) based method is introduced. The method relies on a set of modularization criteria and on clustering to form product and/or service modules. The applicability of the method is illustrated through a test case in the manufacturing sector.

**Keywords:** Product modularity · Service modularity · Clustering · Design Structure Matrix · Variety management

## 1 Introduction

Implementing Mass customization (MC) has several benefits but also comes with several challenges, such as the increased internal complexity resulting from offering high variety for different customers. Several researches have focused on how to decrease this complexity while keeping a reasonable level of offering variety [1]. The principle of modularity a promising means to meet this objective [2]. Modularity ensures reuse of components implying faster response with fewer resources. This helps in providing efficiently tailor made offer to customer [2]. Modularity has been widely used in product design and to some respect in process design [3]. More recent research works have shown that this concept started to gain more interest in the service engineering domain [4–6]. This article focuses specifically on a method for modularizing products and/or services. The aim is generate offering variety in a standardized way of forming modules. Design Structure Matrix (DSM) is used as a tool to evaluate the products and/or services interrelationships using several predefined criteria. A hierarchal clustering algorithm is


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used to form modules based on the similarity criteria. Unlike the traditional methods focusing on product or service separately, the proposed method suggests that similarity is studied also between products and services. This allows for easing the management of the products and services operations during subsequent use phase and is likely to generate potential economies of scales.

The remainder of this paper is structured as follows: Sect. 2 provides a brief overview of modularity, clustering and clustering evaluation. Section 3 describes the general steps of the methodology. Section 4 focuses on an illustrative test case. Section 5 provides concluding remarks and discusses research perspectives.

## 2 Literature Review

This section provides a brief review of the literature on modularity and on clustering. The objective is to gain some insights into whether existing approaches can be adapted to the context of the current research. A major challenge in MC companies that needs to be dealt with is the internal complexity coming from product or service variety. Such complexity is heightened when considering product and service jointly in the offering [7]. Nowadays a key to address these challenges is modularity which is a means for enhancing flexibility and increasing variety [8]. While much research was concerned by either product modularity and to some extent service modularity, little research has focused on applying modularity to a mix of products and services [6]. [9] provided a modularization method of Product Service System (PSS) based on the functional requirement and by using fuzzy clustering algorithm. [10] focused on the relationship between service and product and how they can cope with the customer service and physical needs. Modularization have been coupled with several methods and tools, such as DSM.

DSM is used for modelling and structuring relationships between elements that are part of a complex system [11]. DSM provides a valuable input for the clustering process. This latter relies on several algorithms such as hierarchal clustering and k-means [12]. Algorithms falling under hierarchal clustering category group the elements following a hierarchal procedure. Each element is assigned to a given group (starting with a one object group comprised by the element itself) after which the algorithm iteratively joins the two most similar elements into one cluster. The process continues this way until there is just one big cluster with all the elements [13]. Dendrograms are used to illustrate the results showing the modules. Clustering can then be evaluated using several metrics. [14] provided an evaluation comparison between several clustering method using minimum description length (MDL) which refers to the assignment of elements to a cluster. [15] developed a metric that measures the intra and inter module connectivity in a modularity matrix. Evaluating clustering results provides valuable support for choosing the best way of modularizing the offering consisting of products and services.

While some methods are available in the literature, they have mostly been applied to product domains and to some extent service domain. Next section introduces a holistic method for modularizing products and/or service.

# 3 Proposed Method

The key phases of the proposed method are data preparation and clustering. Data preparation consists of identifying products and/or services and on building the DSM. This is a preparatory phase aiming at (i) identifying the granularity level of existing products and/or services, which are included in the offering and (ii) building the DSM based on gathered data [5]. The focus of the subsequent sections will be on building the DSM and the clustering process, respectively.

## 3.1 Building DSM

Building up the similarity relationship of products and/or services will result in forming the integrated modules. Building DSM is detailed into five steps as shown in Fig. 1.

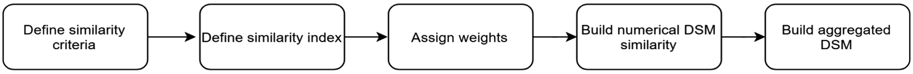



**Fig. 1.** Detailed steps for building DSM

**Define Similarity Criteria.** The first step is to define the needed criteria that will result in finding similarities between the elements (product and/or services components). Due to the complexity of similarity evaluation, it is necessary first to identify appropriate criteria for assessing such similarity. A set of generic criteria have been identified as candidates for this step:

– Functional requirements: refers to which extent given elements contribute to fulfilling the same functional requirement. The resulting similarity can be assessed by customers and design engineers [9].
– Commonality: measures the simultaneous occurrence of given elements in different products and/or services [4].
– Human resources: refers to whether two elements are supported by the same resource. For example, a multi-skilled engineer can be a common resource in two elements that will result in a similarity relationship.
– Technological information: refers to whether two elements rely on the same tools (hardware or software) or share certain information.

**Define Similarity Index.** Based on the defined similarity criteria, the elements' interrelationships are evaluated through experts' judgement resulting in the assignment of similarity indices to these relationships. The value of each similarity index ranges from 0 to 3. A complete similarity receives an index of 3 and 0 is given if there is no similarity. 1 is assigned for weak similarity and 2 is assigned for intermediate similarity.

**Assign Weights.** A weight is computed for each of the predefined criteria based on experts' judgment. The weight of a criterion reflects its relative importance, the nearer it is to 1 the more important this criterion is. The sum of the weights of the indices has to be equal to 1 (see Eq. 1).

$$\sum\nolimits_{k=1}^{n} w_k = 1 \tag{1}$$

Where $w_k$ is the weight assigned to the $k$th similarity criteria and $n$ is the total number of predefined criteria.

**Build Numerical DSM.** DSM is used to visualize and document the similarity indices. Each (product or service) element is represented by one DSM coefficient. A DSM$c$ will be built for each criterion $c$.

**Build Aggregated DSM.** An aggregated matrix $A$ will be generated based on the DSM$c$. The coefficients of $A$ denoted $\mathrm{c}_{\mathrm{ij}}^{\mathrm{A}}$ results from the weighted sum of the ones in step 3 from the initial matrices, denoted $\mathrm{c}_{\mathrm{ij}}^{\mathrm{k}}$. For $n$ criteria, the coefficients of $A$ are calculated according to Eq. 2.

$$c_{ij}^{A} = \sum\nolimits_{k=1}^{n} c_{ij}^{k} \times w_k \tag{2}$$

### 3.2 Cluster Aggregated DSM

The $A$ matrix is the starting point for the clustering. Hierarchal clustering was chosen for realizing the clustering at this point as it is considered one of the most used algorithms in the area of data mining [13]. First, the distance between two elements in the aggregated DSM is calculated by using the Euclidian distance, based on their coefficients in $A$, these results in a distance matrix. The elements with the shortest distance are grouped together first forming an initial cluster. Afterwards, the value of the distance matrix of these two elements is averaged and a new distance matrix is generated. This process continues until all the elements are grouped together into one big cluster. Complementarily, a dendrogram can be used to provide a visual illustration of the hierarchal clustering. A cutting level can be defined according to the expected clustering quality, to derive the clustered modules. The lower the level the higher the number of clustered modules. Depending on the acceptable quality level by the decision makers, several alternative clusters could be identified through the cutting level.

### 3.3 Clustering Evaluation

Several alternative modularization scenarios could be considered out of the clustering process. It is either because of the defining criteria or weight assignment or as well the clustering method. Therefore an evaluation of these alternative scenarios is required to decide which one is the most appropriate. Several modularity indices have been proposed to evaluate the performance of the clustering. One basic evaluation consists in measuring the number of the clustered modules. Another one is to measure the connectivity of inter and intra module of the modularity matrix [15].

# 4 Illustrative Test Case

This section briefly illustrates the proposed method with particular focus on building the DSM and deriving the modules. The target company is a supplier to the wind turbine industry that offers a high variety of services to the customers. In this example, the service ‘transport booking’ with four different variants is used in the method. Modularization of the services is offered by the company to enhance the flexibility and be able to offer new customized offering without designing a service from scratch. The DSM inputs are the activities of the customized service and the outputs are the modules of those activities to form the required services.

## 4.1 Building DSM

The input data for building the DSM are four service blueprints that define the service process for each of the offered service variants. Each service blueprint includes information about activities, resources, technological information and materials. The service blueprints have been analyzed to extract the required information for building the interrelationships.

**Define Relationship Criteria.** Analyzing the data from the blueprints helps in identifying the four criteria to build up the similarity depending on them. All four criteria (functional requirement, commonality, human resources and technical information) that were described in Sect. 3.1 can be used based on the analysis of the blueprints. An example for the functional requirement criteria is “checking whether information is correct” as several activities are done with the purpose of validating the information. As well, several activities share the same purpose of the functional requirement “create the reservation on customer portal system”, meaning that these could be potentially grouped in one module. The HR resources in the data gathered are logistics representative and warehouse operator. The similarity here refers to which extent do the activities share each of the above resources. This principle applies also to the technical information criterion.

**Define Similarity Index.** The activities and criteria are given to a group of experts and managers to assign the similarity indices. They have background about the case specific information as well as industrial engineering and engineering design at large. The interrelationships are assigned indices between 0 and 3 based on each criterion. For example, both activities “insert pallet with unique reference number” and “Upload delivery note to booking” share the same technical material and the needed information that are the customer’s transport management system and the computer. Therefore, the similarity is high and the corresponding index is estimated to 3. On the other hand, the activities “insert pallet with unique reference number” and “print CMR papers” share just 1 out of 3 material and information that is the computer. Because of that, the similarity between them in technology information criterion is weak so they will have 1 as a similarity index.

**Assign Weights.** Based on Eq. 1, the sum of all weights should equal 1. Based on the experts' points of view, all the criteria should have equal weights. Therefore, all of them will have a weight of 0.25.

**Build Numerical DSM.** Four numerical DSMs are formed representing the similarity indices of each the four criteria. An excerpt of the functional requirement DSM is shown in Table 1. Because of the space limit, the full DSM will not be detailed.

**Build Aggregated DSM.** The aggregated matrix 'A' shown in Table 1. By using the data from previous step and applying the weight indices of 0.25 to each criteria, the coefficient between the two activities 'print CMR papers' (A33) and 'upload delivery note to booking' (A31) for the aggregated matrix will be (based on Eq. 2):

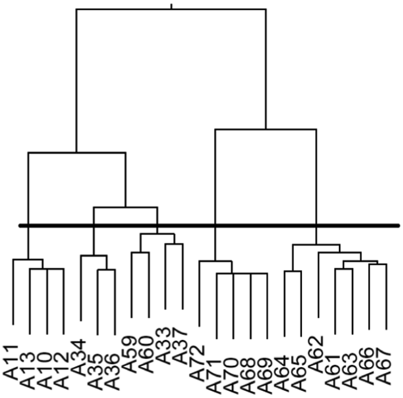
$$c_{3133}^{A} = 0 \times 0.25 + 1 \times 0.25 + 3 \times 0.25 + 1 \times 0.25 = 1.25$$

**Table 1.** Part of the functional criterion DSM and the aggregated DSM

| A | Functional requirement DSM | | | | Aggregated DSM | | | |
|---|---|---|---|---|---|---|---|---|
| | A30 | A31 | A32 | A33 | A30 | A31 | A32 | A33 |
| A30 | 3 | 2 | 3 | 0 | 3 | 2.25 | 2.5 | 1.25 |
| A31 | 2 | 3 | 2 | 0 | 2.25 | 3 | 2.25 | 1.25 |
| A32 | 3 | 2 | 3 | 0 | 2.5 | 2.25 | 3 | 1.25 |
| A33 | 0 | 0 | 0 | 3 | 1.25 | 1.25 | 1.25 | 3 |

## 4.2 Cluster Aggregated DSM

The aggregated matrix *A* will be rearranged to form the initial clusters of service activities that can form the modules. Hierarchal clustering was applied at this point. A dendrogram is used to represent the clustering results (Fig. 2). Several scenarios of forming clusters can be done. One effective factor is the cutting level for the dendrogram plot. With a cutting level at 5 (height in the dendrogram), the activities A11, A12, A13 and A14 are combined in a single module (module 1). By analyzing the modules, it can be seen that module 1 is related to loading the cargo. Clearly, the final decision on the cutting level pertains to the practitioner who can evaluate properly the tradeoffs between clustering quality and implications to the design and operations.




| | |
|---|---|
| A10 | Carrier arrives at Nissens |
| A11 | Carrier gives SHP number to warehouse operative |
| A12 | Carrier loads truck |
| A13 | Carrier takes off from Nissens |
| A33 | Print CMR papers |
| A34 | Handover CMR papers and labels |
| A35 | Put labels in their respective plastic pocket |
| A36 | Labels are glued on pallets |
| A37 | Warehouse operative handover CMR papers to carrier |
| A59 | Enter PO number |
| A60 | Get delivery note from ERP system |
| A61 | Find customer's item number in delivery note |
| A62 | Enter customer's item number |
| A63 | Attach delivery note |
| A64 | Open shipment list |
| A65 | Find number of pallets |
| A66 | Enter number of pallets |
| A67 | Send email to customer |
| A68 | Wait for customer to send back an email with possible delivery slot |
| A69 | Receive email with possible delivery slot |
| A70 | Send email to shipping agent to ask if delivery slot fits |
| A71 | Send new email to customer and request new timeslot |
| A72 | Send confirmation of timeslot |

**Fig. 2.** Part of the Dendrogram for the hierarchal clustering with activities

## 5 Discussion

An illustrative case study of service modularization of a company was addressed. For this case, all the criteria were important to be defined. The method was found effective for service modularization as it brings out modules in a standardized manner. Therefore, it can help in faster design and in more agility against requirement changes. While the test case is a service company, the proposed method can still be applied to product and/or service modularization. For other cases that can be pure product or integration of product and service, the defined criteria can be changed but it will not affect the method as much as it affects the grouping of the elements into modules. Therefore, it is necessary to analyze the criteria that will build up the similarity interrelationships. Therefore, defining the criteria needed is based on the expert's point of view. One other factor that affects the number of output modules is the cutting level for the dendrogarm of hierarchal clustering. Another factor that can affect the output modules is the similarity indices and the weight assignment for building the aggregated DSM matrix. A promising research perspective is how to find the most appropriate modularity scenarios based on a combination of the above factors. Modularizing the offer is likely to reinforce the economies of scales of the company and as well increase the flexibility that will enhance directly the idea of mass customization of product and/or service.

## 6 Conclusion

This paper proposes a new method for modularizing products and/or services. The idea of the method is to be workable for applying it on product and/or service. The method helps in building similarity relationships between products and/or services according to several predefined different criteria. Clustering using hierarchal algorithm was proposed and supports the idea of forming modules through identifying similarity relationships. Evaluating the performance supports the comparison of different modularity scenarios, which will have a valuable support for decision makers of variety management.

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# Customization and Variants in Terms of Form, Place and Time

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**Abstract.** The interest in customization has increased due to globalization, and globalization makes competing on price more difficult if access to low-cost production is unavailable. Customization usually implies the creation of variants, where the final products are customized in form, place and/or time. However, the relation between customization and variants is unclear; therefore, the purpose of this study is to analyze customization in terms of form, place and time, as well as relate it to product proliferation (i.e., variant creation). Here, a time perspective is used, creating a clear relation to flow thinking. Using flow thinking and the two strategic decoupling points related to flow driver (customer order decoupling point) and flow differentiation (customer adaptation decoupling point) provides a better understanding of *what*, *where* and *when* customization can be applied.

**Keywords:** Customization · Product proliferation · Flow thinking · Decoupling point

## 1 Introduction

The increase in globalization and offshoring of production to low-cost countries have led to greater pressure for cost reduction, especially on standardized products. In this context, the ability to offer customization can help offset the disadvantages of producing products in high-cost countries, for example. Customization usually implies a higher degree of product proliferation (i.e., introduction of variants), and although these concepts are closely related, there are some differences between them. However, this distinction is not always straightforward. Customization is a concept that is frequently used to distinguish between standardized and customized items. The pure cases are usually obvious, such as when a company designs and then produces a product based on a specific customer order or when a commodity is produced based on speculation and is stocked and sold in a retail store. However, when a modular product is designed so that it can be configured based on a customer order, using a predefined solution space, it is not as evident in the literature whether the product is standardized or customized. This example is related to the question of *what* is to be produced, that is, **form**. However, according to Debreu [1], an offering is characterized by not only its physical properties (form) but also *where* (**place**) and *when* (**time**) it will be available. Consequently, if place and time are included, more challenges arise in defining whether something is standardized or customized. A variant is also a more general term than


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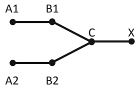
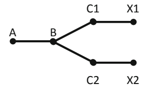
customization since it is not bound to a direct (real) customer demand and may instead depend on the characteristics in the bill of materials (BOM). Therefore, the purpose of this study is to analyze customization in terms of form, place and time, as well as relate it to variants.

## 2 Physical Flow Structures and Time-Phased Flow Structures

Value is created in a network of activities, where input is transformed into output. This value creation is characterized by the resources used, flow control and flow structure, among others. The flow structure is of special interest in customization and variant creation. Nonetheless, as customer demand also covers when a demand arises in relation to the cumulative lead time, the time perspective is of interest as well.

Flow structures focusing on form and place are called physical flow structures. This type of structure involves different levels of abstraction; it is therefore necessary to decide on a specific level. The so-called AVX classification is often used in the material and capacity requirement literature [2]. This classification is based on the item level, where an item is perceived as indivisible, meaning that the activities (production or transportation) required to transform the item are abstracted and not considered. Instead, the focus is on the material structures (i.e., BOM), where the end product is at the top. The so-called VAT classification is similar, also includes resources and is found in the theory of constraints [3]. As such, VAT does not focus on items but on operations, resulting in a lower level of abstraction. The letters V and A in VAT correspond to the same letters in AVX, where T equals X, but the point of departure is the operation rather than the item. For both the AVX and the VAT structures, two flow structures (i.e., converging and diverging) make up the foundation, as illustrated in Table 1. For a converging flow, B1 and B2 are combined to obtain item C; for a diverging flow, item B can result in C1 and/or C2. A converging flow consists of two or more flows joining in a point to form one flow, meaning that from an end product perspective, it is possible to move upstream the flow in order to identify all parts and raw material input of the flow. For diverging flows, the opposite occurs, where one must start from the raw material moving downstream to identify all parts of the flow and the end products. This means that it is difficult to relate to diverging flows from an end product perspective; instead, one should take a raw material perspective. Diverging flows can further be divided into two main types, namely attribute based and decision based. The attribute-based type is passive, meaning that the end result is already given at the point of divergence, such as when a chemical process splits a raw material into two or more materials. The decision-based type is active, meaning that a decision can be made regarding what mix to create, usually termed variants. These three types of flow structures are summarized in Table 1. The interpretation of flow structures in terms of form transformation has already been discussed, but the place transformation has not yet been explained to the same extent. Essentially, it is about relating identity not only to *what* (form) but also to *where* (place), which is the meaning of the term *stock-keeping unit* (SKU). Place is therefore related to having something at one location (central) or at several locations (local). The place dimension is related more to active decisions rather than attributes.

**Table 1.** Combination of flow structures and form/place.

| |  Converging |  Diverging (attr.-based) | Diverging (dec.-based) |
|---|---|---|---|
| Form | Assembling or mixing | Splitting in a process | Creating variants |
| Place | Moving from local to central warehouse | - | Moving from central to local warehouse |

Time (*when*) is another central property in transformation. Complementing form and place with time creates a representation of all three dimensions. One conventional way of doing this is through a time-phased BOM (see Fig. 1), which is usually illustrated horizontally to clearly illuminate the time dimension of the activities performed (in contrast to a traditional BOM). Each segment of the structure shown in Fig. 1 represents a transformation in terms of form and place. The time phasing means that each transformation step is offset by the corresponding time for each segment, that is, its lead time.

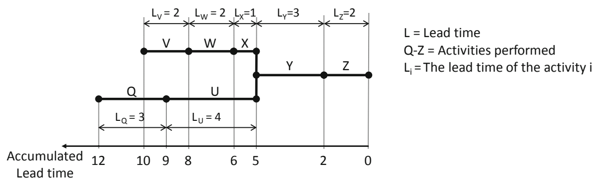



**Fig. 1.** Example of a time-phased flow structure (based on [4]).

The time-phased flow structure depicted in Fig. 1 represents the conditions in a given situation for a given point in time, that is, one state. Since the flow structures can adopt many different forms and combinations, it is difficult to define a generic space of states. Nevertheless, to sum up, this means that all transformations in the three dimensions need to be completed to create customer value. In other words, the demanded combination of form, place and time needs to be attained for the flow state to fulfil the requested state.

## 3 Change of State Through Postponement and Preponement

Flow structures can be changed in several ways, but two concepts explicitly associated with change in form, place and time are postponement [see, e.g., 5, 6] and preponement [7]. The word ‘postpone’ means ‘put off to a later time’ [8]. Although ‘prepone’ is not found in the last cited reference [8], the prefix ‘pre’ means ‘earlier than’, ‘prior to’ or 'before'. To postpone can thus be understood *as to reposition to a later point in time*, whereas to prepone means the opposite, *to reposition to an earlier point in time*. Both postponement and preponement are thus related to changes in an existing state, that is, repositioning an already existing position. Furthermore, both have their basis in the time dimension, meaning that a time-phased flow structure is a suitable point of departure. This also basically means that both terms are based on time and the repositioning of a transformation in relation to a fixed point of reference, which in this case is the customer's requested state. In this paper, the repositioning in time is called 'displacement' and is thus a collective term for postponement and preponement.

### 3.1 Displacement of Form, Place and Time

Displacement of form and place transformation can occur by either creating new flow structures or changing the time required to perform the transformation activities. Table 1 indicates five different types of form and place conversions that can be achieved by displacement. From a form perspective, this means that through postponement, the form is achieved later in the flow (e.g., by modularization), using standardized modules instead of building complete unique products from scratch. In contrast, preponement could be used to create variants of a previously standard product.

Postponement of place transformation usually refers to differentiation in location at a later point in time, for example, by keeping products in a centralized warehouse instead of distributing them to local warehouses. This can be formulated as creating a variant in terms of a product's place property at a later point in time. Correspondingly, preponement means that the variant in terms of the place property is created at an earlier point in time to ensure local availability, for example.

**Table 2.** Combinations of displacement and form, place and time properties.

| | Preponement | Postponement |
|---|---|---|
| Form | Form variant created earlier in the flow structure | Form variant created later in the flow structure |
| Place | Place variant created earlier in the flow structure | Place variant created later in the flow structure |
| Time | Customer order decoupling point (CODP) positioned earlier in the flow structure | CODP positioned later in the flow structure |

Displacement of time seems as if time is counted twice, but here, the term time refers to two different things. Displacement has traditionally pertained to the change of the point in time when a transformation is carried out in relation to the requested delivery lead time [see, e.g., 9]. Displacement therefore conforms to the definition of the customer order decoupling point (CODP), based on how the delivery lead time relates to the system lead time [10]. The CODP is defined as the point that separates the forecast-driven part from the customer-order-driven part of the flow. To summarize, displacement, as well as form, place and time transformation, can be combined in six ways, as shown in Table 2. Basically, there are two types of changes in state. For form and place, the change is related to variants in flow, with an 'absolute' displacement since the displacement is made in time units. Time is then related to the flow driver and a relative displacement since the displacement occurs in relation to the delivery lead time. This also means that for form and place, the points of departure are the individual points of transformation in the flow. In contrast, for time, the point of departure is the CODP, which has its starting point in the delivery lead time.

## 4 Customization and Displacement

Flow structures represent how the transformation of inputs to outputs is performed. The form and the place dimensions specify the type of transformation carried out, whereas the time dimension positions the different transformation activities in relation to each other. Together, these three dimensions can define a state of transformation. Displacement in terms of postponement and preponement then represents how a transformation can be changed, thus signifying a change of the pre-displacement state, which can have a different nature. Changes of form and place are structural in nature, but time is usually related to whether an exogenous customer demand drives the flow or if the flow is based on an anticipated future demand (i.e., a forecast). As such, displacement is intimately related to the CODP. This presents a general overview of how transformation can be described in terms of state and change. Even so, it does not include a distinction between standardized and customized activities. Different types of variants are included in the presented description, but it lacks a clear distinction of whether the variants are based on customer demand or something else.

### 4.1 Customization in Form, Place and Time

Variants from the customer perspective tend to be associated with the distinction between standardized and customized products. Standardized refers to the customers' inability to influence the properties of a product that is offered to all customers (i.e., customer generic). In contrast, customization means that the product has some type of element adapted to a specific customer. From the form perspective, this means that a standard product is not based on an individual customer's requirements. Of course, this does not exclude the possibility of considering the market's expectations when designing the product. However, a customized product is based on individual customer requirements and is thus customer unique. Sometimes, the frequency of the demand is also considered, distinguishing between customer-unique and delivery-unique types. For the latter, the ordered product is obviously unique for a specific customer order, but a customer-unique item could be ordered several times by the same customer.

A comparable reasoning can be stated in terms of the place perspective. A standardized place implies that customers can retrieve their products from a specific place, such as a central or a local warehouse. A customer-unique place should then correspond to a delivery made to a specific postal address, that is exclusively the customer's own location. For the form, the question of frequency is raised, but this does not have the same meaning for the place. The place is more of a grey scale between the completely standardized place, where the product receives its final form, and the customized place, where the product is used. In between them, a number of places are neither completely standardized nor completely customized but intermediate. The two perspectives can be summarized as shown in Table 3, where the columns indicate the degrees of customization in terms of form (F), and the rows present the degrees of customization in terms of place (P). To distinguish among different degrees of uniqueness, various types of strategic decoupling points have been introduced, one being the customer adaptation decoupling point (CADP) [see, e.g., 4, 10, 11]. This means that the top left combination is a complete standardized product, and the bottom right combination is a complete customized product in terms of both form and place. All other combinations are some forms of intermediate products. The CADP is positioned in between customer-unique and customer-order-unique types, and as it relates to form, it can be denoted as $CODP_F$. Similarly, a CADP can be defined for the place dimension, denoted as $CODP_P$, which is correspondingly positioned in between intermediate and local types.

**Table 3.** Customization of form (F) and place (P).

| | F: Customer generic | F: Customer unique | F: Delivery unique |
|---|---|---|---|
| P: Central | Standardized | | |
| P: Intermediate | | | |
| P: Local | | | Customized |

Customization of form and place can be viewed as a scale ranging from standardized to customized, regardless of whether form or place is considered separately or in combination. This distinction between standardized and customized has a long history and is sometimes associated with the driver and the CODP. By combining the driver with uniqueness, as presented in Table 4, four possible combinations are obtained. Case I represents situations where standardized products are made based on forecasts (i.e., standardization is usually associated with activities upstream of the CODP). Case III is the other extreme case where customized products are made due to a commitment to a customer order (i.e., customization is usually associated with activities downstream of the CODP). When the CODP is used to define both uniqueness and flow driver, no more combinations can be found. If the typology is instead aligned with assumptions in [4, 10, 11], the CODP is only related to the flow driver, whereas the CADP is used for the flow differentiation. By using the CADP, one more relevant combination can be found, namely standard products made due to a commitment to customer orders, that is, Case II (see Table 4). However, since customization should not be carried out based on a forecast (speculation), the fourth logical combination is perceived as undesirable and thus considered not applicable (N/A).

**Table 4.** Combinations of driver and uniqueness (based on [4, 11]).

| | Forecast-driven | Customer-order-driven |
|---|---|---|
| Standardized | Case I | Case II |
| Customized | N/A | Case III |

## 5 Summarizing Customization and Displacement

Customization can thus be described as a combination of three dimensions: (1) Regarding form, customization answers the question of *what* and is related to the $CADP_F$. (2) As for place, customization answers the question of *where*, related to the $CADP_P$. (3) Concerning time, the flow driver answers the question of *when*, related to the CODP. Customization can thus be described as a state with three dimensions. A product delivery is thereby a combination of the flow driver in time and the flow differentiation (customization) in form and place. Note that this state is only one subset of the possible states defined as variants, where only a portion is related to 'real' customer demand. Changes in the state of variants can then be made using displacement (i.e., postponement or preponement), meaning that one state (S1) transitions into another state (S2), as illustrated in Fig. 2. Note that S1 and S2 could signify that the same customizations are offered in two different ways, as shown in Fig. 2, or that two different types of customizations are offered. Two examples of states for a structure are illustrated in Fig. 2. In the left part, S1 indicates that B can be used for creating either C1 or C2. A postponement of the variant proliferation point (CADP) would result in S2, where C is kept 'generic' and could be used for creating either X1 or X2. Both structures thus mean that X1 and X2 are created but in two different ways, where S2 means that the customization can be made at a later point in the structure, enabling a shorter delivery lead time.

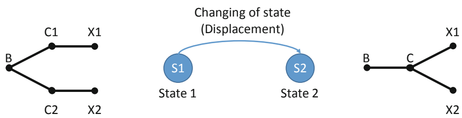



**Fig. 2.** Customization and displacement (based on [10]).

Changing the state in flow structures with a focus on customization brings several challenges. Instead of focusing on form, place and time, the points of departure here are the three types of decoupling points, see in Table 5. Note that the three decoupling points are not independent of each other in creating customization. Unlike the general concept of variants, customization in form, place and time has a point of reference in terms of the customer order. Rational customization requires that a customer order has been received; thus, the CODP constitutes a restriction of how far upstream the $CADP_F$ and the $CADP_P$ should be positioned in a time-phased flow structure. Displacement of 'form and time' and 'place and time', as shown in Table 5, therefore means that form and place are each shifted in time where time is included. Customization in terms of form has traditionally been created in a factory before the product is delivered to a customized place. This means that the $CADP_F$ traditionally is positioned before the $CADP_P$ in the flow. However, new technology, such as additive manufacturing using three-dimensional printing, has enabled customization in form to be created closer to the customers.

**Table 5.** Decoupling points and displacement.

| Decoupling point | Changing state (Displacement) |
|---|---|
| $CADP_F$ | Displacement of form and time, $CADP_F$ should not be upstream of CODP |
| $CADP_P$ | Displacement of place and time, $CADP_P$ should not be upstream of CODP |
| CODP | Time postponement or time preponement |

## 6 Conclusions

The purpose of this study is to analyze customization in terms of form, place and time, as well as relate it to variants. The main conclusion drawn from this study is that both customization and variants are related to flow states, represented by flow structures. A state can be defined in terms of the three dimensions: form, place and time. With their relations to different strategic decoupling points and through the three dimensions, strategies such as postponement and preponement can also be identified as forms of support for changes in a state. Using flow thinking [10] and the two strategic decoupling points (CODP and CADP) provides a better understanding for the questions of *what*, *where* and *when* customization can be applied. Hence, this study contributes to the existing literature by increasing the knowledge of what can be considered standard variants and customization, respectively. Further research could include theoretical development, for instance, where the relationship among postponement, preponement and flow thinking could be more clarified. Practical applications could also be further examined, where the understanding of displacement improves the capability to manage operational development, enabling more effective and efficient flow solutions.

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# A Framework for Identification of Complexity Drivers in Manufacturing Companies

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**Abstract.** The initial issue of complexity management in companies is the identification of the drivers of complexity. However, current literature lacks methods for assisting practitioners in the initial identification of such drivers. This paper, therefore, presents a novel framework for assisting practitioners with identifying complexity drivers in manufacturing companies. The framework uses a generic value chain and a generic product structure as its two dimensions. Multiple workshops are then conducted with company representatives across different value chain fields focusing on two main parts: First, surveys are used to assign complexity ratings to different generic product structure elements. Secondly, the complexity ratings are elaborated on by workshop participants. The process provides valuable insights into the perceived complexity drivers. The framework is then verified through a case study in the process industry. Based on the case study, multiple complexity drivers were identified across both value chain fields and product structure elements. The case study findings show that the framework facilitates practitioners in identifying organization-wide perceived complexity drivers. The framework contributes to both industry and research by addressing a neglected aspect of complexity management. It achieves this by providing a comprehensive and structured approach for the initial identification of complexity drivers across product elements and value chain fields.

**Keywords:** Complexity management · Complexity driver · Identification · Framework · Manufacturing

## 1 Introduction

Globalized markets, increasingly heterogeneous customer requirements, and demands for lower costs are factors pressuring the competitiveness of traditional manufacturing companies [1]. These factors have resulted in increased external complexity for manufacturers. In response, companies have increased the complexity of their own operations to accommodate these changed conditions [1, 2], often resulting in increased costs and reduced performance [3]. Such costs are identified across organizations in supply chain management [3, 4], production systems [5, 6], and various internal projects [7, 8]. However, complexity is not always undesirable, and may even be a source of competitive advantage [8], if managed properly. Most companies are aware of the adverse effects of complexity [1]. Yet, despite attention from industry concrete tools to


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effectively handle complexity related issues in manufacturing companies are lacking [1]. Due to the issues arising from increased complexity in companies complexity management has received increased attention in literature in the last decade [1]. However, before complexity can be managed, it must be understood what causes it [1]. These "causes" are referred to as complexity drivers in literature. Examples of complexity drivers in manufacturing companies include variety [3, 9] and novelty [7] of products, as well as variety of assembly equipment [6]. Identification of complexity drivers is, therefore, critical for the subsequent operationalization and quantification of the complexity costs incurred for the company [1], and investigating this perspective therefore forms the motivation of this paper.

The remainder of the paper is structured as follows: Sect. 2 reviews existing research on identification of complexity drivers in manufacturing industry. Based on these findings, Sect. 3 presents a novel framework aimed at assisting practitioners in this endeavor. Section 4 then introduces the methodology of the case study followed by Sect. 5, which presents the findings from the case study. Section 6 discusses the limitations of the framework after which Sect. 7 concludes on the major findings and suggests areas for further research.

## 2 Literature Review on Complexity Driver Identification

Literature has been reviewed for frameworks to assist in identification of complexity drivers in manufacturing companies. This review consisted of a two-step process. First, relevant papers referenced in Vogel and Lasch [1] were reviewed resulting in 9 papers. Secondly, to ensure the inclusion of the most current research a block search was performed in Elsevier's Scopus and Clarivate's Web of Science covering the period from 2016 to 2019, using the search string: "complexity driver*" OR (driver* NEAR/3 complexity) AND (identi*). Upon screening the 19 papers retrieved, the literature search produced 11 relevant papers. Since this paper focuses on the identification of complexity drivers in industry, all identified papers have been analyzed as follows: First, the identified papers are reviewed concerning the repeatability of the methods presented, as this is considered an important factor for applicability by practitioners. This is evaluated according to the degree of detail with which the initial method of gathering complexity driver data is described. Secondly, the intended usage area of the frameworks is categorized. This is to determine whether the frameworks are intended for general use in manufacturing companies, or specific to a certain subject area such as flexible assembly systems. Due to space constraints, the general findings from the papers referenced by Vogel and Lasch [1] are briefly summarized first. Hereafter, the overall findings from the database searches are presented.

Reviewing the papers cited by Vogel and Lasch [1] found that these are concerned with diverse application areas including the remanufacturing industry, supply chains, and various organizational projects. Furthermore, most of these papers rely on qualitative methods for the identification of complexity drivers, such as literature reviews, interviews, and expert reviews. However, the description of the methods used is in most cases not sufficiently detailed to be replicated by practitioners. For the papers where the methods are described relatively detailed, the methodologies do not allow for adaptation to specific contexts or does not provide a company-wide perspective on complexity issues.

To provide an easier overview of the findings of the subsequent database searches and literature review, the overall results have been summarized in Table 1.

**Table 1.** Reviewed literature categorized according to methods used in identification of complexity drivers as well as the generalizability of the frameworks.

| Paper | Complexity driver data collection method | Complexity driver focus area |
|---|---|---|
| Asadi et al. [6] | Brainstorming, questionnaire | Assembly system |
| Kohr et al. [9] | Interview | Manufacturing industry |
| Kohr et al. [5] | Simulation study, interview, questionnaire, literature review | Manufacturing industry |
| Latos et al. [8] | Interview | Organizational projects |
| Leang et al. [10] | Not specified | Manufacturing industry |
| Piya et al. [3] | Literature review, expert review | Supply chain |
| Schmid et al. [11] | Not specified | Production equipment |
| Schuh et al. [12] | Literature review, expert review | Organizational projects |
| Schuh et al. [13] | Literature review | Organizational projects |
| Schuh et al. [7] | Not specified | Organizational projects |
| Sun et al. [4] | Questionnaire, expert review, workshop | Supply chain |

Asadi et al. [6] acknowledges the need for adapting the complexity driver identification method to specific contexts by allowing survey respondents to add missing complexity drivers. Regardless of the fundamental method used for identifying complexity drivers, Kohr et al. [5] notes that the analysts must determine the relevant sources to use, further implying a focus on context specificity. Most of the literature reviewed base their approach on qualitative methods. Specifically, only 1 out of 11 publications reviewed base their methodology on quantitative methods. Kohr et al. [5] notes that given existing data models, a quantitative approach for identifying complexity drivers may be less resource demanding than a qualitative approach. They contribute this to the manual work involved in designing, performing, and analyzing surveys and interviews [5]. However, for companies where the necessary quantitative data is unavailable, using a qualitative approach may be favorable from a resource perspective. Furthermore, although often considered as inherently objective, data models are still subject to the perspective chosen by the data analyst, thereby questioning the objectivity of the quantitative approach [5].

The results of the literature review indicate that there is a gap in literature concerning detailed and concrete methods for the initial identification of complexity drivers. This presents an issue for both researchers and practitioners undertaking complexity reduction efforts and is therefore important to address.

# 3 Framework for Identification of Complexity Drivers

Based on the identified gap in the existing literature, this section presents a novel framework for the initial identification of perceived complexity drivers in a manufacturing company. The framework constitutes two parts: (i) the structure of the framework and (ii) the associated process to follow. These parts will be described in the following.

## 3.1 Framework Structure

The framework is structured as a multi-dimensional matrix and is illustrated in Fig. 1.

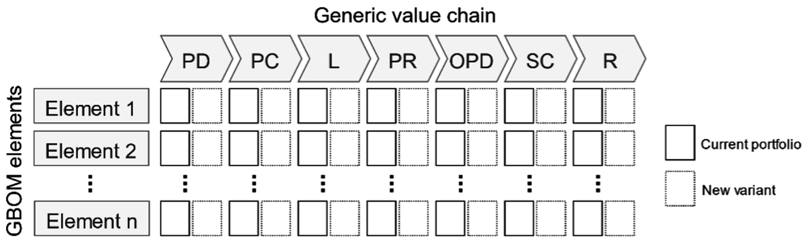


**Fig. 1.** The generic complexity driver identification framework.

The first outer dimension of the framework is a representation of a generic value chain using the seven fields summarized by Vogel and Lasch [1]. The value chain fields are product development (PD), procurement (PC), logistics (L), production (PR), order processing/distribution/sale (OPD), internal supply chain (SC), and remanufacturing (R). Taking outset in a generic value chain makes the framework generally applicable within the manufacturing industry. The framework can be adapted to individual companies by subtracting irrelevant value chain fields, such as the remanufacturing field for companies not engaged in this activity. The second outer dimension of the framework is the generic product structure, which has been implemented through the generic bill-of-materials (GBOM) introduced by Hegge and Wortmann [14]. Describing product families through a generic product structure enables coverage of the full breadth of product variants with only one representation [14]. Providing the intersection between the two dimensions of the framework is the complexity rating matrix. For each GBOM element and value chain field, two values must be provided. The first value denotes the perceived complexity of managing the existing portfolio of GBOM element variants. The second value denotes the perceived complexity associated with adding a new variant to the portfolio. By including complexity ratings for both existing and new GBOM element variants, a holistic perspective of complexity related issues is maintained.

### 3.2 Framework Process

The second part of the framework is the process which enables application of the framework in practice. To ensure inclusion of all value chain fields, workshops should be scheduled for each and include company representatives from corresponding departments. The process involves three overall phases. First, at the beginning of each workshop, a brief introduction to the purpose and objective of the workshop is given. Secondly, the workshop participants are then asked to collectively rate their perceived complexity of each GBOM element. This is done by using a five-point Likert scale, where 1 represents the lowest perceived complexity and 5 the highest perceived complexity. Lastly, based on the complexity ratings provided, the participants are asked to elaborate on each individual rating. This process provides the analysts with valuable insights into which aspects of each GBOM element that are considered complexity drivers by the workshop participants. Through this process, analysts can gather information about potential complexity drivers in their organizations as well as the perceived importance of these. This forms a foundation for further analysis of the costs incurred by each of these perceived drivers of complexity, which in turn guides managers to where complexity reduction initiatives are most needed in their organizations.

## 4 Methodology

To verify the framework and illustrate its applicability in industry it has been applied in a case company. This section first introduces the case company and then describes the approach followed for the workshops conducted.

### 4.1 Case Description

The case company is a mid-sized production company operating in the business-to-business market. The company's main product range is liquid household chemicals produced on either fully or semi-automated production lines. The company is experiencing challenges caused by market developments like those referenced in Sect. 1. This has resulted in a product portfolio which has grown steadily and includes several hundred product variants and a high rate of annual renewal of the portfolio. For these reasons, the company has recently initiated a complexity management program. The company, therefore, makes for an interesting case for studying methods for identification of complexity drivers. During this study, information was primarily obtained through active participation in workshops and interviews with company representatives. Additionally, company records were used in constructing the GBOM.

### 4.2 Case Study Procedure

In preparation for the workshops, the BOMs for the liquid chemical product group were analyzed to extract the GBOM. The GBOM was then verified by product developers from the company. The resulting product structure comprises the five generic elements:

cap, bottle, formula, label, and packaging. The generic value chain fields were verified by managers resulting in exclusion of remanufacturing. Workshops were then scheduled with between two and four representatives from departments corresponding to the value chain fields in the framework. The participants included both managers and specialists, thereby providing insights from both an overall and detailed perspective. Initiating each workshop was a brief introduction to the overall complexity management program followed by an introduction to the framework and purpose of the workshop. Following the introduction, a printout of the framework was handed to the participants, whom were then asked to collectively rate their perceived complexity of each of the five generic subassemblies. To ensure that the participants were not influenced by the ratings made by other departments, a blank framework template was used for each workshop. Once all ratings had been submitted, the participants were asked to elaborate on their ratings by describing them using short keyword sentences on post-its. The post-its were then grouped based on which of the five generic subassemblies they referenced.

## 5 Case Study Findings

Combining the scores from each individual workshop conducted in the case company resulted in the complexity ratings shown in Fig. 2. The ratings have been color-coded based on their severity. Based on the total ratings for each GBOM element, it is found that "Bottle" and "Formula" are the overall highest rated, each with a total score of 39. They can therefore be considered nearly identical in perceived complexity. The complexity ratings for these two subsystems are also close in a majority of the value chain fields. For example, their ratings differ by no more than one score in 9 out of the 12 value chain ratings. Examples of complexity drivers mentioned for the "Bottle" subsystem includes long changeovers when changing between bottle formats in production and high inventory space taken up by bottles when compared with their consumption rate in production. The complexity drivers mentioned for the "Formula" subsystem includes having to revise production schedules when new variants are added to the production mix, as well as getting changes to formulas approved by certification organizations and customers. On the other hand, labels are generally rated as resulting in least complexity for the company, with a total score of just 21. Complexity drivers mentioned for this subsystem are having to track a high number of variants in both physical inventory and keeping them up to date in the ERP system. In total, more than 53 different complexity drivers were mentioned for the five GBOM elements. Considering the value chain fields, it appears that complexity challenges are mostly affecting the logistics and production fields. In comparison, the procurement and supply chain fields appear less affected by complexity, especially when considering complexity related to new variants. In general, visualization of the perceived complexity through the complexity ratings in addition to the complexity drivers enables managers to make decisions concerning where to focus future analysis of complexity costs and subsequent complexity reduction efforts.

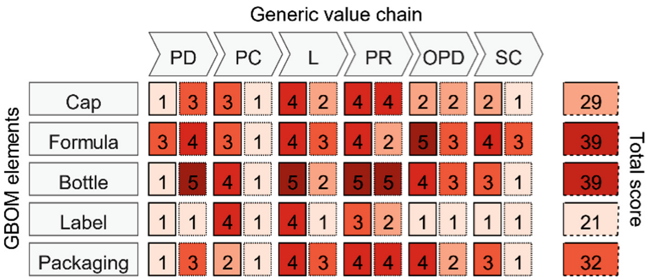


**Fig. 2.** Complexity rating results from applying the framework in the case company.

## 6 Discussion

The aim of the presented framework is to assist practitioners in the initial phase of complexity driver identification: exploring perceived complexity drivers. The case study showed that the framework succeeds in this regard. However, potential limitations of the framework have been noted. The GBOM representation is limited to products similar in structure. Complexity exploration may thus be limited in scope in companies, where the entire product portfolio cannot be represented by a single generic GBOM. Furthermore, while the products analyzed in the case study are simple, consisting of only a handful of elements, very complex products such as automobiles may pose a challenge to manage in the framework. For such products, a different unit of analysis may ensure a manageable level of detail. This may involve either using high-level subsystems (e.g. drivetrain, body, chassis, etc.) or focusing on only a single high-level subsystem (e.g. only drivetrain) and its constituent subsystems. While the framework relies on qualitative data to assess perceived complexity, using quantitative data and automated data processing may facilitate a dynamic framework implemented in e.g., a business intelligence solution. However, pursuing this direction would entail a different set of challenges concerning how complexity-related costs are measured accurately. Another aspect, which may question the validity of the framework is using combined scores for existing and new product variants. If the two aspects have different units of magnitude, weighing them equally risk skewing the results of the framework.

## 7 Conclusion

In this paper we have presented a framework to assist practitioners in the identification of context specific complexity drivers. The framework achieves this by means of the generic value chain and generic bill-of-materials, with the former ensuring a broad perspective on complexity drivers and the latter a detailed insight into these. The framework has been verified in a case company where it facilitated the identification of complexity drivers across company functions and product elements. The combination of the complexity ratings and the identified complexity drivers further assists practitioners in focusing their subsequent investigations of where complexity reduction initiatives in their organization should be directed.

Further research should be aimed at investigating both limitations and potentials of the framework. This involves investigating the applicability of the framework for more complex products as well as the applicability in organizations with dissimilar product structures. Given the framework's focus on application by practitioners, further research should center on prescriptive analytics and address how the results of the framework should be interpreted in addition to presenting guidelines on what actions to take.

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# Identification of Platform Candidates Through Production System Classification Coding

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**Abstract.** Changeable and reconfigurable manufacturing appears as a natural response to a need for improved variety management. Such manufacturing systems are complicated to develop, and it can be advantageous to base or build these systems on product and production platforms. Development of platforms is, however, not a trivial task. Currently, identification and selection of candidates for inclusion in a platform is typically subjective relying on experts and tacit knowledge. The objectivity of this process can be strengthened by collecting data on existing production systems in a company and comparing these systems to each other. To do so, a coherent, consistent and preferably digital representation of multiple production systems is needed. In this research, a production system classification coding (PSCC) scheme is employed to classify and structure data for a number of existing production systems, spanning multiple departments and product families. Candidates for a production platform covering the included production systems are identified based on ranking certain platform drivers, processes and enablers.

**Keywords:** Manufacturing system · Classification code · Platform

## 1 Introduction

Manufacturers have long had ambitions of implementing changeable manufacturing. With decreasing product lifecycle and increasing demand for variety, a growing mismatch between product and production lifecycles has appeared [1]. Manufacturing equipment outlives the products it manufactures, and without the ability to adapt to new product variants or generations, outdated and obsolete equipment will simply be taking up valuable resources. Changeable manufacturing appears as a natural response for this need to accommodate change, but systems enabling economic and efficient change are not trivial to create. One path to developing changeable manufacturing systems and managing variety is through use of platforms, a concept involving standardisation of tangible and intangible assets [2]. Within product design and development this concept is well-known, and research on production platforms are gaining foothold, often centred on development alongside products, i.e. co-development and co-platforming [3–5]. Platforms allow companies to develop, manage and use standardised assets for design


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and develop of new systems, whether these are products or production systems. These platforms and assets can take numerous shapes, both tangible (e.g. a physical component or piece of equipment) or intangible (e.g. a specific process ensuring a good result, or knowledge on a certain subject).

Identification and selection of assets to be developed into or included in a platform is one of the first steps in the process. Successful platform development depends on the selection of appropriate assets. A primary source of platform candidates (i.e. assets with a potential for development into or inclusion in platforms) is expert system stakeholders, who base their selection on a detailed understanding of the systems [6]. This understanding is typically tacit knowledge, making it difficult to communicate or grasp the reasoning behind the decisions. Using a more objective method of identifying platform candidates would help system experts and developers explain and back up their decisions, as well as help managers understand these decisions.

In development processes related to product modularisation and platforming, commonality has previously been used as a basis for forming modules and platforms [7, 8]. This commonality, e.g. similar geometries [9] or shared assets [10], can be difficult to identify across large complex systems such as factories and manufacturing systems. To alleviate this, progress has been made towards classifying the processes of manufacturing systems [11], with the intention of using generic and company-specific ontologies to integrate product and production models [12].

This paper presents an effort in identifying potential platform candidates based on data collected from existing manufacturing systems at an industrial partner. The data is a classification of existing manufacturing systems linked to their corresponding cost structure and performance. Focus for this paper is on the classification coding scheme, therefore, the cost and performance data will not be considered in this publication. Platform candidates will be identified as either production processes for which a platform should be developed, or physical equipment which could be developed into a platform. In this paper, physical equipment carrying out or enabling production system operations are generally referred to as "enablers". The use of "enablers" also covers human operators, who can not be considered manufacturing equipment. Based on the above, the following research question has been formulated:

- How can a production system classification coding scheme be used to identify candidates for a production platform?

Firstly, the method is presented with a brief overview of the classification coding scheme. Secondly, the case study is introduced, followed by a description of the results and identified platform candidates. Finally, the paper ends with a discussion of the results, case study and future research.

## 2 Method

In order to analyse production systems, a digital representation of them are necessary. For this purpose, a production system classification coding (PSCC) scheme is applied [13]. The scheme is based on ElMaraghy's manufacturing systems complexity, coding and classification system [14] and Sorensen's production process classification scheme

[11]. It is a hybrid-code considering system design driving requirements, system layout, production processes and enablers. PSCC is essentially used to create a map of a company's production landscape, classifying and documenting manufacturing systems across departments and production locations [13]. A brief overview of the coding scheme and constituent digits is shown on Fig. 1. Digits D1–D9 capture characteristics for the manufacturing system as a whole, specifically the design drivers (or rationale) and physical layout. Digits D10–D25 classify the individual processes performed by the manufacturing system and the enablers that carry them out. Thus, digits D1–D9 are filled out once per manufacturing system, while multiple instances of D10–D25 exist.

| System Level | | | | | | | | | Cell/Station Level | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Design Driver | | | | | Layout | | | | Processes | | | | | | Enablers | | | | | | | | | |
| D1 | D2 | D3 | D4 | D5 | D6 | D7 | D8 | D9 | D10 | D11 | D12 | D13 | D14 | D15 | D16 | D17 | D18 | D19 | D20 | D21 | D22 | D23 | D24 | D25 |
| Primary driver | Product size | Production Volume | Degree of variety | Manufacturing Paradigm | Production Location | System Shape | Level of Automation | Flow Direction | Core | Position | Category | Family | Class | Sub-class | Position | Structure | Sourcing | Category | Type | First characteristic | Second characteristic | Third characteristic | Fourth characteristic | Fifth characteristic |

**Fig. 1.** Overview of the 25 digits in the production system classification coding scheme (PSCC).

To identify platform candidates based on the PSCC, the populated code for a number of manufacturing systems will be analysed according to certain drivers, outlined in the following section. Potential candidates will be ranked according to each driver, giving each candidate multiple scores. A consolidated score is then used to create the final ranking of candidates.

### 2.1 Drivers for Platform Candidate Identification

A drivers is the driving force, or impetus, which sets something in motion towards a certain destination or state. In the case of identification of platform candidates, drivers are the reasons why a certain asset, whether process or enabler, should be considered a potential platform candidate. The following three drivers are examples of such reasons, which can be determined based solely on the data captured by the PSCC.

1. Frequency: Number of instances of a particular process or enabler across all systems. Frequency does not consider how many times a process or enabler is used e.g. per day. More frequently occurring processes and enablers are ranked higher.
2. Prevalence: Ratio between how many systems a particular process or enabler is used in and the total number of scoped systems. Processes and enablers appearing in more systems are ranked higher.
3. Enabler/process ratio: How many different enablers exist for each process and vice versa. Processes with fewer distinct enablers relative to how often they are carried out are given a higher rank, and similarly for enablers and distinct processes. This driver is also used to determine the number of distinct enablers per type of enabler.

## 3 Case Study

A case study is used to illustrate the application of the PSCC and determine which processes or enablers are appropriate for inclusion in a production platform. This case study was carried out in collaboration with a large Danish manufacturer of discrete products. It covered nine distinct production systems at two different company factories in two different countries. The nine production systems span two departments, assembling products or components for subsequent internal use, others assembling complete products for OEM customers. Automation level, product size and production cycle time vary greatly across the systems. The products manufactured by the systems share the same primary function, but with a variety of supporting and additional functions, aimed at different applications and customer segments.

All nine systems have previously been surveyed for various purposes. Using the data collected on this occasion, each system was classified in accordance with the PSCC. The classified systems were then linked to their respective cost and performance data, which were available in an online data hub. Cost and performance data is not, however, considered in this study as the quality of this data has not been sufficiently ensured. A sample of the available data is illustrated in Fig. 2.

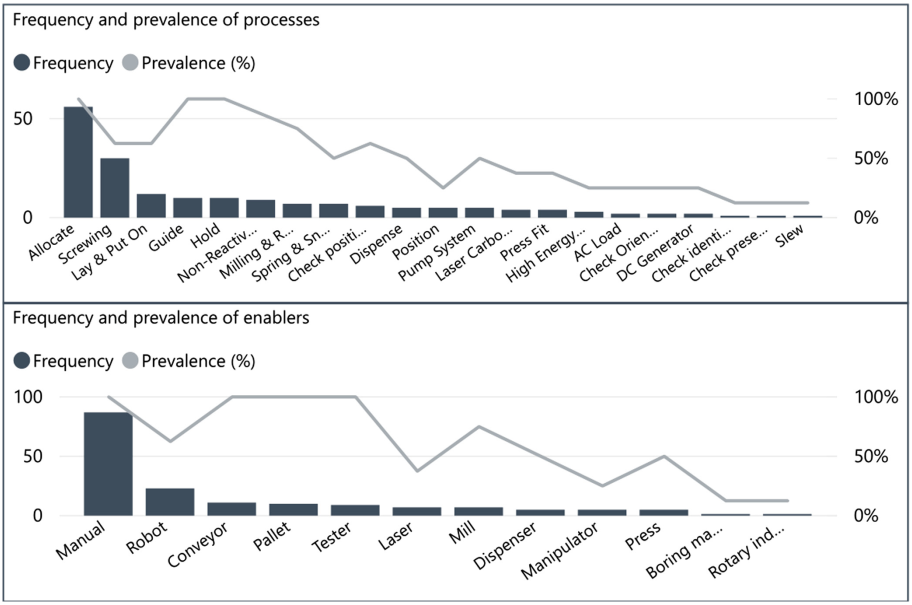


**Fig. 2.** Graphs of frequency and prevalence for processes (top) and enablers (bottom).

# 4 Results

The ranking of process subclasses and enabler types, digits D15 and D20 in the PSCC respectively, are available in Tables 1 and 2. In total, 21 different process subclasses and 12 different enabler types are considered.

**Table 1.** Process subclasses ranked according to the three drivers. Sorted by total rank.

| Process | Frequency | Frequency rank | Prevalence | Prevalence rank | Enabler ratio | Enabler ratio rank | Total score | Total rank |
|---|---|---|---|---|---|---|---|---|
| Allocate | 56 | 1 | 1.000 | 1 | 0.089 | 2 | 4 | 1 |
| Screwing | 30 | 2 | 0.556 | 7 | 0.067 | 1 | 10 | 2 |
| Guide | 10 | 4 | 1.000 | 1 | 0.300 | 7 | 12 | 3 |
| Hold | 10 | 4 | 1.000 | 1 | 0.300 | 7 | 12 | 3 |
| Milling & routing | 7 | 7 | 0.778 | 4 | 0.286 | 6 | 17 | 5 |
| Non-reactive adhesive bonding | 9 | 6 | 0.778 | 4 | 0.444 | 11 | 21 | 6 |
| Lay & put on | 12 | 3 | 0.667 | 6 | 0.667 | 16 | 25 | 7 |
| Laser carbonization | 4 | 13 | 0.444 | 10 | 0.250 | 4 | 27 | 8 |
| Position | 5 | 10 | 0.222 | 14 | 0.200 | 3 | 27 | 8 |
| Press fit | 4 | 13 | 0.444 | 10 | 0.25 | 4 | 27 | 8 |
| Spring & snap fit | 7 | 7 | 0.444 | 10 | 0.429 | 10 | 27 | 8 |
| Check position | 6 | 9 | 0.556 | 7 | 0.500 | 12 | 28 | 12 |
| Dispense | 5 | 10 | 0.556 | 7 | 0.600 | 15 | 32 | 13 |
| Pump system test | 5 | 10 | 0.556 | 7 | 0.800 | 17 | 34 | 14 |
| HEB Welding | 3 | 15 | 0.333 | 13 | 0.333 | 9 | 37 | 15 |
| AC load test | 2 | 16 | 0.222 | 14 | 0.500 | 12 | 42 | 16 |
| Check orientation | 2 | 16 | 0.222 | 14 | 0.500 | 12 | 42 | 16 |
| DC generator test | 2 | 16 | 0.222 | 14 | 1.000 | 18 | 48 | 18 |
| Check identity | 1 | 19 | 0.111 | 18 | 1.000 | 18 | 55 | 19 |
| Check presence | 1 | 19 | 0.111 | 18 | 1.000 | 18 | 55 | 19 |
| Slew | 1 | 19 | 0.111 | 18 | 1.000 | 18 | 55 | 19 |

Allocate, with a final rank of 1, is an obvious candidate. It is defined as the process of creating a partial quantity of parts or components of a certain size, and the movement of said quantity to a target location [11]. Thus, allocate is a material handling process, where new parts or components are assigned a manufacturing system or process. Considering its low enabler variety combined with the high frequency and prevalence, it is likely that a platform already exists for allocate, or that there is simply an agreed

**Table 2.** Enabler types ranked by the three drivers, sorted by total score.

| Enabler | Frequency | Frequency rank | Prevalence | Prevalence rank | Process ratio | Process ratio rank | Enabler ratio | Enabler ratio rank | Total score | Total rank |
|---|---|---|---|---|---|---|---|---|---|---|
| Manual | 89 | 1 | 1.000 | 1 | 0.067 | 1 | 0.067 | 1 | 4 | 1 |
| Conveyor | 11 | 3 | 1.000 | 1 | 0.182 | 5 | 0.273 | 4 | 13 | 2 |
| Pallet | 10 | 4 | 1.000 | 1 | 0.100 | 2 | 0.300 | 7 | 14 | 3 |
| Robot | 23 | 2 | 0.667 | 6 | 0.174 | 4 | 0.261 | 3 | 15 | 4 |
| Mill | 7 | 6 | 0.778 | 5 | 0.143 | 3 | 0.286 | 5 | 19 | 5 |
| Tester | 9 | 5 | 1.000 | 1 | 0.333 | 9 | 0.333 | 8 | 23 | 6 |
| Manipulator | 5 | 8 | 0.222 | 10 | 0.200 | 6 | 0.200 | 2 | 26 | 7 |
| Laser | 7 | 6 | 0.444 | 8 | 0.286 | 8 | 0.286 | 5 | 27 | 8 |
| Dispenser | 5 | 8 | 0.444 | 8 | 0.200 | 6 | 0.600 | 10 | 32 | 9 |
| Press | 5 | 8 | 0.556 | 6 | 0.400 | 10 | 0.400 | 9 | 33 | 10 |
| Boring machine | 1 | 11 | 0.111 | 11 | 1.000 | 11 | 1.000 | 11 | 44 | 11 |
| Rotary index table | 1 | 11 | 0.111 | 11 | 1.000 | 11 | 1.000 | 11 | 44 | 11 |

upon way to carry out this process. If a platform does exist, it needs to be documented, and if it is merely an agreed upon way to carry out the process, it should be developed into an actual platform module and documented as such.

The highest ranked process in the manufacturing category is screwing. While it only ranks 7 in prevalence, it has a high frequency and a low variety, with only two different enabler types. With only one boring machine present across the nine systems, the remaining 29 instances of the processes are carried out manually, meaning this process may already be standardized, and fit for formal development into a platform.

For enablers, the manual enabler, i.e. an operator, clearly comes out on top in all four measures, with the conveyors and product/component pallets coming in second and third. All three have a high prevalence (1.000), low process variety (0.067, 0.182 and 0.100) and 3 or more distinct enablers, making them good candidates for standardization of enablers. The tester, based on its high prevalence (1.000) and relatively high process and enabler variety (0.333 for both) should also be considered for inclusion in a production platform, with the goal of lowering the variety and standardizing testing equipment and process. Finally, the robot enabler is a potential candidate, as it comes in second in frequency and carries out four different processes with six distinct enablers.

## 5 Discussion and Conclusions

A production system classification coding scheme has been used in a case study to classify nine surveyed manufacturing systems. The resulting data is a digital representation of each manufacturing system, its characteristics, structure and functions. Based on three generic drivers for platform identification, the classified manufacturing systems are analysed to identify platform candidates. Candidate processes or enablers are rated and ranked according to these drivers with the highest ranked candidates being recommended for further development into platforms. The PSCC classification coding scheme and subsequent comparison of processes and enablers act as a decision support tool for manufacturers looking to develop production platforms based on their existing production systems, i.e. brownfield platform development.

Additional platform candidate drivers should be considered and added to the rating and ranking process, depending on the requirements of the specific manufacturer. For example, the ratio of instances of a given process subclass defined as a core process (D10 in the coding scheme, Fig. 1) i.e. used for all product variants on the system. Adding to the list of other factors useful in selecting individual instances of enablers, certain qualitative drivers can be considered. Examples of such are whether individual enablers have: (1) been a bottleneck in their respective system, (2) had a long calibration period, (3) frequently broken down or required extra maintenance or (4) been deemed especially important by system experts.

Implementation of a classification coding scheme such as the one employed in this study is not a trivial task. An appropriate level of detail must be found, if implementation is to be successful, and it is advisable to take a gradual approach, selecting one segment of the production at a time in order to ensure the quality of the gathered data and resulting code.

To improve and strengthen the recommendations made through the identification process, the classified systems should be linked to their related performance and cost data. This would allow companies to correlate system characteristics, performance and cost, thus determining the system characteristics usually resulting in high performance and low cost. As digitalisation and big data are areas of interest for increasing number of manufacturers, this data is becoming more readily available for analysis.

Besides the drivers in Sect. 2.1, other factors captured in the PSCC can affect the identification and ranking of potential platform candidates. These factors can modify the scores and rankings of individual instances of processes and enablers to improve the confidence in selection of candidates for further development. Their effect on the scores are decided based on the company's requirements. The purpose of this is to determine the individual instances of already identified processes and enablers which should be prioritized for inclusion in the platform. Selecting the instances, upon which the standard for future systems should be based, is an important step in further platform development. This step will be detailed in future research. Three such factors captured by the PSCC are: (1) enabler structure, (2) sourcing and (3) product variety. Enablers with a modular structure are rated higher than enablers with a fixed structure, and those with a changeable structure are rated even higher. Enablers designed and developed in-house are given a higher rating as it is often a long and costly process, benefiting significantly from standardisation. Finally, processes and enablers in systems handling a higher degree of variety are given a higher rating.

While not captured in the PSCC, the year in which a system was constructed plays a role in selection of candidates. Enablers in newer systems will take priority over enablers in older systems when it comes to inclusion in a production platform.

As previously stated, identification and selection of platform candidates is typically a matter of tacit knowledge held by system experts. When deciding on which platforms to develop, such knowledge can be difficult to back up and communicate. Using a method for platform candidate identification, like the one presented in this paper, would ease the process of making such decisions and backing them up, while improving transparency and standardisation by classifying manufacturing systems throughout the company. It can also lead to the identification of less obvious platform candidates, or platforms that already exist, but have yet to be documented. By identifying platform candidates and developing them further, the development of new systems can be eased through reuse and modification of existing solutions.

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# 5G-Ready in the Industrial IoT-Environment

## Requirements and Needs for IoT Applications from an Industrial Perspective

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**Abstract.** 5G will be a key enabler for future trends in the industry 4.0 environment. Two primary goals exist in this context: The first one regards to complex autonomous automation where ultra-high reliability and low latencies are required for the collaboration between humans and robots. The second one will focus on the Internet of Things (IoT), where vast numbers of connected devices (e.g. sensors and actuators) can communicate with each other. Despite all hypes, 5G is still in development, and most details are not clearly defined yet and far beyond the commercial use.

This paper will show an approach for IoT-related usage in an industrial environment by means of its needs, requirements and potentials using the upcoming telecommunication standard 5G.

Especially IoT-applications with hundreds of hundreds of connected devices will support a highly flexible production-logistics system, which can satisfy the actual customer needs for custom-tailored solutions, services and products.

Finally, as a use case, a demonstrator is shown, which will focus on IoT applications in a future production-logistics environment by using a 5G framework supporting the ideas of Industry 4.0.

**Keywords:** 5G-ready · Flexible production systems · IoT

## 1 Introduction

5G is nowadays a well-known and common term, which has the potential to influence many parts of our lifestyle. Scenarios focus on better-customised solutions and services and will take care of new technical abilities in the industrial environment like high autonomous manufacturing or IoT-supporting applications for area-wide networks of facilities and devices supporting remote control. In addition, to enable these highly flexible systems, a seamless collaboration in communication is required with multiple heterogeneous participants [1]. As 5G does not exist as a running system yet, literature research was done to figure out which aspects are of high relevance in a future application. The following section names the primary pillars of the actual development for commercial use. In the beginning, it will be more attractive for large enterprises (LE), later on, by using the given services, it shall be applied in small and medium-sized


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enterprises (SME) to improve existing solutions. Through guaranteed reliability of >99.999% and latencies below 5 ms [2], it will also have a huge impact on the further development of human-robot-collaboration (HRC)-manufacturing or even robot-supported surgery. For private use, autonomous driving, using the benefits of Smart Cities or Media on demand with ultra-HD resolution will improve the living standards enormously [3].

To achieve these objectives, different developments are in progress, namely [3]:

1. emBB (Enhanced Mobile Broadband), which will be used for large broadcast events, e.g. in places of high interest (stadium, festivals) where many participants use these services within a small area or big cities. Highest availability and multiple bandwidths are required to fulfil the needed capacities.
2. URLLC (Ultra Reliable and Low Latency Communications) which will make autonomous driving possible and is a key factor for HRC due to its high reliability and low latency.
3. mMTC (massive Machine Type Communications) we will be primarily used for machine to machine (m2m) communication, IoT-applications and its devices. These can be used within a Smart City or build the backbone of a Smart Factory.

All three objectives are shown in Fig. 1 aligned with possible use case scenarios by means of their requirements (e.g. enhanced capacity, massive connectivity).

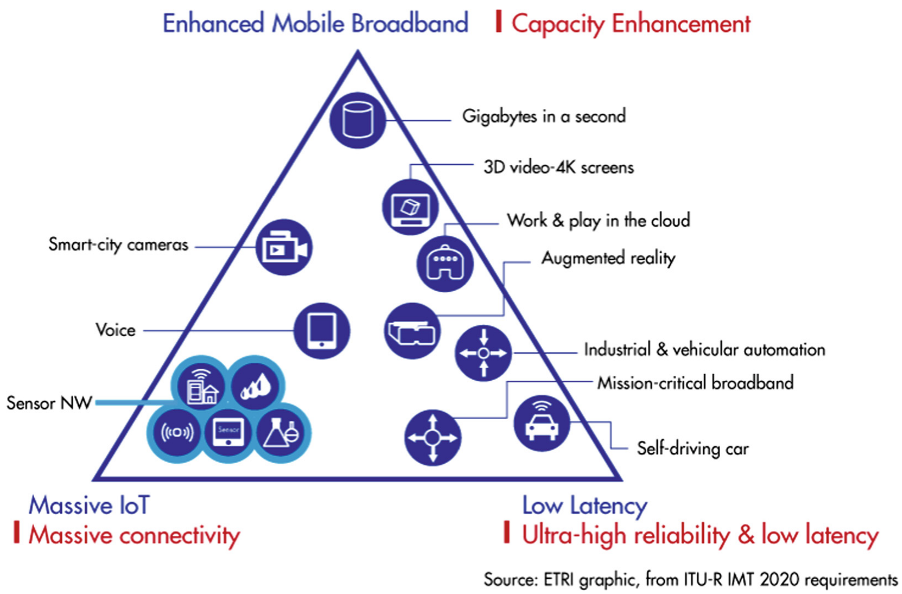


**Fig. 1.** Distribution of 5G use cases by means of their requirements [4]

At the moment, the focus of 5G development mainly lies on emBB with its enhanced capacities for multimedia applications, described in the 3GPP Release 15 [5]. A first trial network was already demonstrated in Seoul during the Winter Olympics in 2018 [6]. MTC and URLLC are mostly developed on the sketch yet, further developments and implementations will be described with the upcoming 3GPP Release 16 at the end of this year [7]. This paper focusses on the industrial environment, especially on mMTC with its IoT-devices and shows, which requirements are necessary to improve the production logistics environment for future connected factories.

## 2 Approach

As already mentioned in the section before, 5G is far from commercial use, especially using IoT. Therefore, the approach emphasises the provision of requirements for the mMTC of 5G to ensure its applicability for the integration of IoT in the scope of industry 4.0, which is motivated in the following.

To develop a proper setup, a very close collaboration between the telecommunication providers and the industrial stakeholder exists and is highly required. Here, the telecommunication providers set the framework, architecture and orchestration for the 5G network, whereas the industrial stakeholders define their needs and technical perspectives [8]. One of these needs are connected, more flexible and decentralised networks for IoT-applications. These applications will normally use IoT related commercial-of-the-shelf (COTS) products such as temperature sensors or simple actuators, which do not need much data traffic; rather their amount of information is limited to a couple of digits.

Nevertheless, it is planned to connect hundreds of devices, their environment and production facilities, which will result in a high density of entities per area. Further, high availability and coverage are required to guarantee a seamless collaboration [9]. This also means that different facilities can be connected to create a flexible cluster on a production site.

Another aspect is that these IoT related entities shall have an extended power duration of up to 10 years per device. To achieve this goal, it is only possible by lower the frequency and narrow bandwidth at a minimum, but still, fulfil a correct data transmission. Through the reduction, less power will be consumed, which results in a longer battery lifetime [8]. For this, a new bandwidth is required and by now not developed. It means in theory, it is there, but the necessary infrastructure for this does not exist yet.

With the background from literature and the demands from the industry to further improvement, a specific research question was deployed, based on the specific background of the institute profile in production and logistics. Of high interest is, which opportunities offer 5G compared to existing, mostly wired, industrial systems, especially with the focus on SMEs.

To change the view to the industrial acceptance of 5G, new services or better service quality are required. Coming from the typical mass production, the modern customer demands specific and individual solutions. Having this in mind, it is clear that by orders on demand, much higher flexibility is required, which should not end up in a mess of heterogeneous product variant services. Cloud services are going to provide the needed transparency and accessibility for many. By putting the orders in a cloud and do the computing and data storage there, new services based on 5G capabilities have to be implemented. For SMEs, this is of high interest because missing services can be purchased. This kind of adaptability enables the idea of a flexible production system (on demand). Moreover, 5G enables the interconnection of different facilities (including the above mentioned IoT devices) in real-time. Thus, a supply chain, which is a compound of multiple SMEs, can be merged virtually. In this case, the compound could react immediately on changing events like changing customer demands, varying product quality or logistical issues. Considering the above-mentioned potential use cases, 5G is applied as an enabler for the corresponding services that have to be created upon it. To enable the inclusion of product usage data, the provision of predictive maintenance approaches, customizable production processes and the digitisation of supply chains into a future Industry 4.0-environment, the following key requirements, coming from literature and multiple stakeholders, for IoT-applications must be considered [3, 8]:

- R1: Support a high density of devices for mMTC-applications to guarantee its functionality
- R2: Low power consumption to extend the lifetime of IoT-components
- R3: High availability to support flexible and decentralised systems
- R4: Cloud services for storing and handling data to support a high availability
- R5: High reliability to guarantee the (and avoid failures) data transmission, which has an impact on the quality of services
- R6: Flexible bandwidths, which will provide the required data transmission all the time
- R7: Real-time monitoring for a transparent view on the production processes
- R8: Tracking/tracing to fulfil the demands in logistic concepts, especially for real-time monitoring
- R9: Security and safety: by means of industrial usage no external shall have access.

## 3 Use Case

After listing the key requirements, a use case based on a production logistics scenario is set up on a low scale for demonstration purpose. With the research question in mind, a test scenario shall be developed with most of the above-mentioned requirements are therefore considered and will be implemented. With a running use case, it will be possible to compare this scenario with common concepts.

The use case itself is based on a simple logistic scenario where a transport box can be tracked and traced, asked about its well-being and analysed delivering goods from one factory to another (Fig. 2) one and start from a theoretical perspective.

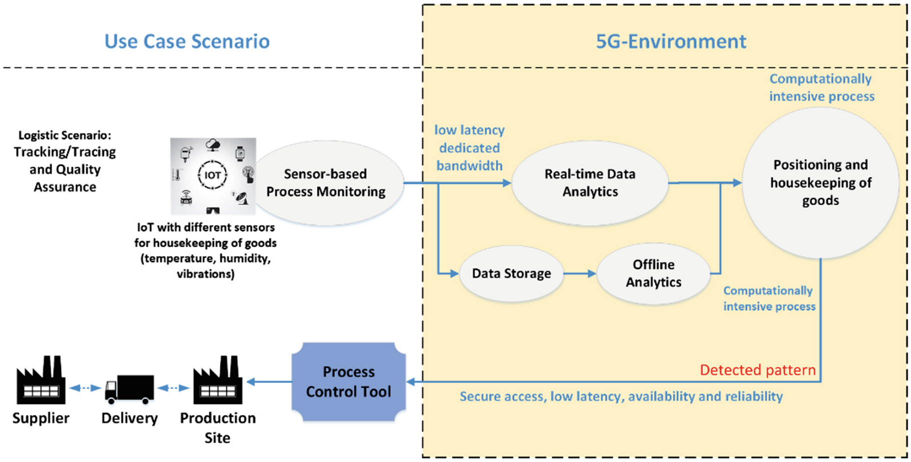


**Fig. 2.** Use case depiction via an application graph

Given is a transport box with sensors (temperature, humidity, vibrations, GPS) (R1, R2, R3) in it to make the box "smart". The box is connected to a cloud (R4) via an LTE-module (as a replacement for 5G) where the housekeeping (R5) will be sent continuously. The different distributed cloud service takes the tasks of the data aggregation and the monitoring to enable an automatic condition based monitoring functionality. Critical states or upcoming trends shall be immediately sent to a decision maker. A decision maker could be both a skilled employee and a tool like a PPS. Also, by using a mobile end device (e.g. tablet) (R6), a user can ask for specific data (e.g. temperature, position) directly to receive actual information in almost real-time (R7, R8). Furthermore, only the user will have access to the stored information and analysis results from the cloud services (R9).

Interesting herby is that the 5G framework will provide computing and orchestration services. The main goal in this use case is to transform the application in a way that it can be used and understood by the 5G framework. Therefore, it is depicted as an application graph so that the telecommunication providers can see all relevant services that are necessary for this setup.

The use case is still in the development phase, but the authors are eager to start with the testing end of the year. The evaluation will use KPIs to quantise the functional requirements.

## 4 Conclusion and Outlook

It should be clear by now that a running IoT-use case using 5G is not possible to be set up at the moment. Furthermore, without an existing 5G infrastructure, no real testing can be done. Nevertheless, the basic needs are described, and with these, the direction of development of the upcoming 5G standard is clear. Starting with a theoretical use case, a test scenario was developed, which uses mostly existing technology (e.g. LTE, Wi-Fi) and will be advanced to 5G when new components are available.

By showing the use case, the first steps in the Industrial 5G-environment are done. It is a major goal of the authors to continue with this work in the industrial environment as they see huge potentials by connecting independent entities and participants in a cluster for more flexible production on demand in the future. In a distant future, it hopefully will be possible to have a running industrial use case using 5G to balance its pros, cons and its limits to the existing models.

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# Complexity Management in Production Systems: Approach for Supporting Problem Solving Through Holistic Structural Consideration

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**Abstract.** Both external and internal influences affect the way production systems are planned and operated. Long-standing trends combined with topics such as digitization and artificial intelligence are increasing the complexity of tackling problems in production systems. Along with this, there is the ever increasing risk of planning errors and the loss of long-term competitiveness. This paper presents an innovative approach that supports problem-solving processes in the planning and operation of production systems. For this purpose, qualitative structural modeling and analysis of problem situations are applied. At its core, the article focuses on a framework, which forms the basis for the modeling of problem situations, their analysis and the organizational and technical integration of the method. Furthermore, with the concept of building block based domain-relation models, a possibility is presented with which the structure of problem situations can be modeled and analyzed.

**Keywords:** Complexity management · Modeling · Production management · Production systems · Collaborative tools

## 1 Introduction and Research Motivation

Manufacturing companies have long been exposed to global trends that have a significant impact on the way they create value. In addition to some temporarily relevant trends, the most significant change drivers in the recent past have been identified by the continuing globalization, the high volatility and dynamics of the markets as well as a change in values towards individualization and sustainability [1]. Thereby, the digital transformation of the industry represents an approach to enable production to meet these challenges [2]. This results in numerous new requirements, which cannot be covered by classical planning procedures [3].

As a consequence of these influences, both the exogenous and the endogenous complexity increase, which affect the planning as well as operation of the production system. In general, three main types of complexity can be distinguished [4]:


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- Environmental complexity - uncontrollable trends from market, customers etc.
- Value/service complexity - diversity and amount of product variants provided
- Internal complexity - variety of elements and processes in the system itself

Figure 1 illustrates the main reasons for increasing complexity in production systems, divided in human, technical and organizational aspects. These influences arise from previous research as the essence of an extensive literature analysis of the past years as well as from experiences from the scientific work and planning practice at Chemnitz University of Technology.

| | Human | Machine | Organization |
|---|---|---|---|
| Environ-mental C. | Production on demand | Disrupting technologies | Ad hoc collaboration networks |
| | Buyer's market | High reaction speeds | Service-orientation |
| Service/Value C. | Variety of products/processes | Complicated product structure | Multiple, changing projects |
| | Interdisciplinary collaboration | High production accuracy | Changing responsibilities |
| | Decentralized knowledge | | Production flexibility |
| Internal C. | Process intransparency | Technological innovations | High amount of tools/methods |
| | Data based decisions | M2M/M2X Communication | Vertical/horizontal integration |
| | Advanced HMI | Artificial intelligence | Time pressure |
| | Individual problem-solving | CPS self-organization | |

**Fig. 1.** Reasons for higher complexity in planning and operation of production systems

In production systems, humans act at various levels and situations as problem solvers in planning and operating. Their activities, however, are becoming increasingly difficult to carry out, since those are to be performed in complex situations - problem areas and effective ranges cannot be sufficiently limited. As a consequence, humans are overwhelmed in assessing prevailing problems and identifying solution providers/hurdles. As a result, typical challenges consist of assessing the scope of the problem, participating domains/persons, critical system elements, interactions between elements etc.

Since the behavior and thus the output of systems result from its structural composition, a structural consideration of production systems and problem situations is considered to be beneficial. From this reasoning, the following overall research question was derived: How can the prevailing structure of production systems in complex problem situations be systematized and analyzed in order to support problem-solving in factory planning and operation through the specific reduction of complexity and to enable managing the complexity in the object area?

As a research method, the Design Science Research (DSR) was chosen, which aims to develop human created artifacts while looping relevance and rigor cycles. So, the potential gap between theory and practice can be reduced, while developing artifacts, which are subjected to repeated evaluation [5]. This article concretizes the stated problem and presents an approach to address the research question by suggesting a method for supporting problem-solving processes in production systems through structural consideration.

## 2 State of the Art of Complexity Management

There is a wide variety of contributions from various disciplines on dealing with complexity. Referring to the DSR rigor cycle, a comprehensive literature analysis was conducted in order to examine the knowledge base for applicable foundations and methodologies.

In Science, there are two mostly different approaches in the field of complexity research. On the one hand there are analytic-reductionist approaches, on the other side systemic-evolutionary ones. In general, the focus in various areas is on developing suitable approaches, concepts and strategies to deal with complexity. This is summarized under the term complexity management. Historically, complexity science originated from scientific findings in Cybernetics [6] as well as classical Systems Science [7, 8] in 1960s. Towards the end of the 1980s research was decisively driven by organizational and management research. Driven by Pioneer Beer [9], the St. Gallen School picked up on these ideas and pushed research in management cybernetics [10–12]. Fricker presents a variety of enterprise-oriented traditional approaches to complexity management [13]. Particularly noteworthy are the works of Malik on management cybernetics [14]. The evolutionary approaches outlined here, which are based on Beer's Viable Systems Model, formed the basis for many other research activities.

With regard to more recent research, especially matrix-based approaches should be emphasized, which build on the analytical complexity management and aim at the modeling and analysis of existing structures. In the context of product development, Lindemann aims to use multi-dimensional matrices to reduce the complexity of projects and thus improve the project results [15]. Building on this, Kreimeyer explored how to extend this approach through metrics and thus improve the analysis capability of multidimensional matrices [16]. Petraus took up those approaches and transferred them into factory planning projects by developing a communication analysis methodology based on the project structure and organization [17].

The review of the state of science revealed (DSR rigor cycle) that so far no methods exist that could meet the objectives set out above. Nevertheless, selected existing approaches should be taken up, transferred or further developed.

## 3 Problem Solving in Planning and Operating of Production Systems

According to Nyhuis [18], a production system is defined as a socio-technical system that transforms input into output by means of value-adding and associated processes. Schmigalla [19] characterizes such a system by a certain amount of elements, processes that take place over these elements as well as a structure which is formed by the resulting relation between the elements. The activities of factory planning and factory operation are closely linked. The planning shapes the potential for the value creation process in the factory. Operation activities are responsible for the productive usage of those potentials. As a consequence, it can be stated that in factory operation control processes and in factory planning design processes take priority [20]. The processes involved in these functions are individual and collective problem-solving processes. These processes are determined by characteristics of the task, the situation and the problem-solving persons [20]. Generally, individual and collective problem solving in a specific organizational context is embedded in a larger context, which decisively influences certain situational characteristics.

In addition to the object area of production, also the planning and control of production can be understood as a system with elements, relationships, which is embedded in an environment. Thus both the object and the methods can be described as complex due to the high number, variability, diversity of their components and the processes taking place in them, as well as the associated uncertainty and limited predictability with regard to system behavior. This means that existing problem-solving processes must deal with complexity – as a result, involved persons are confronted with complex problem and decision situations. With reference to Ashby's law of requisite variety, complexity itself cannot be considered negative; it is even mandatory in systems to survive in complex environmental situations [21]. So complexity is not a problem in production systems per se. Rather, it is the inability of the humans to deal with this complexity, which leads to serious consequences.

In complex situations, knowledge about the structural consideration of problem and solution elements can provide valuable information to facilitate the solution generation process. Nevertheless, in most complex problem situations, the underlying dependencies are unknown, resulting in a lack of structural knowledge. Riedel [20] provides an generic operative model for problem solving in planning and control in factory planning and operation. Based on this, potential fields of application can be derived, in which structural consideration comes into play:

- Analyze and evaluate initial situations and narrow down of goals
- Creation or completion of procedure plans, which fits to structural condition
- Estimation of effect expectations
- Benefits in terms of knowledge activation and isolation of problem scope

In this article, the following illustrative example of a complex problem in a production system is used: Due to expected higher volatility, a project was initiated to increase production flexibility through the possibilities of digitization. Therefore, various sub-projects were started in the production areas, which are confronted with a high level of complexity, due to the large number of simultaneous activities, goals and personal responsibilities. Without adequate complexity management, planning errors, uncoordinated results and high costs are at risk.

# 4 Approach for a Complexity Management Based on Structural Consideration of Problem Situations

## 4.1 Framework and Concept

Based on the previous research, solution approaches for complexity management were developed. Particular consideration was given to preparatory work on the model-based presentation of systems, approaches from evolutionary management cybernetics as well as analytical approaches based on matrices and participatory design. The framework shown in Fig. 2 visualizes the overall proposed concept.

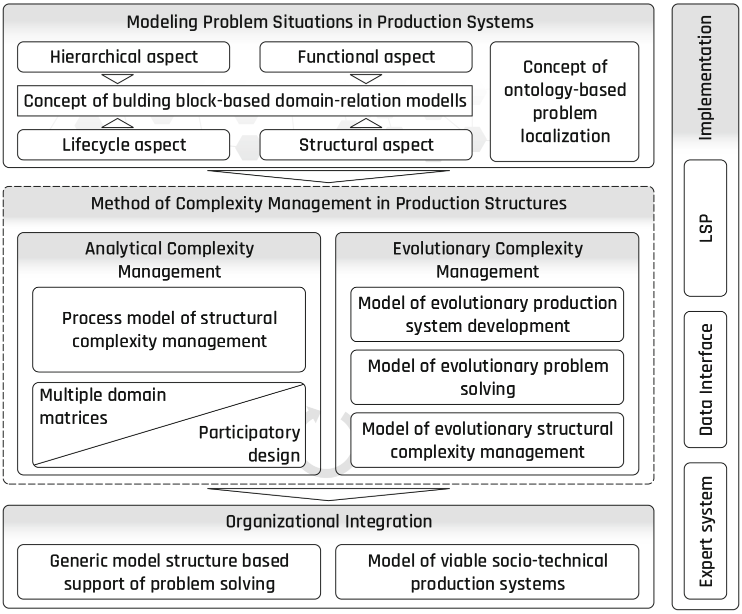


**Fig. 2.** Framework for complexity management in production structures

The framework for complexity management in complex problem situations is based on the idea of socio-technical systems where humans, technology and organization work together to fulfil the primary tasks. The upper section of the framework (organizational aspect) focuses on the foundation of complexity management by providing a general modeling approach. The middle section (human aspect) provides a methodical concept for dealing with the complex situations. Therefore, a clear distinction was made between analytical and evolutionary handling of complexity. The lower section and the bar handle the integration of the whole concept both organizationally and technically. Two main concepts will be presented below in a compact way.

### 4.2 Concept of Modeling Problem Situations

According to Ropohl [22], to fully describe a system, the three views 'Hierarchy', 'Function' and 'Structure' are essential. Based on these considerations, a concept was developed, which uses building blocks based on domain-relation models (origin: graph theory). In this case a domain is defined as the sum of systems entities of a kind. Transferred to problem situations, domains can be technical, organizational or human aspects such as machines, logistics, workers, objectives, customers, documents, qualifications etc. With domains and specified relations between the domains one is able to model problem situations in a qualitative manner.

With the instrument of Multi Domain Matrices (MDM), a problem specific selection of domains and relations can be modeled, where each domain represents a row and a column in the matrix [15, 23]. That opens up the possibility to not only create intra-domain linkages but also inter-domain linkages between elements of different domains. The aim is to enrich certain areas of the MDM with previously hidden content to provide additional knowledge. Thereby already in established algorithms can be used to calculate indirect relations, use metrics or find potential areas of interest.

Referring to the illustrative example, Fig. 3 demonstrates a simple MDM with four domains. The chosen relations between the domains are shown in the meta-model, which already merges the necessary constellation of a problem situation. In this situation, the concept could be used to create an aggregated view of this system showing mutual impact between people based on their planning on production units and their consideration of flexibility enables. Such newly created links could help gaining transparency and could be used for decision-making processes.

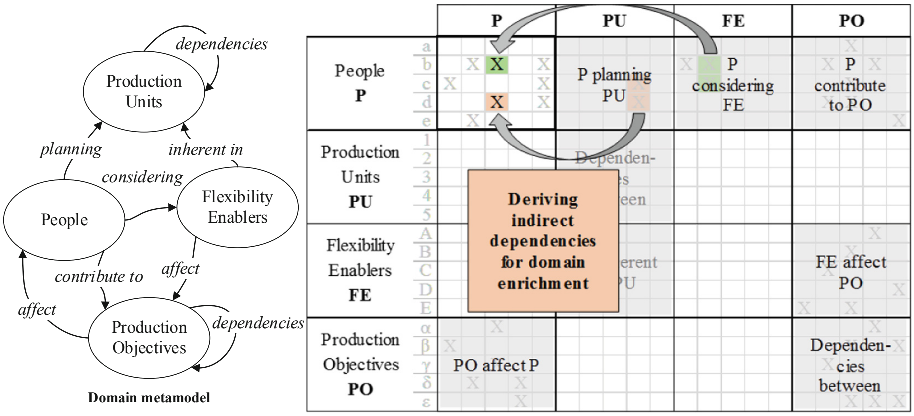


**Fig. 3.** Structural modeling of complex problem situations using MDM (simplified)

### 4.3 Method of Complexity Management in Production Structures

Consisting of two concepts, the method combines both analytical and evolutionary complexity management. This paper focuses on the analytical concept, which is illustrated in Fig. 4. The procedure builds on the preliminary work of Lindemann [15] and was extended and adapted to the current research.

Based on an event or problem in the planning or operation, the overall considered system has to be narrowed down to its relevant components. Therefore, the authors suggest a systems set-up using participatory design methods in order to model desirable future systems states in combination with semantic technologies (e.g. ontologies) to isolate relevant domains. During the following systems definition, the results are transferred into a MDM, covering all necessary facets to get a comprehensive situation model. Typical tasks are the determination of domain and relation, the fixation of granularity of consideration and the analysis of the problem scope.

Once the framework of the MDM has been built, the data retrieval of the individual domain must be triggered. Both manual (e.g. interviews) and automated (e.g. information systems) methods can be used. Afterwards, it is possible to narrow down the situation under consideration. After the already indicated calculation of indirect dependencies has been carried out, the structural analysis tries to gain added value from this new constellation of the structure. Once a satisfactory structural analysis has been performed, the results obtained can be used in further problem-solving activities, that lastly lead to better solutions in the real production system.

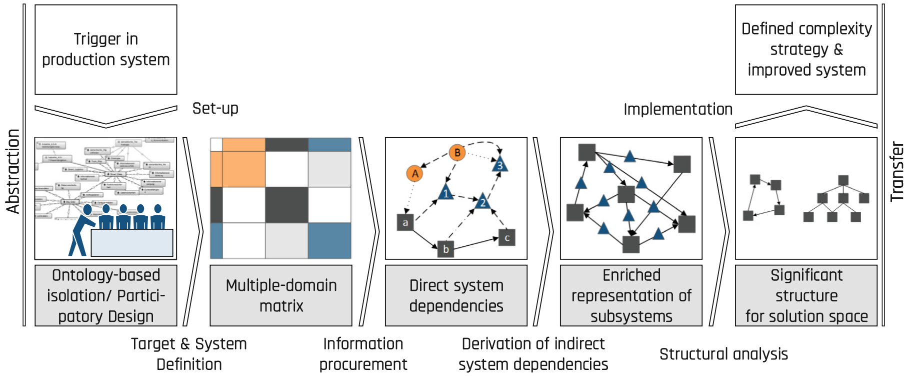


**Fig. 4.** Analytical problem solving with MDM

## 5 Conclusion and Future Research

The proposed concept of complexity management in production systems provides the opportunity for problem solvers to use structural consideration in complex situations to gain more relevant information and thereby to optimize solutions. Particularly in times of strong change and many internal and external influencing factors, it is becoming increasingly important to securely capture, understand and use those situations.

The presented framework provides the basis for a holistic approach to complexity management. It contains human, technical and organizational aspects to model required system sections, to analyze these models as well as to integrate the concept in a production environment. Following points has been worked out for further research and improvement of the proposed concept:

- Industrial survey on relevant domains and validation of concepts (relevance cycle in DSR)
- Research on technical implementation, such as expert systems and artificial intelligence
- Possibilities of data collection and validation, followed by industrial application.

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# Participatory Methods for Supporting the Career Choices in Industrial Engineering and Management Education

# The Teaching of Engineers Focused on Innovative Entrepreneurship

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**Abstract.** Engineering schools have a traditional way of teaching based on a sequence of subjects, beginning with fundamental sciences, mathematics, technologies and finally exploring practice and technics. This kind of program allows to deepen each subject, however, hinders the perception of the connections among the parts of a problem. Some schools changed their course aiming to turn the program more attractive to the students and, at the same time, more focused on the solution of actual problems the professionals face. For that, they used an innovative entrepreneurship approach changing the teaching-learning process. This article aims to identify the factors necessary to implement an innovative entrepreneurial engineering education, as well as explain such factors through literature review. As a result, two major categories of factors are observed, the teaching-learning process and university management. The first one encompasses the role of teachers, students, curriculum, and extracurricular activities. The literature suggests an open speech among students and teachers where they can explore multiple and critical perspectives. The PBL (Project-Based Learning) is recommended as a teaching-learning process. Extracurricular activities like scientific initiation, Incubators, and patents are other factors that contribute to this type of teaching. In university management, the incentive to innovation in engineering education is strongly recommended, besides providing students and teachers with an infrastructure that supports research and development and deployment of organizational culture and structure focusing on innovative entrepreneurship.

**Keywords:** Professional service management · University management engineering education · Entrepreneurship

## 1 Introduction

Good quality engineering education and regional development go together [1], and, with the rapid evolution of technology, an essential feature of the teaching of this professional becomes flexibility, so that the teaching adapts to the new knowledge, techniques, and demands of the market.

Nowadays, job market calls for an innovative professional with a solid basis in mathematics and science, as well as management knowledge, capable of the self-development of technical and transversal skills [2]. However, traditional education prepares engineers with strong technical knowledge, without a focus on management


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skills or the ability to learn autonomously. Besides, many students do not fit the course and interrupt it, producing a high rate of drop out in engineering programs.

Because of this problematic, many engineering schools became interested in courses driven to form engineers-entrepreneurs innovative and proactive [3]. The entrepreneurship programs are based on multidisciplinary interaction, teamwork, and communication. Over time students acquire the basics of engineering, gain perceptions of the business management process, and learn about ethical decisions, leadership, communication, and problem-solving [4]. In addition to these existing entrepreneurship programs, several schools, less evident, practice this experience in a timely, isolated and unshared way. These attitudes are individualized, in the hands of some teachers or a coordinator who believe in the results, but who do not know how to implement it fully.

This article aims to identify in the literature the factors of the teaching-learning process recommended to breed innovative entrepreneur engineers and also, the features of university management that facilitate or hinder the implementation of such education. The teaching-learning process is decoupled in essential elements, involving the teachers-pupils relationship, the teaching material, methodology, and organization of education. University management, instead, refers to the strategy, actions, and control of the results that the educational institution decides to accomplish. We assumed that management should be consistent with the teaching model.

## 2 Methodology

Initially, a review of the literature on innovative entrepreneurial engineering education was conducted, following the process of performing systematic revisions [5]. The characteristics of this systematic revision are the definition of the revision protocol; the establishing of a search strategy that seeks to detect as much relevant literature as possible; documented search strategy so that readers can assess seriousness and completeness; inclusion and exclusion criteria to evaluate each study. The main goal of the review was obtaining information to help to identify the factors that characterize an innovative entrepreneurial engineering school.

As a starting point, four university rankings are examined: the THE (Times Higher Education), the CWUR (Center for World University Rankings), the QS World University Rankings, and the RUF (Ranking of Universities of Folha*). The rankings provided a new view of the engineering schools' assessment process.

After the analysis of the rankings, we searched in academic journals the factors of an innovative entrepreneurial engineering school considering two perspectives: teaching-learning process and the university management. As sources of research, Google Scholar, Web of Science and Science Direct were used. In the search, the following descriptors were used in Portuguese and English language: "Innovative Entrepreneurship", "Higher education", "Engineering", "University Management" and "Teaching-Learning Process". The "AND", "OR" and "AND NOT" logical operators were used for the combination of the descriptors and terms for tracing the publications. The period set for the data collection ranges from 2010 to 2017.

After that, we evaluated the abstracts, the studies that seemed to fill the inclusion criteria were read in full. In the end, 108 articles met all the inclusion criteria. Then, the following aspects were observed: period and place of publication; author; definitions, characteristics of the study; evaluated conclusions; the journal in which the study was published (classified according to JCR Impact Factor). The extraction of data from the articles was made by the authors and consolidated in a model that suggests characteristics of an innovative entrepreneurial engineering school.

## 3 Results

In this study, it was observed that the literature examined the factors that characterize innovative engineering schools each at a time, separated from other factors, mainly when we refer to the teaching-learning process. The teaching-learning process can be understood as the producing process of an engineering school and encompasses the sequence of activities, the method, and material required, the professional role, and the students' activities.

### 3.1 Teaching and Learning Process

The search containing "Teaching-learning" returned 6,858 papers. Below, Fig. 1 shows the number of articles over the years, and we can see that the interest in the subject is stable from 2011 to 2016, with on average almost 1,000 publications per year.

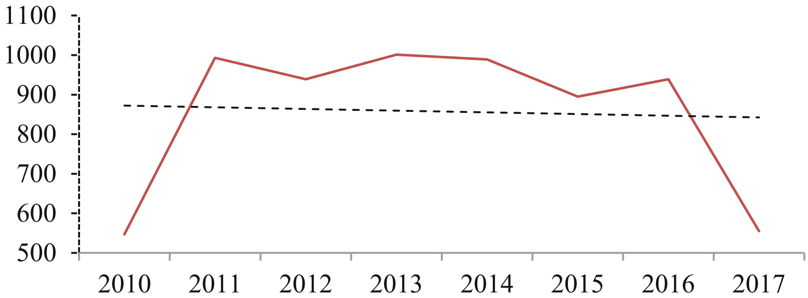


**Fig. 1.** Number of publications concerning the teaching-learning process over the years.

The teaching method undergoes a radical change from the traditional methods of teaching, which tend to focus on the transfer of knowledge, and emphasize individual work to project-based learning which promotes the teamwork and proactive learning, seeking solutions and decision making for the proposed problems. The traditional pedagogical methods are lessons, tests, and written works, while the collected literature recommends for this teaching approach simulation of business, games, development of companies or virtual or real products, visits to companies and entrepreneurs and the elaboration of a business plan [6].

The teacher's attitude is an essential factor to implement the new teaching methodologies and induce the integration of other disciplines. Also, it is up to the teachers to stimulate students to think and act with an entrepreneurial mindset, not conforming to reality, focusing on innovation, with the courage to take risks and experience of market [7].

The changing in the teaching methods also demands a change in the role of the student. Some authors maintain that innovative entrepreneurial education should be focused on the student, who is responsible for learning in an experimental, practical and contextualized way, as this encourages imagination and analysis, preparing the student to deal with uncertainty and lack of resources and preparing them to an innovation process scenario [8].

As for the curriculum, researched authors [9, 10] observed that the engineering school should include specific disciplines related to innovative entrepreneurship and to promote the interdisciplinarity so that the student can have an integrated frame to approach the problems. The engineering curriculum should also balance the development of human skills in the same intensity of their necessary technical skills [11]. The challenge of such programs stays in developing the skills in areas such as negotiation, leadership, creativity, technological innovations, and new product development. Given this, the education of an innovative engineer should not be seen as a separate discipline, but as a set of actions whereby students are instructed to expand their ideas and that this process should be established from the first periods of graduation [12].

Another key issue identified is the extracurricular activities, as the insertion of incubators, student organizations and junior companies, that provide infrastructure and support for microentrepreneurs and accelerate the student's entrepreneur potential [13].

### 3.2 University Management

The second perspective analyzed is university management, which facilitates and stimulates the teaching-learning process, consistent with an innovative entrepreneurial vision. The 2,059 articles collected examine the following factors: strategy, culture and organizational structure, leadership, and internationalization. Figure 2 shows that there is an increasing rate of publications on this subject, reaching its peak in the years 2015 and 2016, which represented the most productive period in publications.

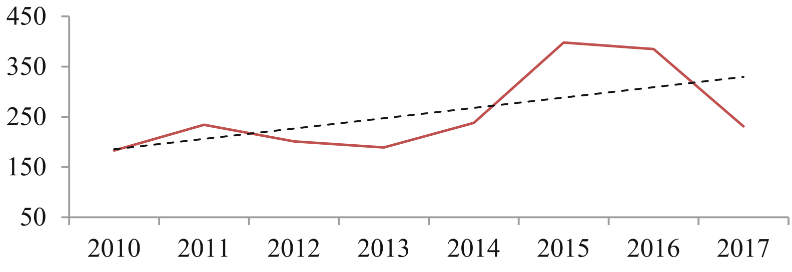


**Fig. 2.** Number of publications about university management over the years

The formation of strategies in an engineering school is a complex management process, mainly because of the high unpredictability and uncertainties of the external environment. Also, the structure is loosely articulated as in organizations where professional experts develop the essential operational work [14].

Higher education institutions have a very broad, ambiguous and intangible mission, which makes it challenging to define and operationalize objectives; planning in these institutions is an isolated and random activity since it works by short-term budget cycles and aims long-term results. Their professionals work independently, motivated by personal objectives, making it difficult for analysts to rationalize structures from their abilities. Higher education institutions have no managerial skills to make rapid changes; their lines of authorities are unclear; their leaders work as catalysts: do not command, but negotiate, they do not plan broadly either solve problems using pre-existing solutions; changes depend on the consensus and the authority of a lot of people [15].

In this way, the main challenge for the management of this type of school is to create an environment conducive to the emergence of entrepreneurs. That points out the need for an integrating organizational culture that can contribute to the development of new ideas and new strategies that cross the boundaries of structures. The entrepreneurial culture is a culture in which entrepreneurship is embraced by the majority, if not by all; therefore, the values belonging to the institution should be shared by people at different levels of the higher education institutions hierarchy. In an entrepreneurial culture, people can deal with risk and respond to fast context change, helping innovation process [16, 17]. Accordingly, the organizational structure must support secure communication among the various specialties, promoting the multidisciplinary of the curriculum.

Also, the University internationalization is an essential factor for the development of the students' entrepreneur skills, as primarily mentioned in the literature [17]. On the one hand, the internationalization allows the student to experience different curriculum models at several levels, as student organizations, incubators, and agencies that promote innovative entrepreneurship. On the other hand, the process of integration abroad, regarding creating organizational bonds and support, can immensely contribute to the student creation of a new vision of social interactions, strengthening innovative entrepreneurial education [16].

Finally, internationalization can be defined as the crossing of cultural frontiers [18] and adds significantly to the innovative entrepreneurial teaching style. It occurs not only when the students go abroad, but also when the school receives international classmates. The teaching-learning process and the extracurricular activities with multicultural groups also strengthen the ability to innovate, giving them new tools to solve problems, aspects so important to entrepreneurs [19].

## 4 Discussion

Entrepreneurship and innovation depend on an ecosystem of interrelated elements [20]. An innovative entrepreneurial ecosystem is defined as an environment endowed with agents (markets, policies, finance, culture, support, and human capital) that contribute to the development of innovation and entrepreneurship through their interactions. One class of agents by itself cannot modify the system, only with the support of other groups of agents it is possible to create a climate favorable to innovation and entrepreneurship, what eventually results in the creation of new markets, jobs, revenue streams, and innovation.

Based on the concept of ecosystem, we believe that an innovative engineering school has to be analyzed considering several factors, which are divided into two views. The first perspective is connected to the learning process, which encompasses the operational elements of an educational institution, that is, presents the most critical factors that contribute for students to acquire knowledge and skills necessary for their profession (role of the teacher, the role of the pupil, curriculum and extracurricular activities). The second perspective represents the university management, which should provide factors that will contribute to good governance in innovative entrepreneurial engineering schools. Infrastructure, strategy, culture and organizational structure, internationalization and leadership are the main management factors for this type of teaching (Fig. 3).

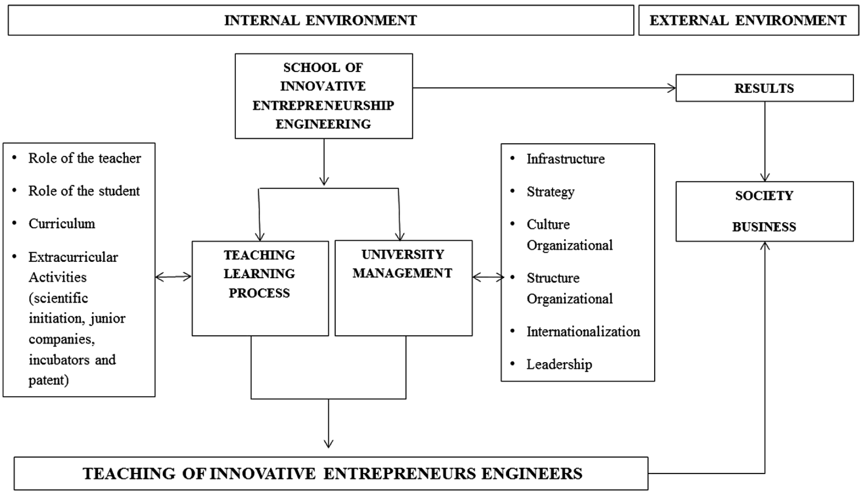


**Fig. 3.** Driving factors for the innovative entrepreneur engineer education

## 5 Conclusion

Our starting point in this article is the understanding of what the job market expects of the future engineer. The job market seeks engineers with a broad vision, a business vision, beyond the technical view. For this to happen, engineering schools need to manage and teach in a different way.

The implications of this concept, both for the school and for the teachers and engineering students, represent a new responsibility, a new culture, a new form of managing, teaching, and learning. Directors, coordinators, teachers, and students must practice the innovative entrepreneurship in daily activities, not only in classrooms or as an academic subject.

A contribution of this research is the identification of a literature gap on research that links the university management to the entrepreneurial teaching-learning process. Studies focusing on teaching-learning factors and management factors in a connected way were not found.

Furthermore, one of the relevant results pointed out by this bibliographical review is that while the publications about the teaching-learning process maintain a constant number over the years, the number of articles on University management has increased from 2010 to 2017. Nevertheless, a change in the management system should not be seen without considering its impact on the teaching-learning process. For that reason, this article defends that both subjects should be faced as parts of the learning ecosystem, and consequently, they should be complementary.

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# Research Initiative: Using Games for Better Career Choices

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**Abstract.** This paper presents a novel research initiative, that is, to measure the effectiveness of specific game playing in gaining insight into the nature of various career paths in industrial management and industrial engineering. An experiment to measure the effect of a game is proposed and the complexity of the measuring task is discussed. The paper is a position paper, calling for an open discussion of this subject of research.

**Keywords:** Serious gaming · Career choices · Industrial engineering and management

## 1 Introduction

Through childhood, adolescence, and young adulthood, people constantly set, maintain, and reflect upon their career preferences and goals. In today's dynamic labor market, this process is actually extended into middle-age or even later as many people today change careers late in their working life. From this internal process, coupled with real life constraints and ad hoc decisions, the career path of the individual emerges.

Extant research [4] recognizes the multifaceted difficulties of career defining decisions. Previous research in career development investigated various determinants leading to the choices made by individuals [5]. Viewed in a larger societal and systemic perspective, an individual's career path is influenced by and impacts the following stakeholders:

**The individual themselves.** Intrinsic determinants are: the individual's occupational aspirations, self-perceived abilities, affinities and inclinations. Extrinsic determinants are: their perception of the labor market, job prestige and reward levels, and how the individual understands what the job implies.

**Family and peers.** A family may have traditions, expectations, and even demands with respect to the career choices of its members. Peers can exert pressure or be role models.

**The education system.** The choices for education outlets (especially during adolescence and young adulthood) are in interplay with the career choices. Recruitment, marketing, open days in schools, and education fairs can lead to influencing both education and career decisions. More recently, the amount of student loans needed for certification is becoming a crucial determinant.


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**The economy, labor market, and society.** Politicians and employers have always complained that graduates are not prepared for the actual job market needs at the time of graduation. However, most modern societies have tools to predict and even to plan the job needs of tomorrow, and this information, if disseminated, can be an important career determinant. National surveys about intended career choices can reveal inconsistencies between those intentions and projected needs for the near or more distant future. Governments and employers can offer various incentives to influence career choices in an attempt to resolve such inconsistencies.

This research proposes a closer look at a novel determinant: games, especially games that are designed purposefully to affect career choices. The interplay between games and career path planning constitutes a very large research area and thus needs to be limited. We look at career paths in industrial engineering and management and games that provide insight into what someone with such a background actually does.

Nevertheless, researching games in this context makes it necessary to include additional research subjects into the societal, systemic view outlined above: the game developer, the game organizer. Researchers interested in this field will investigate the interactions between developers and organizers, and also the interactions with the industry, governance, and education system. There is overlap with other fields of research, for example the classic career development studies, and psychology related areas, like career counseling.

## 2 Background

Games, from a commercial perspective, can be largely categorized into ones that are developed for entertainment, and those that are used for other reasons (like training, research, persuasion). The former we call *entertainment* games and the latter *serious* games. The focus here is on serious games. For this particular research, the organizers of the game are the stakeholders in the labor market like governments and various industries, which forecast future employment needs and occupational trends.

The interventionist approach to labor market governance is prevalent in economies that have a strategic planning component—a typical example is China, with its 5 year plans, but also other Asian economies like Japan, Taiwan and South Korea. Also the Nordic and Benelux economies in Europe have strategic governance agencies[1] that want to have leverage in how the labor force of the future is shaped via educational means. For example, in the Netherlands, the Ministry of Education is funding initiatives that use resources (e.g. money, people, expertise) from the higher education to educate K–12 pupils about the reality of careers with many current or projected job openings [9].

Today's children, adolescents, and young adults are exposed to many kinds of gaming, for example on their phones and on social media. Despite societal

[1] E.g. in the Netherlands the Social Cultural Planning office.

criticism, research reveals that gaming in general has a positive influence on the young population [3]. Their skills and propensity to understand issues and acquire skills and knowledge via games is recognized in education research as a promising trend.

Many disciplines are using games to supplement their educational tool sets. The authors have been involved in designing and organizing games for pupils in elementary schools (grade six) in the Netherlands that give them a preliminary perspective on jobs in the area of logistics (e.g., inventory manager).

Less researched is whether games can be used to influence career choices. Some anecdotal evidence on this topic has started to emerge, a journalistic source reported an interview from which we take the following quote:

> ‘It was no secret that I hated school. I hated career days, I hated maths, and most of all, I hated having to think about what I wanted to do when I reached adulthood. As a break from all that, I was a kid that spent way too much time on video games.’ (Pilot, lawyer, medic: meet the people who turned video game careers into real ones – The Guardian, March 20$^{\text{th}}$ 2019 [6])

After extensively playing a court game (Phoenix Wright: Ace Attorney), the woman quoted above decided she wanted to become a lawyer. It is also assumed that the younger generation of airplane pilots (both military and commercial, on board and remote) have played lots of flying simulation games before choosing that career and receiving any training. Another example is that creative industries like game development and animation tend to recruit those young people who are the most adept at playing various games.

The Netherlands and other countries in the developed world are confronted with a shortage of labor in the multidisciplinary area of industrial engineering and industrial management. This is due partially to the trend to make people select educational paths and jobs that are focused on a core competency and are very specialized (and thus less multidisciplinary). Another researched reason [10] is that the hybrid type of jobs that include both aspects of engineering and management are less known and understood, because they are not technical enough to appeal to the more technically inclined person, but they are infused by technology related aspects in a way that exceeds the competences of a person inclined to think in a broader, more managerial way.

The position taken in this paper is that governments and employers should apply games to affect career choices and stimulate the creation of games that fit their (projected) needs. When these games exist, schools can use them to give more insight into this kind of jobs. First, research needs to show the efficacy of game based interventions. An experiment for such research is proposed in the next section. If this proves fruitful and games are subsequently implemented on a larger a scale, a longitudinal study should be conducted.

## 3 Proposition for Experiments

The authors have some experience with developing and deploying a game that offers insight into various jobs in logistics for pupils in sixth grade. However, no measurements were taken of these pupils to determine the effect of the game. Playing the game was part of larger project [9] (*Dutch only*), that proposed and experimented with the enlargement of the current curriculum in elementary schools in the Netherlands, specifically for more education about logistics as a discipline and an important industrial sector. Among the goals for this project was to give more insight into logistic jobs, because it was revealed in other surveys that this kind of job is not considered interesting and attractive to pupils of various ages.

### 3.1 Instruments to Measure Changes in Pupils

The aim of this research is to determine if pupils can be enticed to consider career options they otherwise may not have. This allows them to feel competence in a field they were not previously aware of. The feeling of competence within the ability to successfully fulfill a task in a certain job is called *occupational self-efficacy* and instruments for measuring it are available [8] While some pupils may experience an increase in their occupational self-efficacy it could decrease in others. It is therefore necessary to test the occupational self-efficacy both before and after playing the game. We can then compare changes in individuals, not just within the aggregate of the group.

To design such an experiment and to formulate the questions is still work in progress. It is a difficult task because it necessitates knowledge from both studies in career choices and psychology. Ideally, this research should be done by a multidisciplinary team. Starting points here are the works of Bandura and Schunck [1] and Barak [2], which led to the career interests emergence model of Lent, Brown, and Hackett [5].

### 3.2 Game Design

The game mentioned above[2] will serve as the foundation for this research. In its current form the game allows pupils to manage a store: they are placing and fulfilling orders, keeping stocks, investing in warehousing and/or transportation, etc. The game is aimed at sixth graders (the last year of Dutch primary school) and it is intended to be learned and played individually in a single session. The players can measure their success in several ways: the amount of money the make, their customers' satisfaction or their score which incorporates several such factors. The score is intended as an objective measure of success, though players are encouraged to find their own fun.

We envision several potential extensions of this game. Implementing and researching these will help refine how a game can influence career path determinants. Examples of such extensions are:

[2] Available in Dutch and English at: http://ontdeklogistiek.nl/game/.

- Additional measures, for example: environmental impact, can be added to further diversify "success".
- "Develop/Affect" a buying/selling strategy which can be tweaked but does not require continuous input from the player.
- A multiplayer component, where supply and demand are shared (and competed over) among several players.
- Playing over a longer period (e.g. a week) showing differences between short- and long term strategies.

### 3.3 Effects to Be Measured

First, we intend to show that games have an impact on a player's perceptions. A very relevant measure for which instruments already exist is occupational self-efficacy. A change there indicates that the player has adjusted their own expected success in that particular field. Our hypothesis is that this effect is (generally) positive for jobs one would like to encourage people to choose, though persuading people not to choose *overfull* career paths can also be valuable. Self-efficacy alone is not enough however, as research by Lent reveals: 'self-efficacy may not translate into interests unless people expect their activity involvement to be rewarded' [5]. For example, the perception of rewards and prestige of a kind of job have to be taken into account. Whether that should be in the scope of this research remains to be seen.

## 4 Discussion and New Avenues for Research

The experiment proposed in the previous section is a short-term experiment that measures the job-insight impact of playing the game only once (measuring only occupational self-efficacy). However, if these games are made widely available, data should be collected over a longer time. Periodically, a thorough analysis can be done based on this data, and our understanding of the effectiveness of the game can be incrementally refined. Longer period monitoring of volunteering participants will yield a more complete insight into the inherently long term process of career path development.

Among the many hurdles to pursue this research, the main one is that (further) developing such a game is expensive. It also necessitates a large interdisciplinary effort. Therefore, questions arise: who is paying for the research, development and playing of career path influencing games and which disciplines should be involved? Below, two strategies for approaching the, potential, market are discussed.

First, both industrial and governmental agencies have a strategic stake in future labor markets. They are the obvious avenues for funding the development of such games, by (specialized) commercial partners. These games could even be part of the public image of a company, the way games have been used to cross-promote movies and television shows [7].

An alternative to such a game development and deployment scheme would be that industry and government invest in academic centers that are specialized in participatory methods for education (as their research focus). Current experience of developing games in such a context shows that using Commercial off-the-shelf (COTS) tools en components for games[3] lead to results that are comparable in look and feel to the commercial games. A hybrid between the two aforementioned development schemes is also possible. The results of the research presented can serve as a basis for a thorough stakeholder analysis to explore what the current market can support.

More technical issues and questions related to the game development are related to the game architecture. From other serious games, is there an architecture that is appropriate for this task? For example, is it better to have a multiplayer game, which involve cooperation and competition between human players, or individually played games? Should the game be immersive, giving the player the sense of being transported into another world, or should it be firmly grounded in their current reality? These architectural choices have a big impact on how the game is developed, played, and maintained. They also affect what a player can potentially learn from the game, i.e. can the game reflect the social (multiplayer) aspects of a job?

Additionally, from an even more generic architecture perspective, the game based approach is not the only participatory method that could bring this type of insight into the nature of a job. Other research can look into alternative participatory educational activities and tools, for example co-creation during hackathons, which can be either in a real or a simulated environment.

## 5 Conclusion

This paper is mostly a position paper, and its main contribution is to start a discussion on how this research should be conducted and what are promising avenues of exploration. First a novel research initiative is explained, that is to measure the effectiveness of specific game playing in gaining insight into the nature of various career paths in industrial management and industrial engineering. Next, an experiment to measure the influence of a game on a players occupational self-efficacy in a controlled environment is tentatively proposed and the complexity of the research undertaking towards the measuring task is discussed.

More generally, the research could be extended to investigate the comparative impact of participatory methods on career determinants. Interested readers are encouraged to participate in workshops that further discuss this subject of research.

[3] E.g., COTS like game engines, real-world simulators, multiplayer game servers.

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# Blockchain in Supply Chain Management

# Blockchain as Middleware+

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**Abstract.** In supporting decision making of manufacturing companies, the added value of cross-domain data exchange for aggregating information is well established in enterprise organization research and is represented, for example, in the reference model "Internet of Production" (IoP). Currently, there is little research regarding the role of Blockchain technology in such a reference model and how specifically the IoP needs to be expanded to address cross-company data exchange. This paper presents a proposal for such an extension to outline the use of Blockchain technology and to elaborate the open research demands for implementation. In particular, desk research and the development of concrete use cases for cross-company data exchange between business application systems were carried out. The results are, on the one hand, extending the IoP by a third dimension, which corresponds to the supply chain, and, on the other hand clarification of the role Blockchain technology can take in this context.

**Keywords:** Blockchain · Supply-Chain-Management · Middleware+ · Internet of Production · Supply-Chain-Data-Management

## 1 Introduction

### 1.1 Challenges in Supply Chain Management

The decline in value added per individual company observed in recent decades will continue over the next few years [1]. This is facilitated by increasingly complex products, which in turn means that more and more different suppliers have to be integrated into the value chain for the production of a product [2]. There is a need to cooperate with more and more value creation partners. At the same time, ever-shorter product life cycles and the associated ever more frequent changes to products mean that value-adding partners have to be changed more and more quickly.

Increasing competitive pressure and the shift from the seller to the buyer's market are forcing companies to exploit the potential for optimization through digital data exchange, previously considered to be too costly or insufficiently productive [3]. For example, the use of data from the supplier can prevent a company from having to re-collect data itself, which often avoids inaccuracies and duplication of effort. Collaboration concepts such as just-in-sequence, in which the supplier delivers the parts according to the sequence at the car manufacturer, should reduce inventory and handling costs. The prerequisite is that the car manufacturer transmits the sequence to the supplier - digitally to keep the administrative costs reasonably low.


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Ultimately, therefore, there is the need for quickly established digital networking with many value-added partners. The concept of the organization of the data exchange along a value chain should be called Supply-Chain-Data-Management in the further.

### 1.2 Digital Connection/Industry 4.0

"Industry 4.0" has established as term for the mass connection of information and communication technologies [4]. It refers to the real-time capable, intelligent, horizontal and vertical networking of people, machines, objects and information and communication technology in order to be able to manage complex systems [5]. For implementation in production, Klocke et al. define the reference architecture "Internet of Production" (see Sect. 2) and present some use cases of such connection.

As part of **change requests** in production, technical changes in the form of state changes of actually released products are necessary [6, 7]. Due to the increasing dynamisation of the industrial environment, technical change management has become increasingly important [6, 8]. Due to the many negative effects of such requests (budget overruns, time delays), companies usually try to avoid them if possible. Cost drivers in change management are in particular cross-departmental coordination efforts and media discontinuities in the participating operational application systems. A significant improvement of the change request process could therefore be achieved, among other things, through meaningful linking of CAQ, PLM, CAD, FEM, and ERP systems: The introduction of the change request without this link often leads to large expenses in the manual transfer of data between the systems mentioned and ultimately to inconsistent data and ultimately to high error and failure costs [9].

The **design of additional systems for technical process stabilization** in order to retrofit them to a machine is necessary, for example, if the machine has critical structural vibrations during operation. These vibrations could be alleviated with the help of individually designed multi-mass dampers. Such additional systems are usually easier to implement than structural adjustments. The design of such systems requires the availability of data such as the frequency and waveform as well as the equivalent oscillating mass of the machine structure. Therefore at least data from the CAD and the FEM system are necessary [9].

The use cases presented impressively show the added value of connecting various business application systems, but remain at the corporate level. Even in those use cases in which customers are involved, not their systems but self-used systems with customer data are used. In the following chapter, the Internet of Production is introduced, presenting a framework that is able to address the digital connection between business application systems used in the presented use cases.

### 1.3 Internet of Production

Figure 1 shows the reference architecture of the Internet of Production, which was presented at the Aachen Machine Tool Colloquium in 2017 and culminated in 2018 in the eponymous Aachen Cluster of Excellence sponsored by the DFG. Seen from left to right, it includes the three phases "Development Cycle", "Production Cycle" and the "User Cycle". At the lowest level, the raw data usually generated in the respective phases and (graphically above) the application software in which this data is managed are displayed. At the highest level, the vision of decision support Smart Expert systems is presented, which support the employees in the respective phases. They feed on the layer of so-called "smart data", i.e. data which has already been pre-refined by analytical methods. Input for these data analyzes comes from the already mentioned application software systems. The access to the proprietary operational application systems therefore is allowed by a Middleware+, which, however, has not been further specified in its design [9].

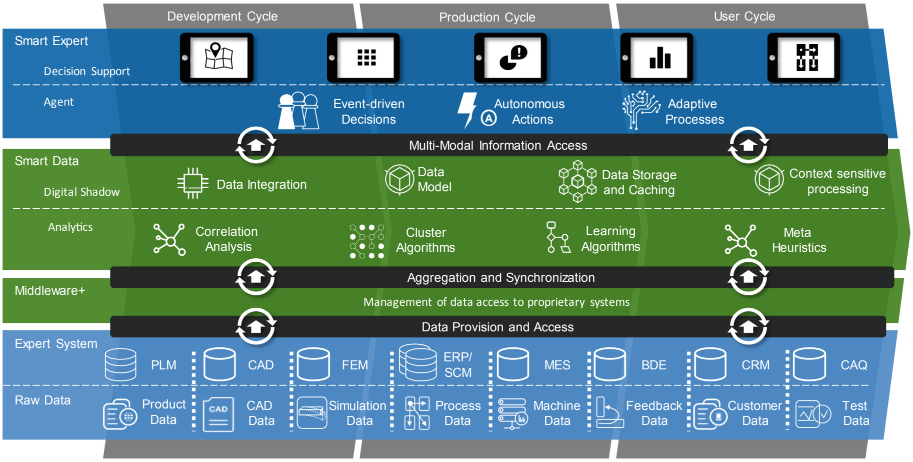


**Fig. 1.** Internet of Production [9]

## 2 Cross-Company Internet of Production (Three-Dimensional)

The attempt to expand the IoP with regard to cross-company data connection is carried out per level below.

The lowest level of **raw data and application software systems** remains company-specific. The attempt to create data through the use of common systems across companies would fail due to the aspiration to quickly achieve connection with new partners. Any change of value-added partners would be associated with the introduction of new business application systems - at least if it can be assumed that systems that are not globally consistent will be used. With the example of ERP systems it becomes clear: More than 2000 different systems are currently offered on the market [10]. Correspondingly, a cross-company representation of the IoP would have to show a separate raw data and application software layer.

The **Smart Expert** view, including the apps shown there, contains expert systems that specifically provide those users with information that is relevant to them. However, the information to be extracted from each company's data may differ significantly from company to company. For example, it may be helpful for the customer of an aluminum parts supplier to see how well their supplier has met the prescribed component tolerances. The employees of the aluminum supplier, on the other hand, are more likely to receive orders from the customer in the Smart Expert System. In many cases, there is a high overlap of the contents of the Smart Expert systems along the supply chain - once developed apps can be used in several companies. However, standardization of the level must be avoided.

This results in a direct conclusion for the **Smart Data** layer. Features such as data integration or the data model, as well as the data analysis method to use, are highly dependent on what results are displayed on the Smart Expert level. Consequently, the same applies here as for the Smart Expert level: there is certainly a high degree of reusability of the functions used. However, standardization does not make sense.

The situation is different at the level of **Middleware+**: especially in this area, a breakthrough in the form of cross-company connection is indicated and would enable many use cases along the supply chain. A Middleware+, which would ensure overall management of data access to proprietary systems and data there, would enable organizations to efficiently use data from their value-added partners. A connection via a shared Middleware+ would also reduce the connection costs of new partners, since the number of interfaces is considerably reduced - the rapid change of the value-added partners and the connection of many partners for the realization of Supply-Chain-Data-Management are therefore possible (Fig. 2).

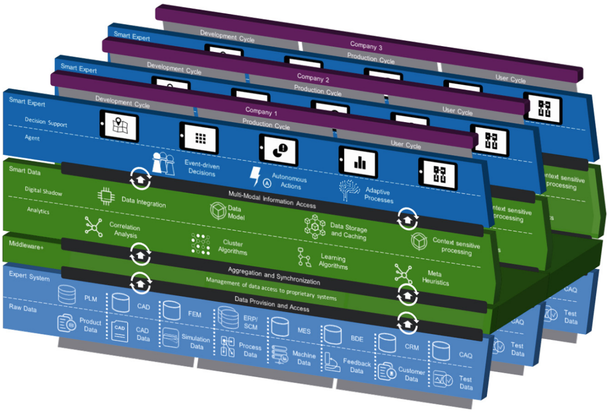


**Fig. 2.** Cross-Company Internet of Production

The selected form of representation extends the IoP by one dimension: the different value creation stages. Two problems of this form of representation should be briefly addressed. On the one hand, this representation could give the impression that expressly only classical value chains with a defined sequence are displayed instead of value networks. In fact, the order of the companies here is not decisive, a connection between company 1 and company 3 is possible. On the other hand, in the industrial supplier-customer relationship, the "user cycle" of one company is often the "production cycle" of the follow-up company. This is not explicitly made clear in the presentation, but also irrelevant for multilateral networking. The fact that test data in the CAQ could come from the customer's BDE is already taken into account by the fact that the Middleware+ is consistent across all cycles.

For the concrete design of such a cross-company Middleware+ is to be noted that there is a conflict of trust between the companies. Even with in-house connection, it has become apparent that the specific technical design of a Middleware+ is not trivial. In the case of a cross-company perspective, it is to be expected that this arrangement will be much more difficult. While there is an escalation level in the organization of a corresponding implementation project with a higher hierarchical level, which can simply make a decision in the event of disagreements between the stakeholders, such an escalation level is missing in the cross-company case. Furthermore, simple authentication methods for in-house connection can prevent data from being illegally manipulated - this is not the case with cross-company connection. Centralized approaches (platforms) have so far hardly established themselves for such sensitive business areas. Blockchain technology was introduced in 2008 as a technology which, without a trusting intermediary, should make data forgery-proof and highly available; even with this technology, the industrial use is already much discussed, but hardly brought into the real application [11]. The mentioned Blockchain technology will be further considered in more detail for fit as Middleware+ in cross-company IoP.

## 3 Blockchain as Middleware+

### 3.1 Blockchain Technology

A scientifically recognized, uniform definition of the term "Blockchain" does not currently exist [12]. There is general agreement, however, about some properties of the Blockchain technology, which will be explained below. A Blockchain is a decentralized database (often called "distributed database"). The included data is usually not available at a central or a small number of distributed locations to which authorized participants can access (see Clouds on central servers or on distributed server networks), but completely for each participant in a network of distributed, decentralized units. The data is stored in the form of transactions in blocks of data arranged chronologically [12, 13].

This decentralized structure prevents a loss of one or more network nodes from permanently losing the stored data - as long as at least one network node remains intact [12]. With a sufficient number of participants, the loss-security of the data is sufficiently high. The involved network nodes continuously synchronize their data status, new information is sent to all nodes in the network [14].

A block consists of a block header and its associated transactions. The transactions are combined via a hash tree to a root, which is part of the block header. In addition to the "hash value of the predecessor block" explained below, a timestamp is usually stored in the block header which indicates the date of origin of the block. Depending on the Blockchain also the storage of further data is provided [13].

A key feature in the data structure of Blockchain technology is that the individual data blocks are linked using hash functions. For the subsequent blocks, these are linked in chronological order by means of pointers. The replacement of the simple reference with a cryptographic hash function yields an authenticated data structure which, with sufficient probability, ensures that the previous data is not compromised. This anti-counterfeiting security benefits those elements that are included in the calculation of the linking hash value. In the case of a Blockchain, a cryptographic hash function is usually used for linking the blocks, for which the preceding block header is used as data input. Since the block header contains the root of the hash tree of the associated transactions, the security against forgery thus extends to the entire previous block and ultimately to the entire data structure [13, 15].

Consciously, a more detailed description of the Blockchain technology and specific sub-technologies (hash functions, consensus algorithms, cryptography, etc.) should be omitted here - the reader should refer to the relevant specialist literature.

### 3.2 Blockchain in the Internet of Production

It becomes clear that the Blockchain technology is transaction-based. As a redundant database, it can provide data forgery-proof and high availability of Data. As part of the reference architecture of the IoP, the Blockchain could therefore serve as Middleware+. This application would solve the problem that in use cases of cross-company data usage, a comprehensive data storage or accessibility solution can not be easily installed. Which of the two mentioned would be the Blockchain, incidentally, would depend on the configuration. It would be possible to use the Blockchain for storing access authorizations to proprietary systems as well as the use for storing the data itself, which would then be redundant with storage in the company's own databases. Since the first case has been little explored so far it will be assumed from the second in the following.

In order to clarify the mode of operation, a few potential use cases are briefly outlined, in which the Blockchain technology is used as Middleware+ in the cross-company Internet of Production.

In the BDE system of an aluminum supplier, the **process parameters from the production** process are stored unambiguously per component. These process parameters have a significant influence on the material properties and thus on the machine parameters to be set during further processing. The process parameters can be written from the supplier's BDE to a Blockchain, with the summary of the process parameters corresponding to part of a transaction. During further processing of the parts, the parameters can be retrieved by the appropriate operational application systems. It would be conceivable in addition to the transmission of the process parameters and the transmission of desired-dimension deviations that are then used in further processing - e.g. in the assembly robot offset these deviations. As a result, the processing company could allow higher deviations, which in turn would save costs.

In the ERP/ME-System, especially for convergent and divergent material flows, the **relationships between the predecessor and successor** parts are maintained and relevant data is copied to a Blockchain. The transactions in the Blockchain contain the information about which components were merged. Through the documentation along the entire value chain, it is thus possible to ensure the traceability of a product or all of its components across the entire value chain. If several faulty products are identified, it can be determined by a simple analysis, where similarities lie - for example, in the fact that with all faulty products a component was manufactured on the same day. Thus, callbacks can be carried out in a particularly targeted manner.

The BDE of a company documents how many **working hours** a particular machine has been used. The distributor of the machine offers additional industrial services, such as maintenance contracts or subscription models. The BDE transfers the data necessary for the implementation and/or billing of the specific services into a Blockchain. Thus, for example, a maintenance contract, which provides for maintenance after a certain period of use, or a pay-per-use billing can be created.

## 4 Summary, Outlook and Research Needs

In this paper, it was presented which current developments force companies to operate Supply-Chain-Data-Management, i.e. to share data along the value chain. One of the challenges of this cross-company data management is the technical feasibility. It was also shown that the reference architecture of the Internet of Production is suitable for enabling use cases of cross-domain networking - however, cross-company networking could not yet be represented in the IoP. Consequently, the architecture has been extended to a cross-company Internet of Production.

Furthermore, it was explained how the Blockchain technology - which is often described as an enabler for cross-company data exchange - can be classified in the cross-company IoP: it assumes the role of Middleware+ Also how these solutions addressed the problems that are to be expected in the Supply-Chain-Data-Management was executed.

It becomes clear that the described use cases of cross-company data exchange can be implemented with a Blockchain as Middleware+, but the demands on this Blockchain are clearly different per use case. These claims and the use-case-specific design of the respective Blockchain are not trivial. In the beginning it was already stated that the technology is not described in a uniform way. There is a lack of a comprehensive description of the technology and its various features and feature types to explain how to design the specific Blockchain, depending on the use case. The description of features such as the type of data to be stored, the information release, etc. could provide a remedy.

Also it remains an open technical problem that data in Blockchains are indeed stored counterfeit-proof, but this does not guarantee that they were correct when they were created. The consensus algorithm is expressly only to ensure the immutability of the data and not to verify their accuracy.

A non-technical problem, which is best described under the name "Supply-Chain-Project-Management", also weighs heavily: Even if it is technically possible to execute the mentioned use cases, this does not mean that they can be implemented. The lack of a superior authority, the necessary economic advantage per company and the lack of initiative by an involved company can mean that digital connection across corporate boundaries is never implemented. This is similar to a problem of component design: There are components that can be drawn and in this form perform certain functions very well - but can not be produced after all because, for example, screw points would not be reached.

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# Towards a Blockchain Based Traceability Process: A Case Study from Pharma Industry

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**Abstract.** The technological boost brought by the world-wide program Industry 4.0 is leading the modernization of enterprises with solutions able to improve the automation of the factory. The pharmaceutical industry and the actors of the whole supply chain, adhering to strict regulations for ensuring the compliance to quality and safety standards, represents one of the most important stakeholders of the Industry 4.0 benefits.

In this paper, the serialization regulation and the technological solution adopted by an Italian pharmaceutical industry for the packaging lines of the factory is presented. As it will be shown, the conception of a traceability solution based on the blockchain technology is under investigation.

**Keywords:** Serialization · Vision control systems · Blockchain · Smart-contracts

## 1 Introduction

Industry 4.0 is a world-wide strategic initiative aiming to bring a technological revolution in the industry field [1]. By the mean of the well-known enabling technologies, production systems should be updated to an intelligent level, gaining the qualification of *smart* equipment. The factory should also be interconnected not only at a physical level but, and most of all, at the informative and automation level allowing to achieve a real-time communication and cooperation with humans, machines, sensors and so forth [2] in order to address a dynamic and global market [3].

To encourage this technology advancement, in these last years, many countries have destinated huge financing to industry. In Italy, this important initiative has taken place with the 2017 Budget Law that has established incentives, tax credits and benefits in relation to Industry 4.0 technologies, and investments in staff engaged in research and development (R&D) [4].

In current years, Industry 4.0 solutions have been employed in the pharmaceutical industry under the regulation of several stakeholders to ensure safety and to protect the wellbeing of whole society [5]. In fact, pharmaceutical sector is a high-technology, knowledge-intensive and heavily regulated industry. All aspects of the life-cycle of


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new drugs are regulated, from patent application to marketing approval, commercial exploitation, patent expiration and competition with generics [6]. This applies to the other participants of the pharmaceutical supply chain, including distributors, healthcare providers, pharmacies, wholesalers, retailers and prescribing physicians who are subject to regulatory controls. This helps to ensure the product efficacy and safety which are not immediately observable [6].

This paper presents the solution that was applied for the serialization packaging process of SIFI® SPA, an Italian pharmaceutical industry, specialized in the preparation of ophthalmic products. As it will be shown, the serialization is the first of many improvements planned by the company which aim to modernize the factory with the enabling Industry 4.0 technologies. The conception of an improved traceability solution has been based on the blockchain technology.

The paper is organized as follows: in Sect. 2 the serialization regulation is presented. Section 3 gives a brief overview of the Company, illustrating the implemented serialization solution and the possible improvement of the traceability process based on blockchain technology. Finally, conclusions and future researches are depicted in Sect. 4.

## 2 Serialization in Pharma Supply Chain

With the European Union's Directive 2011/62/EU, the European Parliament has provided a catalog of measures which are intended to prevent falsified medicinal products from entering the legal distribution chain. The 2011/62/EU Directive firmly regulates that, in the future, all prescription drugs must have safety labels that enable verification checks along the entire supply chain. Counterfeit drugs and falsified medicines [7] can then be identified immediately and safely withdrawn from circulation. The solution to this problem has been identified with the name of *serialization* [8]. Prerequisite for safeguarding against falsified medicines is the assignment of a unique serial number linked to the item production data (item identification code, expiry date, and batch number) in the form of a Data Matrix Code. Technology to automate the process of serial number generation, labelling and packaging is already in place in several pharmaceutical industries that are equipped with advanced machineries able to fully connect to the internet, realizing the IoT paradigm. In Italy, this process is being financed by the program Industry 4.0 [9].

Traceability is an essential key to safe drugs and the basis for absolute confidence on the part of the consumer in the pharmaceutical industry and its products. Figure 1 shows the supply process that involves several actors including the dispatching to the final customer. It is possible to notice that before any shipping, the Pharmaceutical Manufacturer has to communicate to a central regulatory (for instance, the European Medicines Verification Organisation in Europe, EMVO) all the serial numbers of drugs packages introduced into the distribution chain.

Safety, security, confidentiality, resilience and reliability related to the quality of the product and its transactions throughout the life-time and distribution chain must be guaranteed by the central regulatory although all the other actors (except the patient) are called to maintain for several years some of these information, in particular the one

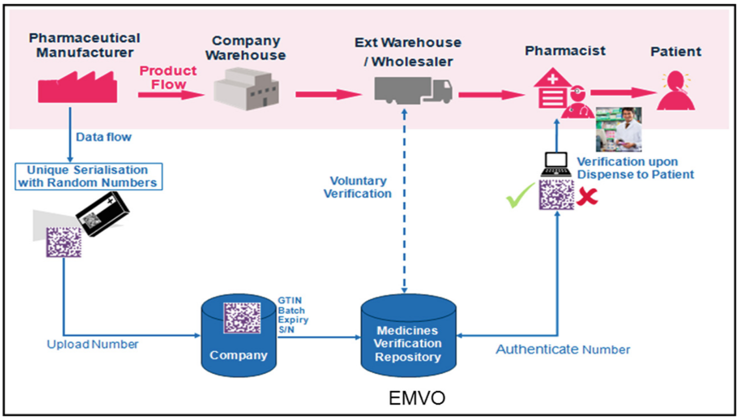


**Fig. 1.** Serialization and traceability

related to their individual responsibility. With this approach, any of these actors is responsible for its data and for the synchronization process with the regulatory that must behave as central authority.

## 3 Case of Study: The SIFI SPA Serialization Process

SIFI® SPA is a pharmaceutical company located in Lavinaio (CT), Italy, leader of the ophthalmic sector. SIFI® is also specialized in the production of medical and surgical devices mainly used in cataract surgery and diagnostic tools for ophthalmology. In this specific sector SIFI® boasts a modern and innovative production process and employs highly automated systems. With its products, SIFI® is present in the markets of Europe, Asia and America. Currently, SIFI® is engaged in a process of technology modernization in order to be compliant with the European Union's Directive 2011/62/EU and challenge the EU market, including Russia and Turkey.

The company promotes qualified scientific partnerships able to support this process and aims to extend and share with all the actors of the supply chain those technological initiatives which can bring to an improvement of the products quality for the final client.

### 3.1 Packaging Area Layout Description

The packaging area is characterized by three different automated lines which serve respectively the single-dose vial, the multi-dose vial and the unguent/ointment products. More specifically, the single-dose and multi-dose vials lines are constituted by two packaging stages, the primary and the secondary. The machines of the first stage fill the primary vials (single or multi-dose) with the ophthalmic product, while the machines of the secondary stage arrange the final packaging boxes. To this end, the primary vials are placed inside their corresponding product box; different boxes are grouped into cases which will finally constitute the unit-load to be shipped.

The unguent/ointment production is independent and performs the whole packaging within the same line.

## 3.2 The Serialization Process

The main objective of the serialization is to allow, at each level of the supply chain, the reconstruction of the packaging hierarchy of each box and the verification of the product quality. To achieve this goal and be compliant with the serialization specifications, each box must be marked with a unique identifier. The codification of the identifier must respect several rules that depends on the packaging level (Unit Box, Case Box, Unit-Load), on the product and, more important, on the encoding specification of the country in which the product will be commercialized.

As shown in Fig. 2, the marking of each box with a unique identifier allows to date back from the outer to the inner packaging level and vice versa, assuming that the packaging hierarchy is known and tracked in a computerized database. In fact, unit-loads are not assembled randomly but according to the information carried by the *work order*. To this aim, the packaging process is initiated by the ERP that interacts with the packaging machines and with the vision system. This latter is a real-time system that, communicating to the printers of the packaging machines, verifies the correct marking of the identifier into the packaging boxes. Moreover, in the secondary packaging line, the vision system keeps track of the boxes that have been placed into each case and of the cases which have been placed into each unit-load. As soon the secondary packaging process has terminated, the serialization software sends the hierarchy matrix list to the ERP that closes the work order and elaborates the beginning of the next phases (storage, batch release, delivery/shipping). During the batch release, the serialization software sends to the central regulatory the official hierarchy matrix list which has to be stored permanently in the database of the serialization software.

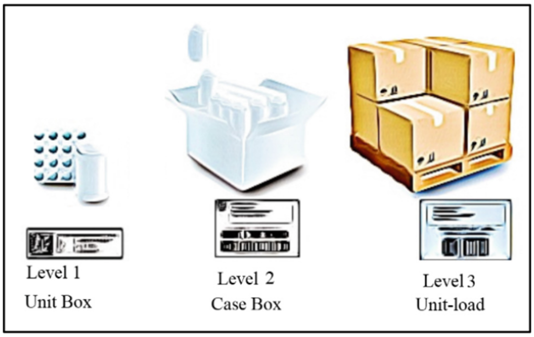


**Fig. 2.** Serialization and packaging hierarchy

To achieve the solution above described, many technological interventions have been realized exploiting the Industry 4.0 funding. A real-time control vision system has been installed and interfaced with the ERP by an ad-hoc customization of the serialization software. This latter is a multi-layer software solution constituted by several modules that act at all the levels of the manufacturing process (Fig. 3). Moreover, the machines of the secondary packaging lines for both the single and multi-dose products (labeling machine, cartoning machine and palletizer) have been replaced with new equipment that can be interfaced with the factory informative system, adopting industrial standard communication protocols like OPC, ODBC and IOT.

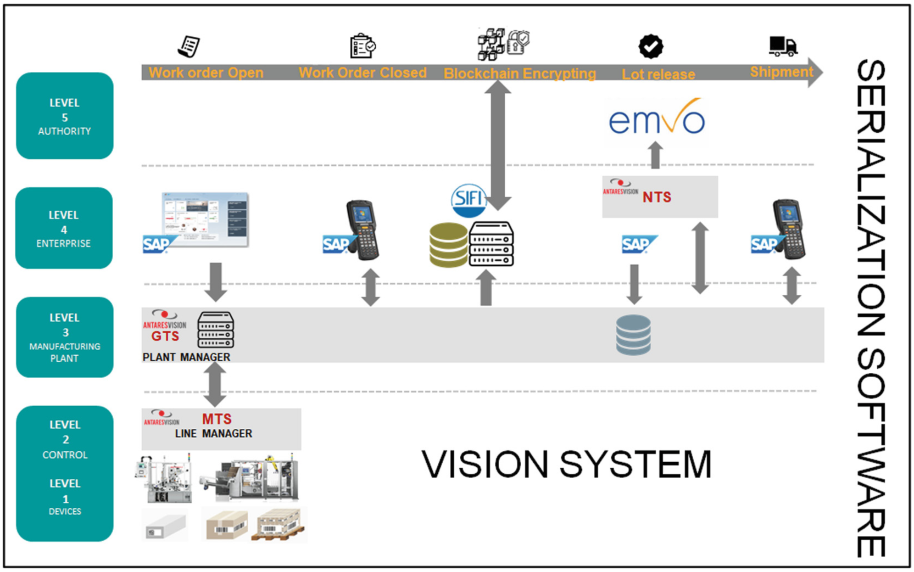


**Fig. 3.** Architecture of the serialization software and blockchain enhancement (courtesy of SIFI®)

### 3.3 The Blockchain Enhancement

As discussed in Sect. 2, all the other actors of the supply chain are called to maintain for several years many information about the products. According to this principle, all the actors are responsible for its data and for the synchronization process with the regulatory that must behave as central authority.

Blockchain seems to offer a breakthrough in this important sector with a shared decentralized ledger resistant to tampering and able of preventing fraud [10]. It is not a case that further evolutions of the blockchain protocol are already being implemented [11, 12] and are becoming part of the business solutions offered by important players like IBM (Watson), SAP (Leonardo), DNV-GL, etc. Among them, smart contracts [13] represent the most promising blockchain application in business relationships. The main goal of a smart contract is to enable two anonymous parties to trade and do business with each other, usually over the internet, without the need for a middleman.

The main idea under investigation is to encrypt and store the hierarchy matrix list within a blockchain ledger. The process of serialization, including the blockchain enhancement, is shown in Fig. 3.

After the work-order closure, the software of Level 3 (GTS Plant Manager) sends the hierarchy matrix list and related information to the enterprise server of Level 4 in charge to invoke the smart contract of the blockchain for storing and encrypting these data. In this way, the same information sent to the central regulatory will live permanently in the blockchain. Figure 4 shows the IT architecture (installed in the factory) that handle the traceability process via the blockchain network. In fact, data stored in the blockchain can be accessed by each actor of the traceability process and, to this end, ad-hoc Web3 HMI can be programmed.

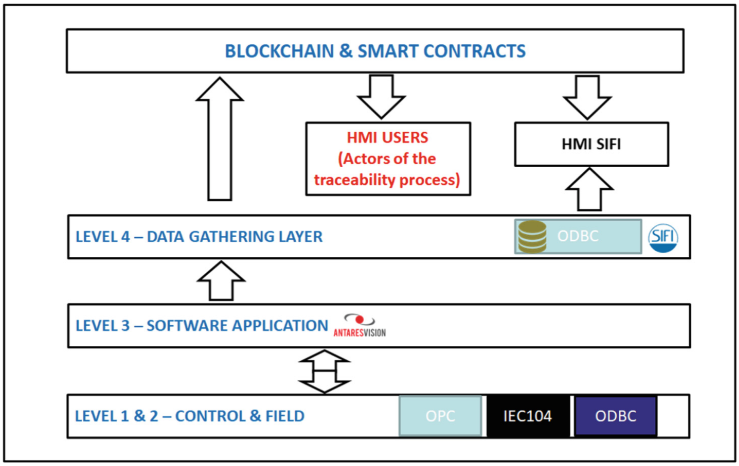


**Fig. 4.** IT architecture handling the traceability process via the blockchain network.

Further developments of the proposed application require the participation of the other actors of the supply chain. Exploiting the modern IT devices (nowadays fully connected to the internet), it is looks straightforward the possibility to implement an automated process that store into the blockchain the relevant information of the supply-chain distribution process. In this way, together with the matrix list produced by SIFI®, the actors of the traceability process can retrieve all this information and be guaranteed about the quality of the product along the supply chain. Moreover, exploiting these features, more complex B2B smart contracts [14] can be programmed in order to seal and verify the agreements among the various actors and guarantee, at any step of the distribution process, the compliance of the terms of contract.

## 4 Conclusions and Future Researches

In this paper, the serialization process of a pharmaceutical company has been illustrated. The main features of such regulation have been resumed and a case of study of an Italian industry was presented. The research collaboration with the company has brought to the conception of a blockchain solution for the serialization and traceability along the supply chain. To this end, the following activities will be carried on:

1. Analyze the state-of-the-art of the commercial and open-source blockchain platform;
2. Identify the main actors of the distribution process and the critical variables;
3. Design a theoretical model of smart contract for the serialization process and the distribution chain;
4. Implement a prototype using an open-source blockchain platform.

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# An Architecture of IoT-Based Product Tracking with Blockchain in Multi-sided B2B Platform

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**Abstract.** Business-to-Business (B2B) enterprise systems and services have become increasingly important for Small and Medium Enterprises (SMEs) over the last few years. Their major potential is observable in the massive reduction of business transaction costs and enhanced cross-sectoral collaboration. A successful B2B marketplace should ensure greater transparency and trust while performing business processes. Among different ways to build transparency and trust, IoT-based traceability system can enable partners to track products and monitor the quality of production processes. Partners can principally trust each other and can avoid fraudulent malpractices. It is, however, still insufficient to prevent fraud and fight against counterfeit and inferior products due to data manipulation. Blockchain technology is a promising technology to prevent fraud through its data immutability characteristic. However, the adoption of Blockchain technology in IoT-based traceability system for SMEs entails significant challenges. For example, the transition of a large volume of IoT data from company-owned databases to Blockchain network would require a significant shift in terms of IT infrastructure. This paper discusses the typical challenges and presents an approach to handle them. It can be helpful to pave the way to support SMEs adopt Blockchain technology in IoT-based traceability system.

**Keywords:** IoT · Sensors · Traceability · Blockchain · Multi-sided platforms

## 1 Introduction

In many industries, the basis of value creation depends on a complex network of organizations that share or exchange information, services, and goods. They use information and communication technologies to manage these processes efficiently with minimum costs. Digital business-to-business (B2B) platforms are one of the recent vital topics in this field. These platforms focus on different domains, such as manufacturing, logistics, smart cities, and e-commerce for data, services, and products [1].

NIMBLE [2] is a multi-sided, federated, digital platform with a B2B marketplace for products and services. Its source-code is under a permissive license, which allows


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third parties to use it for any purpose. One of its fundamental business requirements is that buyers want to access recent and precise information about their ordered products. This information includes, for instance, current and past locations, and product-related events. The location information helps the buyer to schedule activities accurately, which can reduce the cost of idle times and re-planning. An example of a relevant event is the exposure to contractually defined environmental conditions, such as temperatures above 0 °C. Often such environmental conditions require an Internet of Things (IoT) application where products and locations contain sensors. A benefit of IoT information is that it can support employees in the identification of product quality problems, responsibilities in warranty cases, and plagiarism. Tracking and Tracing (T&T) are software functions that meet the requirements as mentioned earlier.

Typically, a service provider is responsible for the T&T information of the supply chain partners. The latter have to trust the provider that the information is accurate and securely stored. In today's global supply chains, this trust is not always a prerequisite. New data storage technologies, such as Blockchain, address the trust and the security issue. Several activities currently focus on the development and demonstration of T&T solutions with Blockchain technology like OriginTrail [3], Ambrosus [4].

This paper presents an architecture for a T&T solution that merges IoT and Blockchain and integrates it in a digital B2B platform. This architecture is the basis of the T&T solution implemented and tested in the NIMBLE platform. Its source code is available on GitHub [5].

The paper structure is as follows: Sect. 2 illustrates concisely a practical Use Case Scenario and some challenges that scenario faces. Section 3 provides a brief overview of the technologies and related works of Blockchain and IoT-related tracing in the research paradigm. Section 4 proposes an approach to the challenges mentioned in Sect. 2. The paper ends with concluding remarks in Sect. 5.

## 2 Use Case and Challenges

A use case helps researchers to identify problems worth of research to evaluate the results. The latter is especially important if the research focuses on technology application. The authors identified a use case for these purposes. It relies on the production and logistics processes of two real companies from the construction industry. The factories are in northern Europe and experience temperatures below −30 °C during winters. The focused product is a composite structure used within construction. Intense changes in temperature and humidity can damage its strength leading to failure during operations and may lead to high warranty claims. The producer of the structure has to monitor the production and storage environment for this particular reason. Figure 1 illustrates an overview of a production scenario for the producer of the composite structure.

Company 1 is the supplier of the composite structure, and company 2 is the customer that mounts it in a larger product. The companies have separate factories at different locations. They use trucks to transport the structures from one factory to the other. The test implementation focuses on the first company. Its production has four steps that require tracking. It begins with a robot work area and ends with cold storage

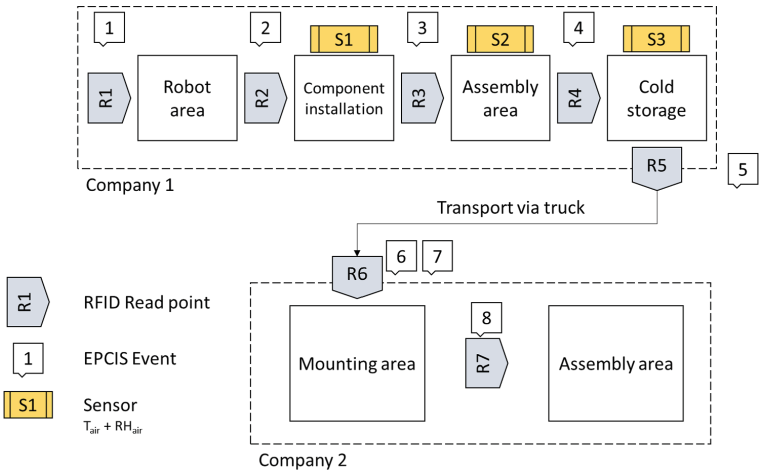


**Fig. 1.** Production scenario for a composite structure and logistics overview

outside the factory. RFID readers monitor the entrance/exit of each area. Temperature and humidity sensors monitor the environment of steps two, three, and four.

These two companies can trust each other. However, adequate trust is not always present between company 1 and other customer companies. Through its immutable and irrevocable properties, a Blockchain solution is increasingly prominent for trust; however, challenges in adopting Blockchain within the IoT-based product traceability system still exist. The authors identify three significant challenges standing in the way:

- **Flexible usage of Blockchain technologies:** Blockchain represents a significant advancement in technological innovation that facilitates consensus within a trustless environment. However, Blockchain does not always make sense in different application scenarios [6]. For instance, when all supply chain partners can trust each other, it is not necessary to adopt Blockchain technologies. Traceability system should allow companies to choose whether and which type of Blockchain to use, according to the requirements of specific application scenarios.
- **Infrastructural transition to Blockchain technologies:** The transition from the world of company-owned databases to Blockchain network would require a significant shift in terms of IT infrastructure. Furthermore, companies may have worries, for instance, loss of control of their data, and exposure of sensitive production data during this transition phase.
- **A large volume of IoT data:** Companies can capture an enormous amount of IoT data in the production processes for traceability and quality monitoring. This IoT data include, for instance, EPCIS events, and various sensor data. For quality assurance, interest from customer companies is not only the sensor data at the specific time of the EPCIS event occurrence but also sensor data in the period between EPCIS events. In the use case scenario, temperature and humidity sensors monitor the environment of steps two, three, and four. If one considers a sensor that measures the temperature and humidity every one second, then for a single hour,

there will be $2 \times 3600$ total measurements. When a product stays in "cold storage" in step four for one single day, the relevant number of measurements will range $2 \times 24 \times 3600$ measurements. It is a significant challenge to put this large volume of IoT data into Blockchain at reasonable scalability and cost, taking into account the storage volume in each Blockchain transaction, transaction fee, and transaction rates.

# 3 Background and Related Works

## 3.1 IoT-Based Product Traceability

Increasing competition for similar products in the present day markets requires the manufacturers' attention and awareness regarding each stage a product goes through during the supply chain and manufacturing process. The emphasis lays on the fact that by tracking the events of the products under consideration helps improve the quality and determine any faults or error that might occur. Tracking and Tracing systems widely use the EPCglobal and EPCIS from the GS1 [7]. Representation of physical products in a digital form is achievable by using EPCglobal. EPCglobal provides a method to identify physical products through unique codes. EPCIS provides a method to acquire the events for the products and allows sharing this event information in an interoperable manner. The identification of the products occurs by scanning the RFID tags via dedicated RFID scanners. An event capturing mechanism provides all other necessary filterings of the data generated from the readers, and finally, a dedicated EPCIS server stores the event-based information. Byun and Kim [8] provide an open source platform, namely Oliot EPCIS, which provides a base for experimentation with sensors along with the integration of EPCIS standard.

With the rapid growth in the IoT sector, metadata like environmental parameters of the events the product experiences within the processes could be captured via constrained sensor and actuator nodes and provide deep insight on factors that might affect the quality of the product at present or for later purposes. IoT within the supply chain as well as manufacturing processes opens a new paradigm of integrating ICT-based intelligence, in turn opening the prospect of Smart Products. Such additional information enhances the possibility to trace reasons for product failures or defects and help manufacturers pinpoint the root cause. Work presented by Woo et al. [9] provides an approach to integrate IoT information from cars into the EPCIS structure. They extend the EPCIS structure using the *Extension* field to add relevant automobile information like RPM, braking, steering wheel data, GPS locations at the particular instance of the event when the car is driven. Based on different events like 'Repairing,' 'Scrapping,' the authors use geo-locations using a GPS module to add extensions to the various Events. The solution from the authors sends information periodically to an EPCIS server in the form of XML documents and use the information to provide tracking and tracing solution for connected cars. Authors of Oliot EPCIS [8] validate the platform by conducting experiments in the healthcare sector. They measure medical sensor values via using Bluetooth (BLE) along with another IoT standard Constrained Application Protocol (CoAP) and generate events based on the sensor data capture. Alfian et al. [10]

provide a food traceability system for Kimchi supply chain in Korea which amalgamates RFID system for product identification, wireless sensor networks (WSN) for environmental condition monitoring and data mining on the data collection for the estimation of missing sensor data during wireless transmission within the supply chain.

Works presented by authors in [8–10] manifest strong efforts of inculcating IoT into standard product traceability within different sectors like healthcare, automobile, and food and emphasis of their work improves upon the overall understanding of product quality within standard supply chains.

### 3.2 Blockchain and Traceability Systems

Blockchain could provide essential features such as assurance of the product genuineness as well as transparency within the supply and manufacturing chains. There are already practical efforts to use EPCIS information from products with Blockchain, as well as IoT information. OriginTrail provides an IT solution to decentralize supply chains using Blockchains. OriginTrail [3] leverages the EPCIS framework for data interoperability among different organization within the supply chains. It also incorporates the WoT (Web of Things) Framework [11] for IoT sensor data by W3C. IoTeX [12] is another solution, which provides a Blockchain powered for IoT information. It leverages the concept of "Blockchains in Blockchains" where multiple private Blockchains termed as "subchain" interact with IoT devices and these "sub-chains" interact to a public Blockchain (rootchain). The concept provides a form of abstraction to the public Blockchain and the IoT devices. These solutions can only guarantee limited flexibility on the use of Blockchain technologies and cannot easily validate the large-volume relevant sensor data in the tracking process.

Figorilli et al. [13] provide a prototype Blockchain implementation of chestnut boards traceability within the lumbering industry. The authors use RFID systems alongside QR codes and Android mobile applications for tracing lumber products within the supply chain and use well-known Ethereum [14] Blockchain solution for more transparency within supply chains. Tian [15] illustrates a traceability system in the food supply chain for tracking real-time product information using Blockchain, IoT based on Hazard Analysis and Critical Control Points (HACCP). The work describes the usage of decentralized databases to store information, right from the harvested crop plants via RFID tags all the to the retailers and controlling authorities, subsequently enabling transparency and collaboration via Blockchain based solution. Hepp et al. in their novel approach [16] are already addressing issues of securing physical products to Blockchain by using varnishes that produce a unique crack pattern that cannot be replicated or cloned on inferior products.

## 4 Approach

Figure 2 illustrates the architecture proposed in this study. It integrates Blockchain technologies as a value-added service in the traceability system. The bottom part of the figure is the infrastructure of an example supply chain. Each company in the supply chain has its local infrastructure for the management of traceability relevant IoT data.

Besides an EPCIS data repository, it uses a separate time series database for the management sensor data. Based on the time series databases, companies can realize visualization and monitoring of the collected sensor data. When companies have no requirements on the usage of Blockchain for specific production orders, they can keep all traceability data in their infrastructures. In the case of Blockchain, it is necessary for the reason of, for instance, fraud prevention, that companies send traceability data of relevant production orders into Blockchain through additional value-added APIs.

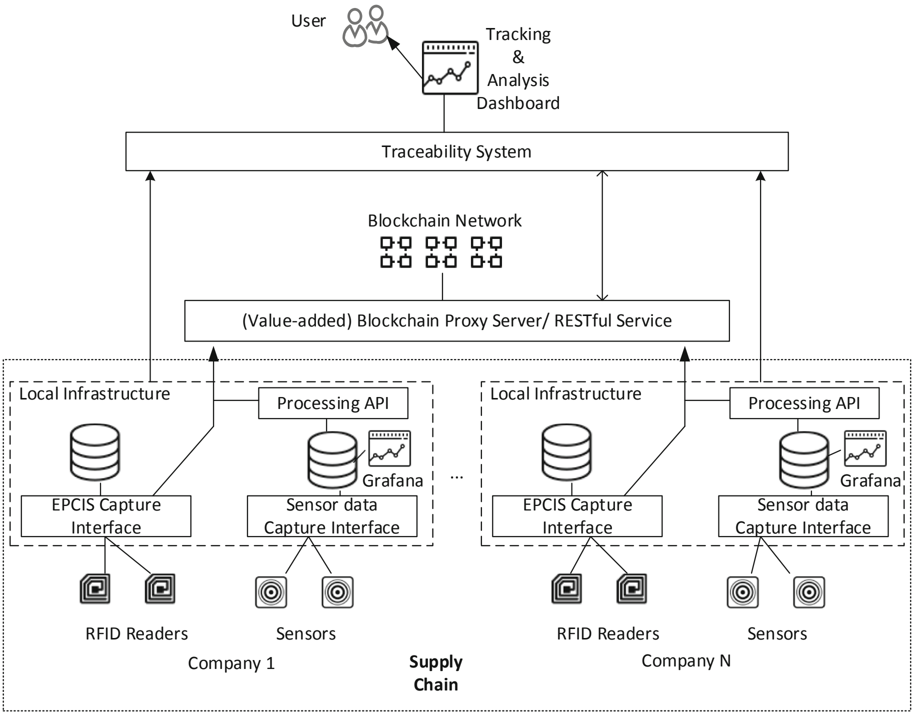


**Fig. 2.** Architecture of IoT-based product tracking with Blockchain as a value-added service

When companies choose to use Blockchain Services, it is only mandatory to send cryptographic-hash rather than raw traceability data into Blockchain. On the generation of cryptographic-hash for traceability data, the authors adapt ideas from Traceable resource unit (TRU). TRU is a unique identification of the resource representation with similar characteristics that must be traceable [17]. It can have different granularity levels, for instance, single product item, or a batch or product items. In this study, the Traceable Data Unit (TDU) is defined as a unit of data representation that should be traceable and verifiable. Users can define different granularity levels of TDU for EPCIS data and sensor data. For EPCIS data, the authors, take every single EPCIS event as a TDU and generate a cryptographic-hash for each EPCIS event. On the tracking and tracing process, users can retrieve the EPCIS events from data storage of supply chain partners, and then generate cryptographic-hash and verify the validity of the retrieved EPCIS events with Blockchain. For sensor data, users can verify the validity of sensor data as well based on the defined TDU, with the cryptographic-hash stored in the Blockchain. For example, it is possible to define sensor data in one hour starting from every hour exactly (e.g., from 9:00 sharp to 10:00 sharp) as a TDU. Assume a product has been in a storage area for 1 h from 01:20 to 02:20, users only need to calculate the cryptographic-hash for the batch of sensor data from two TDUs (i.e., from 01:00 to 02:00 and from 02:00 to 03:00). They can then check the existence of calculated cryptographic-hash in Blockchain to verify the correctness of the retrieved sensor data. This kind of validation with Blockchain can ensure that supply chain partners have not manipulated or tampered the traceability data in their local storages.

## 5 Conclusions

In this work, the authors have proposed an architecture that integrates Blockchain technologies as value-added services in IoT-based Product T&T solution. This architecture is the basis of the T&T solution implemented and tested in a digital B2B platform, i.e., NIMBLE platform. It takes Blockchain technology as an optional value-added service to address trust and security issues. Companies, i.e., SMEs, can choose whether to use Blockchain services, according to requirements of their specific application scenarios. This architecture introduces the concept of Traceable Data Unit to handle large-volume of IoT data, SMEs can define different granularity levels on the traceable data unit and sends only cryptographic-hash of each Traceable Data Unit rather than raw IoT data into Blockchain networks. With this approach, SMEs have total control of their data and can benefit from the immutable and irrevocable properties of Blockchain with flexible scalability and cost.

Nonetheless, this approach is still a work in progress. As future work, the authors are seeking to address online product quality monitoring and quality assurance with smart contracts in Blockchain. Another limitation of this research is the risk of inaccurate data in Blockchain. Blockchain technology can help to prevent data tampering for the data stored in Blockchain, but cannot avoid the situation that companies send incorrect data, e.g., sensor data into Blockchain.

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# A Blockchain Application Supporting the Manufacturing Value Chain

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**Abstract.** Blockchain applications supporting the manufacturing value chain are beginning to appear; early adaptors are testing blockchain technology for applications like trace and track, life cycle management by digital twins, protection of intellectual property rights, enforcement of licensing agreements, and trading platforms for 3D printed parts. The aim of this paper is to discuss the use of blockchain applications in the value chain of manufacturers followed by a case study of a blockchain application used in the value chain of a Norwegian furniture manufacturer involving the manufacturer, a third-party service provider, a retailer, and the end-customer. The application supports a product configurator providing product selection and customization, a delivery planner and a product tracker using an open public blockchain for inter-organizational data-sharing.

**Keywords:** Manufacturing value chain · Inter-organizational processes · Blockchain

## 1 Introduction

This paper presents a case study using blockchains to support business-to-business operations. The complexity of business networks makes interoperability across organizations a challenging task. Blockchains have been seen as a potential solution to enforce intellectual property rights of information, as well as offering a way of sharing information in a network without mutual trust between the parties. It is based on algorithms that lead to consensus among the network nodes and market mechanisms that motivate the nodes to behave in a non-opportunistic manner [1]. This is recognized by the business environment as well as the research community as illustrated by the quote from Mendling et al.: “the emerging blockchain technology has the potential to drastically change the environment in which inter-organizational processes are able to operate” [1].

For companies, this puts forward a need to explore blockchain technologies for their external business operations. This paper presents the use case of how a furniture manufacturing company explore blockchain technologies for tracking furniture in their distribution chain consisting of a third-party service provider, a retailer, and an end-customer.


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## 2 Literature Review

### 2.1 Blockchains

A blockchain, is an overlay network on top of the internet. The blockchain technology is the underlying technology for the Bitcoin cryptocurrency designed by [2] who stated that the purpose of the Bitcoin cryptocurrency was "A purely peer-to-peer version of electronic cash would allow online payments to be sent directly from one party to another without going through a financial institution". The design was realized shortly after when the original Bitcoin network started on January 3, 2009. The network has since then seen a rapid growth, both in value and in the number of transactions, and a lot of other blockchain-based networks are being developed and deployed.

This paper is based on the use of an open public blockchain (OPBC). Any OPBC could be used, but we selected the latest version of the original blockchain by Nakamoto, the Bitcoin Satoshi's Vision called Bitcoin SV [3, 4]. The main reasons for using an OPBC are; they include a free, open for all, and shared distributed database infrastructure on top of the internet, they become more reliable as they grow, they are immutable for all practical purposes, they can store arbitrary data including user-defined computer programs (smart contracts) using Bitcoin script, and they have an embedded run-time environment that executes the smart contracts stored in the blockchain [5].

### 2.2 Inter-organizational Processes

Recent developments show a growing erosion of traditional organizational bounds [6]. Work is mostly done within organizations. However, work can increasingly be coordinated through formal arrangements among institutions like consortia, institutes, and partnerships, and through more informal communities of practice, and multi-team systems that cross or even exist outside of the boundaries of traditional organizations. As an example, consider the manufacturing industries. A single company traditionally executed the major portion of manufacturing operations needed to create a final product [7]. Over the years, companies found it cost efficient to specialize in core competencies while outsourcing supporting activities, and thus adding an increasing number of connections, resulting in a global network of manufacturers. Now the major part of a product comes from many collaborating manufacturers, as can be seen from the large portion of the value creation that goes to purchasing. The 2.1 million enterprises classified as manufacturers in the European Union, spent on average 74% of their turnover on purchases of goods and services [8]. Hence, the manufacturing of products has become a networking endeavor.

However, these business-to-business network operations are not supported by standard information system solutions. Business-to-business operations involve a myriad of companies and organizations, manufacturers, third-party logistics providers (3PLs), freight forwarders, transportation providers, banks, insurance companies, and authorities. While ERP systems support and automate the business processes of each enterprise, the support and automation of business-to-business processes of the extended value network are missing. Contemporary networked operations depend on partly manual processes involving spreadsheets, email, Electronic Data Interchange (EDI) and proprietary software solutions. Integration, synchronization and a system of record and transparency that are taken for granted within enterprises by ERP systems are not attended to in a systematic manner in the external value network. Any changes in the business-to-business operations are costly to follow up on for trading partners. The data latency is high, and the ERP systems of companies involved must be consolidated and eventual disputes resolved [9, 10]. IBM reports that they need to resolve around 27 000 disputes yearly related to invoices alone in their financial service sector, even if that amounts to just under 1% of the total number of invoices handled per year, the cost is substantial since they require manual intervention and delay [11].

In analogy with ERP systems for intra-organizational process integration and data sharing, the open public blockchain can be seen as a database shared among companies for inter-organizational process integration and data sharing.

# 3 Case Study

## 3.1 Background

Ekornes ASA is the largest furniture manufacturer in Norway and owns such brand names as Ekornes©, Stressless©, Svane©, and IMG©. Manufacturing takes place at the group's nine factories, five of which are located in Norway, one in the USA, two in Thailand and one in Vietnam. Ekornes was acquired by Qumei Home Furnishing Group in 2018 [12].

Ekornes has an ongoing project to establish a new digital platform that will allow them to showcase products online, either through their own websites or through their distributors' websites. The platform is intended to enable online sales of products as well, directly to customers, in combination with retailers, or completely through the retailer's online sales channels. Regardless of the sales channel selected, Ekornes has the strategy to establish a strong digital platform to support their retailers, while at the same time they prepare for direct communication with the end-customers both in sales and to gain insights into customer needs [12].

Ekornes started looking at the blockchain technology in 2018. They have been engaging master students to investigate the theme as their thesis topic, and Ekornes has started the development of a demonstrator as part of the business case presented here involving the use of blockchain technology partly funded by Manufacturing Networks 4.0, a research project by the Norwegian Research Council.

Ekornes has always been focused on adopting the latest technology to develop the company. The business idea is the development, manufacturing, and sale of furniture. They recognize the need to adopt new technology and new competence to stay competitive, especially regarding the fast progression of digitalization. Traditionally, Ekornes has been at the forefront with regards to the automation of production with extensive use of industrial robots. Now Ekornes believe the biggest benefits of digitalization are to be found on the sales side:

"*The customer's entire journey, from the moment she first becomes interested in a product until it has been bought and paid for, is changing radically as a result of digitalization. The first thing many people do now when they are looking to buy a new piece of furniture, is to scour the internet. Online sales of furniture are rising sharply. New players have entered the market, and existing players are evaluating new business models to adapt to this new reality*" [12].

The actors in the value chain of Ekornes are the skin producers, the transporters, part producers, shipping companies, the logistics service providers, the retailers, the initial customers, and eventual second-hand customers, as illustrated in Fig. 1.

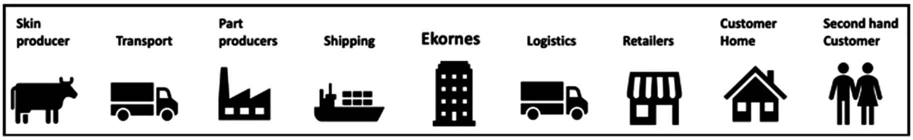


**Fig. 1.** The Ekornes value chain.

In light of the envisioned potential of blockchains for inter-organizational processes and the choice to focus on the sales side, Ekornes decided to explore blockchain in the distribution part of their blockchain. A case study was selected involving four actors in the distribution chain on the right side of Fig. 1; The Ekornes furniture manufacturer, a logistics service provider, a retailer, and an initial customer. Customers want to be able to customize their product and have an exact delivery date. This involves all four parties in the distribution chain. The manufacturer's production strategy is made-to-order for standard products giving delivery times of 4–6 weeks. In addition, they offer a QuickShip segment for a smaller selection following the assemble-to-order strategy allowing delivery within 72 h.

### 3.2 The AS-IS Scenario

During a workshop discussing potential use cases focusing on the end-customer's journey, the following scenario was described:

*A store clerk working in the retail sector has attention given to the conversion process of getting them to select a product and then getting the selection converted to a payment. Visibility might help increase conversion. For some of the failed conversions, retailers lose the potential sales because they cannot provide detailed information on product variety and delivery dates at the point of sale. Take for example a customer who is at a store in a mall in Norway and has asked for item ABC, but that item is with the wrong material in the store and the time-to-delivery is given as a rough estimate of 4–6 weeks. Typically, this is a lost sale and the customer is leaving empty handed. (from workshop discussion).*

The current AS-IS process is modeled in Fig. 2 and shows the steps involved in the end-customers journey when purchasing furniture. Each participating actor is represented in a separate lane and has full control of the activities within their lane. Dotted lines represent information flow and solid lines represent process flow.

The end-customers journey starts when a potential customer visits the retailer with an interest in buying furniture. The furniture retailer representative greets the customer and provides product information on the availability and characteristics of the products of interest. The availability information is updated for each manufacturer on a weekly basis.

If the customer decides to order, the retailer subsequently orders by the manufacturer the same day by email. The manufacturer then confirms the order to the retailer by email the same or next day, together with an as-good-as-possible forecast for the delivery schedule. The retailer then forwards the information to the customer by SMS.

After a short delay, the manufacturer starts production and assembles the different components for shipment and orders transportation by the distributor, which picks up and deliver the order to the retailer. At the same time when the order is picked up; the manufacturer informs the retailer by email. If not previously agreed upon, the retailer contacts the customer and agrees on how to deliver the customer order, before the actual delivery takes place. The customer relates only to the retailer, preventing end-customer information from reaching the manufacturer.

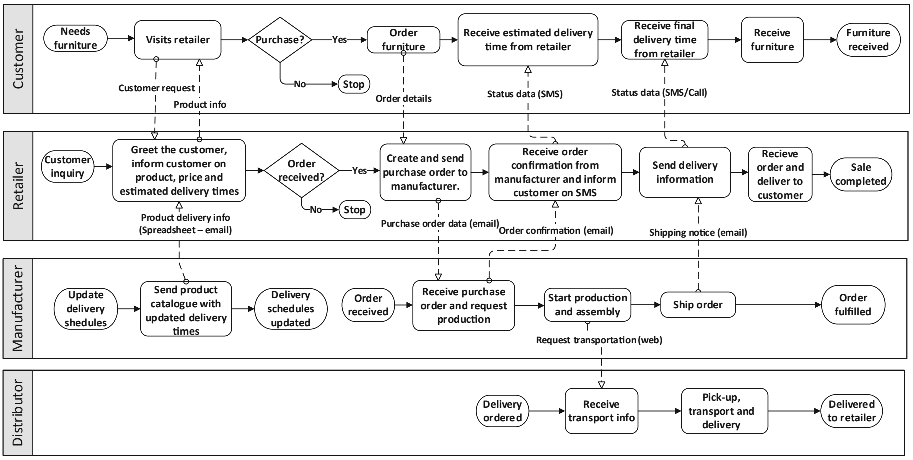


**Fig. 2.** Inter-organizational process diagram of the AS-IS scenario with each actor operating in a silo fashion with limited information exchange between each other.

## 3.3 The TO-BE Scenario

The TO-BE scenario starts as the AS-IS scenario, but after the last sentence "Typically, this is a lost sale and the customer is leaving empty-handed.", the following scenario is added:

> *... With the right visibility tools, the salesperson can give detailed information on the optional materials and detailed delivery date for each selection. Now, when the customer looks disappointed the store clerk brings up the product configurator on his notepad and says "wait one second, I'll show you the optional materials together with a detailed delivery time for each option. And we'll give you a five percent discount for the inconvenience. Also, we support the QuickShip segment with delivery times within 72 h ... and so on (from workshop discussion).*

Based on this it was decided to build a demonstrator of a Product Configurator that would involve all the four parties. The traditional approach would be to build a portal or a hub to share data among the parties. This is costly, time-consuming and require testing. The parties can alternatively use the OPBC as a shared database. It is free, ready to use and very reliable. Thus, the Product Configurator should use an OPBC.

Using the Product Configurator, the sales clerk take the customer on a product tour. The sales clerk start by scanning the product of interest. The product, containing an NFC or a QR code with the unique product ID pops up in a web-app on a notepad. The customer selects options like the type of base, skin, textile, and color. When the product is configured as requested by the customer, the Sales Clerk retrieves exact delivery information directly from the producer. The Sales contract between the retailer and the customer is then ready to be completed directly from within the web-app.

The TO-BE process is modeled in Fig. 3 and from it is it clear that the start of the end-customers journey is near equal to the AS-IS scenario. However, we realize a significant difference in the way the retailer interacts with the customer through the Product Configurator which supports product selection and customization. Furthermore, the delivery planner functionality of the demonstrator ensures consistent delivery information retrieved directly from the manufacturers ERP system via the OPBC.

If the customer decides to place an order, the retailer subsequently places the order at the manufacturer by using the web-app, which store the complete order information as a transaction in the OPBC.

After receiving the customer order, the manufacturer allows for a short delay before the order is released to production and assembly. At any time, the customer and retailer might enquire for production milestones and delivery status via the web-app.

When the product is ready to be shipped, a transportation request is automatically sent to the distributor via the blockchain. The distributor pick-up the shipment and writes transactions into the OPBC at various handling points throughout the distribution process. These transactions can be viewed by all actors at any time.

After the shipment is delivered to the retailer's warehouse, the retailer arranges for the final delivery to the end-customer. A customer requests for a change in the delivery schedule can be handled directly from within the web-app. When the order is delivered to the end-customer, the warranty period is automatically started and registered in the blockchain. In this TO-BE scenario, the manufacturer does have access to end-customer information that can be used for future interactions and sales promotions via e.g. referrals with discounts.

Both the AS-IS and the TO-BE process models are simplified for the sake of clarity. Some of the issues left out are the handling of payment, the various technologies and document formats for communication.

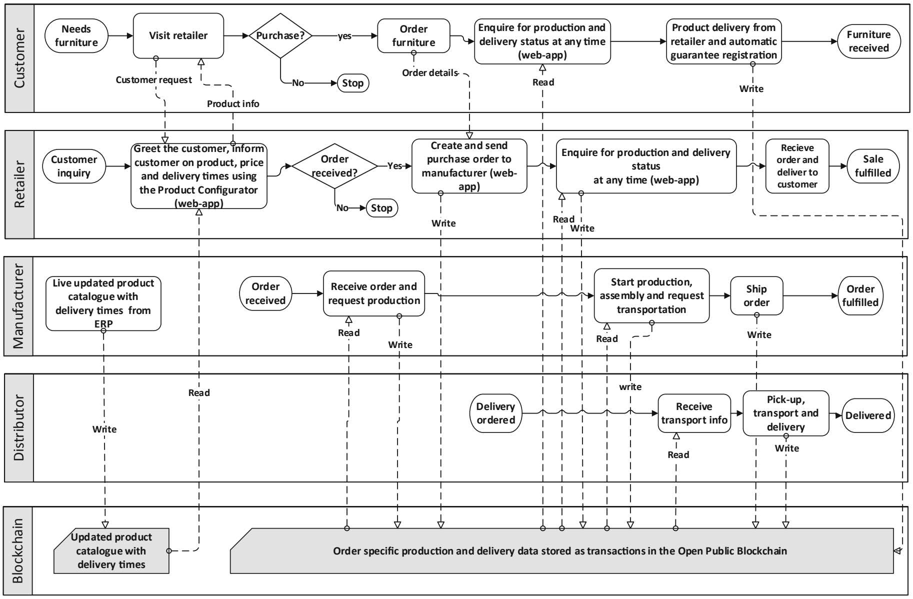


**Fig. 3.** Inter-organizational process diagram of the TO-BE scenario utilizing the open public blockchain as a shared data layer.

## 4 Discussion

The key differences between the scenarios are: In the AS-IS scenario no one has the full picture – information exists, however it is fragmented and spread between the actors. In addition, the information is uncertain since it must be updated through each process, e.g. delivery information requires multiple messages from retailer to the end-customer, and delivery times are only updated on a weekly basis. The AS-IS problems include redundancy, lack of data control, a mix of interfaces, delays, lack of reliability and lack of data integration. In the TO-BE scenario, actors get exact information through the shared blockchain, including delivery times that is important for planning purposes and to increase the conversion rate of sales at retailers. If there is a need to keep the information secret, the information in the OPBC can be encrypted and keys distributed to actors that are granted access.

The use of a blockchain in this context might seem unnecessarily complex since the small number of actors of four gives little substantiation to justify the added value of using a blockchain. However, a blockchain based solution will be more useful as the number of participants increase, and since it is not controlled by any of the participants the risk of any partner exercising power over other partners is low, increasing the likelihood of the partners being willing to share information. The manufacturer in our case study had a need to build competence in a long-term perspective to explore models suitable for following a product through its entire life-cycle across multiple owners and users as part of their move towards sustainability by circular economy models.

## 5 Conclusion

This paper discussed the use of blockchains in the value chain of manufacturers including a case study of a blockchain application used in the distribution chain of a Norwegian furniture manufacturer involving the manufacturer, a third-party service provider, a retailer, and an end-customer. The application utilizes an open public blockchain as a shared data repository for integrating processes across the actors demonstrating how manufacturers can build competence and explore ways to support information sharing in business-to-business networks.

**Acknowledgments.** We thank the Manufacturing Network 4.0 project for support of the research presented in this paper.

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# Design of a Blockchain-Driven System for Product Counterfeiting Restraint in the Supply Chain

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**Abstract.** The production and distribution of counterfeited products is an issue for decades in different industry sectors. The trade in fake goods is growing and is affecting the sales and profits of the companies exposed to this phenomenon. It influences governments, world trade, businesses, and consumers, by reducing revenues, economic growth, and consumers' health. This paper aims to present a proposed system for restriction of product counterfeit. This system will be applied in the supply chain of goods, including operations like production, distribution, and sales. In order to ensure the identification and traceability of genuine products throughout the supply chain, the blockchain technology and secure marking techniques of the products will be used. The paper presents the conceptual design of the system, its functionality, the methodological approach for its development and its application in selected industry sectors, as well as the expected results by its use in the supply chain of products.

**Keywords:** Supply chain · Counterfeit · Fake products · Blockchain · Information system · Research project

## 1 Introduction

Counterfeiting is defined as the deliberate alteration of the real nature or the originality of a thing for deception purposes, in order to give a misleading impression of facts/evidence/documents/test results [1]. Counterfeiting refers to a wide range of stakeholders in a way that goes beyond the direct impact on legitimate businesses. Consumers who buy these products inadvertently purchase products of inferior quality or safety characteristics and potentially pose severe risks without having the necessary guarantees [2]. Counterfeit traffickers usually do not comply with labor, tax, or trade laws. As a result, governments receive lower tax revenues and eventually increase their spending on welfare, health services, and crime prevention [3]. Even the legitimate businesses operating in an industry where there is intense counterfeiting, are damagingly affected, as the counterfeit products have a significant market share. This situation act as a barrier for legitimate competitors to enter the market and get a market share [4].


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Product falsification is a vast and ever-increasing phenomenon, as evidenced by the latest available statistics for 2016 collected in a study conducted by the European Patent Office and the Organization for Economic Cooperation and Development. Based on the data for 2016, it is estimated that the volume of international trade in counterfeit products amounted to USD 509 billion, representing 3.3% of world trade. The previous OECD-EUIPO study, which was based on the same methodology and concerned research into counterfeit products for the year 2013, had concluded that the trade of counterfeit products amounted to 2.5% of world trade, equivalent to 461 billion US dollars. Counterfeit products can be found in a large and growing number of industries such as consumer goods (footwear, cosmetics, toys), business-to-business products (spare parts or chemicals), IT products (phones, batteries), luxury products (fashion, watches). It is crucial that many counterfeit products, in particular pharmaceuticals, food and beverages, and medical equipment, can pose severe health and safety risks [5].

Every year, 83 billion and 790.000 jobs are missing across the European Union due to counterfeit and pirated products. In particular, as a result of the distribution of these products, more than EUR 48 billion or 7.4% of sales in 9 sectors are lost, while public revenue losses estimate to 14.3 billion euros (non-payment of income tax, VAT and excise duties). More specifically, in 2017, 10% of EU consumers or about 43 million citizens, were deceived into buying a fake product instead of a genuine one, taking along with all the security risks associated with it [6]. Besides, it should be noted that the EU economy is losing another EUR 35 billion due to the indirect impact of counterfeiting and piracy in these sectors, as manufacturers buy fewer goods and services from suppliers, thus causing knock-on effects to other branches. Lost sales lead to the immediate loss of 500,000 jobs in the specific sectors of the European Union economy as legitimate manufacturers and, in some cases, the distributors of the respective products employ fewer people than they would have if they were not on the market counterfeiting and piracy. Taking into account the knock-on effects of counterfeit products on other sectors, the number of more 290.000 lost jobs has to be taken into account [5].

Especially in Greece, it is estimated that the loss of sales per year due to the illegal trade is about 17 billion Euros, and only by the counterfeiting is 2.1 billion. Losses in euro per capita in Greece are 125 euro. The total number of jobs lost annually due to the trade in counterfeit products is proven to be 24.000. It is worth noting that Greece ranks 1st in terms of relative job losses due to the circulation of counterfeit products and fourth in terms of lost sales. Finally, the five sectors with the most significant loss of sales in Greece are medicines, clothing, cosmetics, smartphones, wines and spirits [7].

Thus, the subject of this paper is to present the conceptual design of a new system for product counterfeiting restraint in the entire supply chain. This system incorporates new technology to guarantee the traceability and the identity of genuine products, based on blockchain.

In the remainder of this paper, the contribution of blockchain technology in modern information systems is presented in Sect. 2. Section 3 introduces the system's conceptual design and its development approach as part of a research project. In Sect. 4, conclusions and further research are discussed, featuring the next steps of the research in order to develop a blockchain-driven system for product counterfeiting restraint in the supply chain.

## 2 Application of Blockchain Technology in the Supply Chain of Products

In recent years, blockchain technology has begun to be used in many new industrial applications, going beyond its initial application to cryptocurrency [8]. Some great efforts include those of [9–13]. The reasons behind this trend are transparency, security, quality assurance, global peer-to-peer transactions and the decentralization provided by blockchain [14]. In practice, a blockchain is a public, distributed list that contains chain blocks, each of which consists of several transactions. These blocks have been authorized globally and transparently to guarantee security, consisting only of valid and fair transactions. Blocks are shared and synchronized between nodes through a peer-to-peer, distributed and decentralized structure [15]. Despite the potentiality offered by this technology, its integration into the supply chain to counter anti-counterfeiting has not yet been widely exploited [16]. The challenge of the new system is to take advantage of this promising technology to combat counterfeiting, aiming essentially to turn the centralized supply chain to a new, decentralized one. The aim of the new system is the creation of a blockchain-based system to restrict counterfeiting in the supply chain of different kind of products.

The system will consist of a product traceability platform as well as a multilayer blockchain platform. The system will focus on the categories of products that are most frequently counterfeited and consumed by people, such as food and beverages. This category of fake products can shave serious health risks, except for financial damage of their legitimate producer and distributor. The primary solution to the problem of counterfeiting, introduced by blockchain technology, is radically redesigning traceability of the supply chain. The decentralized database offered by blockchain technology will be able to store any transaction or activity in the supply chain, thus offering increased recognition capability, traceability and security. Each step along the supply chain will contribute by providing data to a decentralized and secure network that can prove the originality of the product, identifying whom it belongs to and providing authentication. The system will also provide the ability to monitor each product by assigning a unique ID for each piece. To achieve this, appropriate techniques will be developed to link the system to the packaging of the product. This set of data will allow for the detection of all product-related information across the supply chain, thus ensuring its transparency and adequate counterfeit protection.

# 3 An Information System for Counterfeiting Restraint

## 3.1 Methodological Approach for System Development

This paper presents the ongoing work and the initial results of a research project in Greece. The implementation methodology followed is based on two main phases. The first phase is to explore and evaluate system requirements, methods, and techniques that will be implemented to confront product counterfeiting and link the blockchain based system to product packaging, as well as the integration of blockchain technology for traceability and data security. Finally, this phase includes the detailed specifications of the new system. The second phase is the development, testing, and validation of the original system under real-world conditions in a specific industry. The industry sector of food and beverages has been selected for the system's validation, focusing on alcoholic and non-alcoholic drinks that are commonly counterfeited. The research project's methodology is presented in Fig. 1, including the two phases as mentioned above and their main activities.

More specifically, in the first phase, a detailed review of the research field on the problem of counterfeiting of products, focusing on food and beverages, is held. This product category is often subjected to such counterfeits with both economic and consumer health implications. Methods and techniques for linking the system to product packages are also considered so that each product can be detected separately within the supply chain. At the same time, methods and techniques are explored to incorporate blockchain technology for better and safer data management and sharing. Next, the analysis that has been done in conjunction with the examination of a set of real traceability problems leads to the development of the business process for use-cases and the design of specifications. The next step is a more detailed assessment and analysis of the methods and techniques identified in the literature review and field research to identify the aspects and techniques that match the problem of counterfeit products. At the same time, the choice of IT technologies for usage in the development of the system, as well as the integration of blockchain technology are finalized in order to securely and transparently manage and store the data obtained throughout the supply chain.

In the second phase, all the selected methods and techniques are implemented in integrated software, utilizing contemporary IT technologies. This software can ensure safe and original products distribution in the food and beverage supply chain. As a result, the system under development will be used as a decentralized platform, accessible and remotely controlled, which will operate and provided as "Software as a Service" solution. Then, methods and techniques against counterfeiting, methods for linking product packaging, techniques for integrating blockchain technology into the system (for better and safer data management and sharing), as well as the developed software, will be tested in business processes in food and beverage supply chain. Through the development of simulation scenarios in specific companies participating in the supply chain, the effectiveness of the selected methods and techniques will be tested.

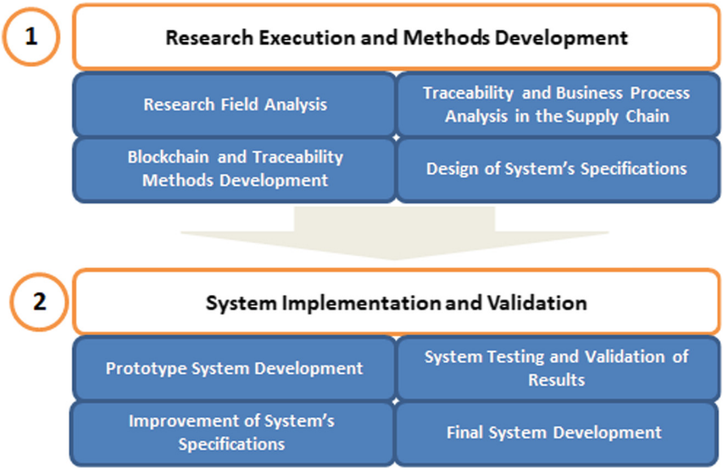


**Fig. 1.** Research project's phases for system development

### 3.2 System's Functionality

The final software solution is based on the cloud computing concept, as the system runs on the cloud under the responsibility of the system provider. Every user of the blockchain-based system for product counterfeiting restraint can access its functionality as a software service. The producer can generate a unique product ID, which can be traced until the latest part of the supply chain (the consumer). Every part of the supply chain can add in this ID the different states of the product (warehousing, distribution, sale) using the blockchain technology in order to guarantee the safety of data and the authenticity of the product.

The system will also guarantee accurate traceability of the products. Once produced, they will be registered on the traceability platform, from which they can then be traced, identified and updated at each stage of their journey. The platform will allow trading partners to share information about physical movements and product status as they travel across the supply chain, from business to business to the final consumer. The goal of the platform will be to allow dissimilar and distinct applications and processes (as is usually the case between business) to create and communicate events both internally (on-premise) and externally (with their partners). This event data exchange will aim to allow users to gain a common view of physical or digital objects within the company's context. Since the ownership of products is changing along the supply chain, its ownership will be transferred along the blockchain platform. Along with this technology, the necessary data of the products will be recorded, from their production until they reach the retailer.

### 3.3 System's Blockchain Advantages

First research results for decentralized data management and sharing, like Simple Public Key Infrastructure, were developed in the late 1990s, but they were not deployed. However, with the success of BitCoin and Ethereum, decentralized solutions have now become widely accepted. In this new situation, the new system can achieve real decentralization and can implement security solutions that do not require any "root of trust," by leveraging the blockchain technology. This is not just a theoretical advantage, but a critical property that will increase trust and allow fast adoption by companies.

In order to support data authority and privacy, the system adopts a multi-level approach to the storage of data, including private and public data storage approaches. It includes a private data store managed entirely by the stakeholder, a private blockchain for another level of data storage, containing data that is shared between collaborating stakeholders (for example producer, resellers and retailers in the food and beverages supply chain). Also, data can also be shared and stored in a public blockchain like BitCoin or Ethereum. Thus, the system will guarantee the authenticity of a product, keeping personal data safe and without any compromise on privacy. In this way, the products can be traced without the need for publishing confidential information.

### 3.4 Expected Results

The new system aims at the long-term and medium-term objectives. The main objectives and expected results at the medium-term level include:

(1) To offer improved detection and prevention of counterfeiting of the products.
(2) To support extended visibility of the products, from its source to the final consumer throughout the supply chain.
(3) To increase the trust of participants in the supply chain and effectively deal with data management and sharing, avoiding interception.
(4) To lead the transformation of existing business models or create new business models to provide innovative services and products that support modern supply chain business processes.

The long-term level objectives and results of the system include:

(1) To contribute effectively in reducing the financial losses suffered by the Greek and other economies, as a result of the counterfeiting of products.
(2) To eliminate serious health risks associated with counterfeiting of products consumed by people (like food and beverages), in addition to the economic losses by companies and governments. According to the statistics, the food and beverages industry sector belong to the five industry sectors in Greece with the most significant loss of sales due to counterfeiting.

## 4 Conclusions

This paper presents the development phases and the conceptual design of an integrated web-based software solution to support product counterfeiting restraint within the supply chain. Counterfeit products range from high-end consumer luxury goods such as watches, perfumes or leather goods, to business-to-business products such as machines, chemicals or spare parts, to conventional consumer products such as toys, pharmaceuticals, cosmetics, and foodstuffs. In fact, any intellectual property protected product can be counterfeited [17]. Some counterfeit products, such as pharmaceuticals, spare parts, and toys, could be of low quality and thus create significant health and safety threats. The proposed system can contribute to the immediate alignment with the overall efforts of the European Union countries to restrict and eventually eliminate the counterfeit of products.

The software is based on blockchain technology for safer decentralized data management and data sharing within the supply chain. The software will be offered as a Software as a Service to its business users. The anti-counterfeiting system will be implemented in the food and beverage supply chain, covering the need for advanced tools and methods to support the traceability process of modern products. The system can assist producers of goods, wholesalers, distributors, retailers, and consumers in preventing the counterfeit. Every involved part in the supply chain can gain access to the product's data and ID to ensure that it is original and safe. This access to data can be achieved through blockchain technology and advanced technological solutions. The key stakeholders of the system are the producers of goods and their consumers, but every part of the supply chain can benefit the advantages of the new system.

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# Designing and Delivering Smart Services in the Digital Age

# A Dual Perspective Workflow to Improve Data Collection for Maintenance Delivery: An Industrial Case Study

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**Abstract.** Due to the commodisation and globalization of the markets, manufacturing companies have been pursuing new business models based on product-service bundles, which in literature have been investigated under the broad term of Product-Service Systems (PSS). Efficient provision of PSS is not immediate since it requires as a first condition a deep integration of product and service components and the related delivery processes. As regards durable equipment, maintenance is one of the most relevant and common services offered to the market. The identification of the best maintenance policy, and the expected improvement of availability and productivity of the industrial asset depends upon the knowledge, cognition, and expertise that the provider has on the machine and the related operating conditions. With this regard, it is fundamental to wisely collect and analyze data related to the machine and its delivery process, extracting useful information guiding the policy selection. By investigating the case of a durable equipment manufacturer, the paper focuses on the problem related to the creation of a proper engineering process and data infrastructure for supporting a gradual and robust transition towards a PSS-based business model. A dual perspective vision for ensuring a continuous improvement of maintenance services is proposed and discussed, based on a cross-analysis of the on-field collected data from the industrial asset and the maintenance delivery processes.

**Keywords:** Maintenance · Product-Service Systems (PSS) · Data collection · Industry 4.0

## 1 Introduction

Commodisation of the markets has forced manufacturing companies to explore new strategies for enriching their product offering with additional services in order to differentiate themselves from global competitors and to open new market niches. The advent and consolidation of key technologies positioned under the umbrella of Industry 4.0 (I4.0) have undoubtedly provided an important leverage for improving their processes and fostering their transition towards the adoption of new business models, based on the provision of integrated bundles of products and related services. This phenomenon has been extensively and deeply investigated in literature under different


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terms, in a first instance as servitisation strategy and provision of Product-Service Systems (PSS) [1].

However, despite the presumed benefits deriving from a long-standing relation and fidelisation with the client base and a consequent expected profit increase, the transition from a product-centric to a PSS-based offering is not so seamless. Integration of product and services must be designed and engineered since the first conceptual stages, properly customized in order to create real value within the customer's processes, but, at the same time, efficiently standardized in order to avoid being trapped in the service paradox [2].

Hence, PSS providers need to adopt suitable approaches and to invest in enabling technologies to support PSS delivery both from a strategical and an operational point of view. One of the most relevant services that can benefit from the introduction of I4.0 technologies is undoubtedly maintenance, whose delivery is subjected to provider's capabilities, competencies, and knowledge. Depending on the maintenance policy offered, and technology adopted, companies must deal with different benefits and risks. The provision of preventive or predictive based contracts, though a potential business opportunity for a service provider, can turn out in higher risks in terms of emerging operational costs (reflecting contract penalties) and reputational losses.

In order to address this issue, this paper proposes a workflow and the related methods for maintenance process improvement crossing data from the asset and from the maintenance provision processes. Then, it describes its application in a manufacturing company, producing durable equipment, that is moving from the provision of corrective and preventive maintenance services towards the offering of a more distinctive PSS offering. In particular, the paper focuses on the initial phase of the workflow, putting emphasis on the need to assess and deploy a standard procedure to collect maintenance data from the field and from the technicians delivering the maintenance interventions to acquire the proper knowledge and capabilities before proposing more challenging services.

The paper is structured as follows: Sect. 2 shortly introduces the context and proposes a workflow for maintenance process improvement. Section 3 deals with the case study. Eventually, Sect. 4 concludes the paper summarizing the results from the case study, the main limitations and delineating future researches.

## 2 Maintenance Delivery Process Improvement

Product-Service System is based on the joint sale of products and services aimed at satisfying specific customer needs [3] ranging from a transactional Product-Oriented to a more Use-Oriented and Result-Oriented relationship with the customer [4, 5]. As mentioned earlier, the simple juxtaposition of products and services is not sufficient to guarantee a prolific PSS delivery [2, 6], especially if a supporting technological and organisational infrastructure is not available. In this regard, [7] state that the adoption of new technologies, such as I4.0 ones (e.g. cyber-physical systems, big data, simulation), can foster the transition towards PSS offering, reducing the risk of incurring in the service paradox trap and increasing the efficiency of service delivery. As [8–10] affirm, the integration of technologies into PSS can support and enhance the delivery of more effective services but this is subordinated to the definition of a formalized approach to the PSS delivery.

Given the possibilities offered by I4.0 technologies in terms of data generation, the approach should be based on data collection [11], management [12], and exploitation [13]. In particular, it should take into account product and service components, considering the data generated both during the product usage and during the service delivery process [14]. Regarding product components, a deep knowledge of the asset working conditions is crucial for the definition of the most suitable maintenance policy. In fact, while the vendor knows its machine from the design phase, he does not know its behavior under the user's operating conditions. This would not be possible without the availability of field data and their interpretation and translation into knowledge for predicting future states of machines. On the other hand, the service component entails all the knowledge related to how the service (i.e. maintenance) is provided to customers, mainly in terms of time, costs, objects and resources used. In both cases a data collection strategy is essential to sort and extract only useful data, guaranteeing at the same time a certain quality in data collection [11]. This is necessary also to favor the following data integration phase, which is a challenging task due to problems that may arise when data collected from different sources have to be integrated [12]. A formalized approach to data collection and management facilitates data processing, favoring the extraction of useful information from the dataset under analysis [13].

Starting from these remarks, Fig. 1 proposes a dual perspective workflow for ensuring a maintenance delivery continuous improvement process based on the analysis of data related to industrial asset and to its maintenance process.

From the machine perspective, the first action consists in the identification of the critical components of the asset by using some consolidated techniques such as the Failure Modes, Effects and Criticality Analysis (FMECA) [15]. Then, depending on the critical components identified, technical data should be continuously gathered from the asset in working conditions. Then, methods such as Root Cause Analysis (RCA) and Machine Learning (ML) techniques would allow to infer the current machine health status and predetermine the Remaining Useful Life (RUL) of the components [16, 17].

From the process perspective, a first analysis of the *as-is* service delivery workflow would allow to derive the main process criticalities. Then, according to the maintenance policy adopted, a strategy for collecting data related to the intervention should be designed and implemented.

Once collected, data from products and processes should be cross-analyzed to extract valuable information on maintenance delivery. In particular, the analysis of data related to components' failure along with maintenance delivery process would allow an update of the asset component criticality. This update would directly impact the maintenance policies adopted by the company and, thus, their delivery process. For example, it might emerge the need for more frequent maintenance actions on certain components due to the length of maintenance intervention, previously underestimated, or to the time required to retrieve spare parts. On the contrary, it might arise the possibility to reduce the frequency of the maintenance intervention, thanks to an upgrade of the technicians' expertise or to the availability of new diagnostics tools. Thanks to the information emerging from the cross analysis, corrective measures should be adopted both on the asset and on the process side. In addition, based on the feedbacks from the field, also components and machines may be re-engineered to make them more reliable and able to sustain different working conditions.

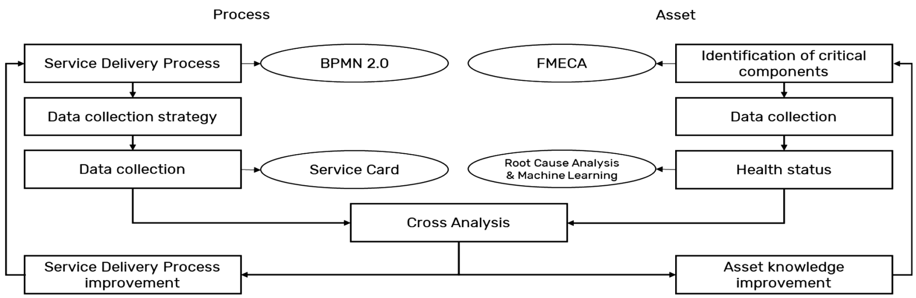


**Fig. 1.** The dual perspective workflow for maintenance delivery improvement

# 3 The Case Study

The case study has been carried out in the context of the PROMETEØ project (funded by Lombardia region) in one of the partner companies, Balance Systems (in short BS), an Italian company founded in 1975 and operating worldwide. Its core business areas are related to the production of balancing machines for rotary components and the development of process control systems for machine tools. Traditionally focused on the technological excellence of their machines, the company is enriching its solutions with service components in order to come along with the increasing and challenging requests from the markets.

To approach this transition, BS is trying to improve its maintenance provision creating a structured knowledge at both product and process level, leveraging on data acquisition, management, and processing. The definition of a formalized way to handle and create knowledge and wisdom on the process is a necessary step for the company moving towards a PSS business model. To this purpose, the workflow described in Fig. 1 has been applied to the company following a gradual multi-step approach, which is still underway. Specifically, BS has been focusing on the first three steps of the product and process improvement, which were carried out in parallel.

Within the project, two researchers have carried out multiple semi-structured interviews to collect data related to the asset and the current maintenance delivery process. Information has been then used to define a clear picture of the activities currently performed and the way information collected during and after maintenance were used and shared inside the company.

Regarding the asset, the company started applying a basic FMECA analysis. A pilot project has been carried out on one machine. Since BS machines are made up by standard groups, which are assembled differently in accordance with customer requirements, the company will be able to easily extend the FMECA analysis to other machine configurations. The purpose behind the FMECA application has been to analyze in depth the machine's structure and identify the main causes and effects for each component failure. To do so, a team composed by researchers and company experts has performed the machine's functional breakdown starting from the main working groups and ending with the single components. For each component, a list of possible failures and causes has been created. Following, the company experts have evaluated each component in terms of failure's Severity (S), Detectability (D) and Probability (P). The multiplication of the three factors has led to the definition of the Risk Priority Number (RPN), used to prioritize the risks deriving from each component failure.

Regarding the process, the company started from the analysis of the current maintenance delivery process (*as is*) that has been mapped using BPMN 2.0. From the interviews with the Service Engineering Supervisor, it has emerged that BS offering includes both corrective and preventive maintenance interventions. The analysis of the *as is* processes has led to the identification of several issues. One of the first criticalities emerged in the corrective maintenance is in the diagnostic phase, where a lack of knowledge on failure causes and effects often lead to a maintenance delivery slow-down. Other criticalities have been found in the scheduling phase, where multiple iterations are required to select the technician due to difficulties in matching customer requirements with technician skills and availability. Regarding preventive maintenance, criticalities are mainly related to intervention scheduling, due to the poor exploitation of data collected from the process, caused by an ineffective data collection strategy. Indeed, during the maintenance delivery, BS technicians used to fill out a form in an electronic sheet, created in Microsoft Excel®, called Service Card, to report the information on the maintenance activity. The previous version of the Service Card was not user-friendly; technicians used to fill it out wrongly or partially. For this reason, information was used only for the final quotation to customers but not to generate new knowledge on maintenance. To address this issue, the Service Card has been re-engineered to simplify the filling phase. Moreover, to improve data collection, and to facilitate the analysis of critical components, the FMECA has been used as an input for the Service Card. The new version, with drop-down menus, guides the technician while specifying the critical components and entering the information of failure causes and relative fixing actions. In the scope of favoring data analysis, data extraction, storage, and management have been reconfigured, and a specific database has been created. In particular, since the efficiency of the maintenance service offering is bonded to the ability to collect and analyze historical data, the following data are now collected through the Service Card (Fig. 2): (i) general data of the client and kind of manufacturing process; (ii) information related to machines that underwent maintenance operation; (iii) hours and pieces worked by the equipment before breaking; (iv) the problem identified by the technician; (v) the spare parts used to fix it; (vi) the time spent by the technician on the machine.

This has led to the possibility to improve the knowledge of maintenance interventions (length, problems, spare parts used) that can be used for multiple purposes: updating maintenance plans, upgrading design of machines, rearranging spare parts management, improving service offering and delivery, etc. to obtain benefits both on asset and process sides.

BS can now use data collected from maintenance interventions to extract relevant information. For instance, the engineering department is now able to analyze failures mode in those components most subjected to failures, as identified through the FMECA.

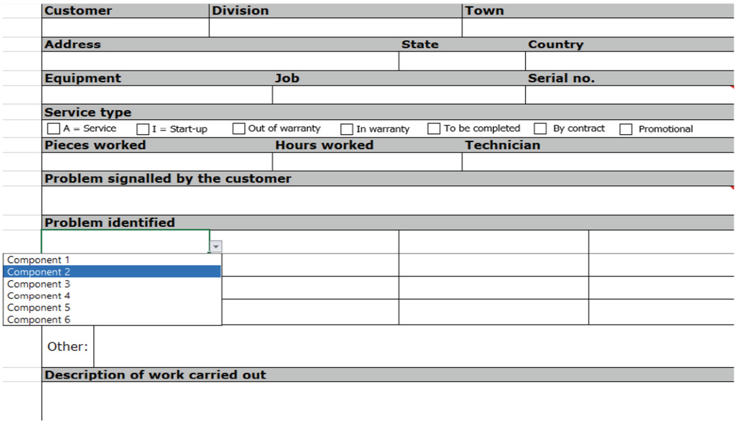
Customer | Division | Town
Address | State | Country
Equipment | Job | Serial no.
Service type
☐ A = Service ☐ I = Start-up ☐ Out of warranty ☐ In warranty ☐ To be completed ☐ By contract ☐ Promotional
Pieces worked | Hours worked | Technician
Problem signalled by the customer
Problem identified
Component 1
Component 2
Component 3
Component 4
Component 5
Component 6
Other:
Description of work carried out

**Fig. 2.** An excerpt of the upgraded version of the Service Card adopted in BS

As an example, the horizontal axis belt has been recognized as one of the most critical components; for this reason, more in-depth analyses have been carried out on the belt and on other components that were discovered critical. Data related to the power absorption when the horizontal axis belt was at the right tensioning have been collected. Then, the belt tensioning has been changed several times to collect new data on power absorption. The aim of this procedure was to collect data on the right and wrong power absorption to identify useful patterns that could be used to detect problems during the machine worktime. In particular, four ML classification techniques (Multinomial Logit, Discriminant Analysis, K-neighbor, and Neural Networks) have been used to analyze the dataset to understand if they could be used in this scope and to identify the one with the better performance.

Information collected on customers such as location, Service Level Agreement (SLA), machines, and a list of those technicians who usually deliver maintenance interventions is now fruitfully used to customize the service offering, creating new proposals tailored on their characteristics. For example, the same technician could be sent every time to the same customer, improving the knowledge level on the customer and machine issues. The proposal of new product-service contract bundles would be supported by historical data recorded about service timings and related costs. Different types of SLA-based contracts could be proposed according to the machines and customers characteristics. This is particularly importance considering the different PSS offerings, where the bond between machines and associated services could differ consistently depending on the way they are sold and perceived by customers.

## 4 Conclusions

The transition toward advanced PSS business models without incurring in the service paradox trap is not an easy task for a company. To this purpose, a dual perspective workflow for maintenance delivery improvement, based on the analysis of asset and its maintenance process data is proposed, and a case study shortly described. The analysis of the *as is* maintenance delivery process of the company demonstrated the presence of criticalities, and improvements were conducted both on the process and asset sides. If on the asset side, FMECA and machine learning approaches has been applied to identify and analyse critical components (e.g. for the analysis of the belt power absorption), on the process side, a traditional tool used to collect data on maintenance intervention, namely the Service Card, has been re-engineered to make it more user-friendly and enable a systematized data collection, favoring the subsequent analyses. A structured database has been created to store data from maintenance in the scope of using them to improve the service offering. Despite the results achieved, the transition of Balance Systems towards PSS is only at the beginning.

In conclusion, the profitable offering of corrective, preventive or predictive maintenance is strictly subjected to the capacity of the company to exploit data from both the maintenance delivery process and product, allowing the company to improve its efficiency and make the right decision supported by data. In this sense, the role played by technologies, as machine learning techniques, is crucial since they are a support for a more formalized data collection, management, and analysis.

Concerning limitations, the workflow and case study developed in the paper could be improved in different ways. Regarding the workflow, a more detailed analysis of methods and tools supporting the different phases should be carried out, providing some guidelines to help companies in selecting the most suitable ones. Regarding the case study, the first two parts of the workflow has been applied to a single company with the aim of formalizing the data collection and management phases both regarding the asset and the maintenance delivery.

Future developments require to carry out a cross-analysis phase (when a good set of data will be available) which should enable a consistent update of the asset and process information as well as a better understanding of the tools more suitable for inferring decisions on the service maintenance strategies and policies to adopt and supporting the definition of new contracts customized on both the machines and the customer's needs.

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# The Impact of Digital Technologies on Services Characteristics: Towards Digital Servitization

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**Abstract.** Despite that digital technologies play a fundamental role in enabling innovation in service delivery processes, the understanding of how they influence services characteristics, and service provider – customer interactions still remains a critical point. On these premises, this paper introduces a study to explore such influences, through the adoption of a two-dimensional matrix, representing a service provider – customer interaction typology, and describing how digital technologies influence the five main services characteristics (viz. intangibility, inventory, inseparability, inconsistency, and involvement). The matrix was built upon a literature review, and further refined through brainstorming sessions with researchers and practitioners. The results found suggest that digital servitization, the "digital transformation of services", brings about new dynamics in service provider – customer interactions by impacting on the service delivery processes elements. For this reason, the achieved matrix can help service researchers and managers to understand how digital technologies increase/decrease the presence and the role of the service provider in a service delivery process, and the presence and the role of the customer of the service in a service delivery itself.

**Keywords:** Service systems · Product-Service systems · Digitalization · Digital technologies · Services characteristics · Service provider · Customer · Interactions

## 1 Introduction

Recent studies have addressed the role of *digital technologies* in services and product-service bundles delivery processes towards *digital servitization* [1, 2]. As suggested by [3, 4], the *digitalization of services* influences the nature of a service itself, including its characteristics, since it implies a "(re-)organisation" of the service delivery process. Despite the large interest of research towards digital technologies in the service industry, often too little attention is still given to exploring how *services characteristics* [5] are evolving when *digital technologies* [6] are introduced in service delivery processes, thus, creating new forms of *service provider – customer interactions.* Such knowledge would instead allow to better develop and organise processes and resources,


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as well as to identify the most suitable digital technologies (e.g. see Table 1) to be adopted for a specific service or product-service delivery solution. In such a context, this paper aims to analyse how *digital technologies* influence the *characteristics of services* in existing and new service provider – customer interactions as they are digitalized in B2C & B2B domains. To do this, we classify digital technologies in a two-dimensional matrix, and use this categorisation to verify how they affect each of the “characteristics of services”.

**Table 1.** Digital technologies and their impact on services: examples

| | |
|---|---|
| Augmented Reality (AR)/ Virtual Reality (VR) | • AR/VR can improve customer support agents training.<br>• AR/VR can enrich services “tangibility”, thus, customer experience |
| Autonomous Guided Vehicles (AGVs) | • AGVs can support service delivery processes (e.g. logistics services) |
| Chatbots | • Chatbots can improve the availability of customer service and support |
| Big Data Analytics (BDA) | • BDA insights integration with human, assisted, or automated service delivery processes can ultimately improve customer experience |
| Cloud Computing (CC) | • CC resources “elasticity” can offer at each point in time the needed resources to match the current service demand as closely as possible |
| Horizontal Integration (HI)/ Vertical Integration (VI) | • HI/VI can improve service delivery processes, and services quality, by enriching the value creation capabilities of a service value chain |
| Internet of Things (IoT) | • IoT can improve the delivery of current, and provisioning of new services to smart, connected products & assets (e.g. product-services) |
| Simulations | • Advanced simulations will continue to support the design of services |

## 2 Services: Categories, Characteristics, and Types of Interaction

Among different perspectives and interpretations of *service features,* the majority of studies in the service domain attribute five distinctive characteristics to *services,* also known as the five “I’s” [5]. These are: (i) *Intangibility,* since services are intangible; (ii) *Inventory (perishability),* since services cannot be stored; (iii) *Inseparability,* since service provider is indispensable for a service delivery; (iv) *Inconsistency (variability),* since each service is unique; and (v) *Involvement,* since services require customer participation in the service delivery process.

Based on these characteristics, different classification methods both in marketing and in services operations management areas have been developed over the years to describe the main service dimensions and their relationships [7]. An exploration in the field of *service process delivery* has been carried out to develop a better understanding of how *service provider – customer interactions* co-create value in the emerging *digital servitization domain* [8]. In this context, [9] have proposed a service classification, where the level of participation of the customer in the service delivery process goes from (i) *self-services,* defined as “services in which there is no direct assistance from or interaction with a human service provider” to (ii) *super-services,* defined as “services in which there is no direct participation of the human customer”. On the other hand, [10] has proposed a classification where the level of participation of humans goes from (i) *human-services,* defined as “services in which there is direct assistance from or interaction between the human service provider and the human customer” to (ii) *autonomous-services,* defined as “services in which there is no interaction between the human service provider and the human customer”.

Hence, based on the categorisations of [9, 10], we can argue that in a *digitalized service delivery process,* four types (i–iv) of *service provider – customer interactions* can exist. These interactions depend on: (a) the presence (i.e. yes/no) and the role (i.e. active/passive) of the service provider in a service delivery process, and (b) the presence (i.e. yes/no) and the role (i.e. active/passive) of the customer of the service in a service delivery itself. Table 2 describes the four *types of interactions* that have been identified in this research: (i) *Human to Human (H2H),* where digital technologies do not modify the “active role” of the human service provider, neither the human customer, in the *human-service* delivery process. However, they can create new forms of or enrich their interactions (e.g. augmented reality, virtual reality, mixed reality, and haptic devices), or allow these interactions to take place remotely and in real-time (e.g. phone-calls, instant messaging, and video conferencing); (ii) *Human to Machine (H2M),* where digital technologies enable the possibility of a human *self-service* process, thanks to an intuitive human-machine interface already available in the machine service provider. Within this type, the human customer is the only “active part” in the service delivery process; (iii) *Human to Machine (H2M),* where digital technologies allow the possibility of a *super-service* process, thanks to remote operation capabilities. These capabilities allow the human service provider to act on behalf of the customer, and make the human customer a “passive entity” in the service delivery process; and (iv) *Machine to Machine (M2M),* where digital technologies create an *autonomous-service* delivery process, thus, making unnecessary the existence of a human-machine interface in order to deliver the service. Therefore, both human service provider, and human customer presences are “passive” or “inexistent” in the service delivery process.

**Table 2.** Service provider – customer interaction typology

| | Passive | Active |
|---|---|---|
| Passive | Machine to Machine – M2M (autonomous-service) | Human to Machine – H2M (super-service) |
| Active | Human to Machine – H2M (self-service) | Human to Human – H2H (human-service) |

## 3 The Evolution of Services Characteristics

This section discusses how *digital technologies* influence the *characteristics of services* (viz. intangibility, inventory (perishability), inseparability, inconsistency (variability), and involvement [5]) as a result of their *digitalization* in the above-mentioned service provider – customer interaction typology (see Tables 3, 4, 5, 6 and 7).

### 3.1 Intangibility

Based on the service provider – customer interaction nature, determined by the role of *digital technologies* in the "service delivery process", the *degree of intangibility* of a *service* can be classified as: "low, medium, or high", depending on two main factors: (a) the presence of the human customer of the service in a service delivery process, and (b) the contribution of the digital technologies to give a sense of <tangibility> to the service itself. Hence, in the first interaction-type, human service provider to human customer (i.e. human-service), the service degree of intangibility is considered: "low", because of a face-to-face and/or a virtual interaction takes place in real-time between the two parties involved, making the service delivery process more vivid, and therefore, more tangible. In the second and third interaction-types, the degree of intangibility is considered: "medium", since in both types, being human customer to machine service provider (i.e. self-service), or human service provider to machine customer (i.e. super-service), a human-machine interface will permit a certain live-experience of the service delivery process for the human as a customer, or as a service provider, and a user interface will allow a certain tangibility of the service itself. Lastly, in the fourth interaction-type, the service degree of intangibility is considered: "high", due to an autonomous-service delivery process (i.e. autonomous-service) in a machine service provider to machine customer interaction, making the service delivery process completely intangible for the human as a customer, or as a service provider.

**Table 3.** Intangibility in service provider – customer interaction-types

| | Passive | Active |
|---|---|---|
| Passive | M2M<br>(high intangibility in autonomous-services) | H2M<br>(medium intangibility in super-services) |
| Active | H2M<br>(medium intangibility in self-services) | H2H<br>(low intangibility in human-services) |

### 3.2 Inventory (Perishability)

Based on a service physical or digital nature, its *capability* for being stored may change, and can be classified as: "low, medium, or high". In this sense, a *physical service* cannot be stored, but a *digital service* can be in what computer scientists call a services library or a services directory. *Digital services* can be retrieved from digital storage, manually or automatically, for their (i) execution as they are, (ii) customization/configuration first and later execution, or (iii) composition with other digital services for the co-creation of a particular meta-service, or service bundles. Thus, in the first interaction-type, human service provider to human customer (i.e. human-service), a physical service cannot be stored due to its physical nature, and human delivery channel. Therefore, digital technologies can only facilitate the service delivery process, and as a result, its perishability level is considered: "high". In the second interaction-type, human customer to machine service provider (i.e. self-service), a digital (standard) service can be stored in a service delivery device, and the human customer can consume it on-demand. So, digital technologies act as a service delivery channel, and the service perishability level is considered: "low" since we are referring to the consumption of a digital (standard) service. In the third interaction-type, human service provider to machine customer (i.e. super-service), a physical service or a digital (standard) service cannot be stored and/or consumed on-demand. Consequently, digital technologies can only help to make more efficient the delivery processes, since some level of customization/configuration may be needed before for the service delivery, and as a result, the perishability level is considered: "medium". Lastly, in the fourth interaction-type, machine service provider to machine customer, digital (standard) services can be stored in an e-library or e-directory, so that digital technologies can create *autonomous-services* without human intervention as a customer or as a service provider, and as a result their perishability level is considered: "low".

**Table 4.** Inventory (perishability) in service provider – customer interaction-types

| | Passive | Active |
|---|---|---|
| Passive | M2M<br>(low perishability in autonomous-services) | H2M<br>(medium perishability in super-services) |
| Active | H2M<br>(low perishability in self-services) | H2H<br>(high perishability in human-services) |

### 3.3 Inseparability

Based also on the service provider – customer interaction nature, determined by the role of *digital technologies,* and their "automation capabilities", the *degree of inseparability* between the human service provider and the service delivery process can be classified as: "low, medium, or high". Hence, in the first interaction-type, human service provider to human customer, the degree of inseparability is considered: "high", since we are dealing with a *human-service.* In the second and third interaction-types, the degree of inseparability is considered: "medium", since in both cases, it would be possible to automate the human service provider role or the human customer role correspondingly, being the cases for *self-services* and *super-services.* Lastly, in the fourth interaction-type, the degree of inseparability is considered: "low", because we are referring to an *autonomous-service* delivery process that does not require human intervention in the role of a service provider or a customer.

**Table 5.** Inseparability in service provider – customer interaction-types

| | Passive | Active |
|---|---|---|
| Passive | M2M<br>(low inseparability in autonomous-services) | H2M<br>(medium inseparability in super-services) |
| Active | H2M<br>(medium inseparability in self-services) | H2H<br>(high inseparability in human-services) |

### 3.4 Inconsistency (Variability)

Based on a service physical or digital nature, its replicability and quality standardization in a service delivery process can be more or less easy to manage, so considering the complexity of its exact reproducibility, its *variability* level can be classified as: "low, medium, or high". Thus, in the first interaction-type, human service provider to human customer, the service has a physical and a *human-service* nature. Therefore, allowing high possibilities of service inconsistencies, since both service provider and customer are humans, and they could find difficult to reproduce exactly a previous service and its delivery experience, consequently, the service variability level is considered: "high". In the second interaction-type, human customer to machine service provider, service inconsistencies, in the context of *self-services,* have a tendency to be medium. Indeed, the human customer role is partially standardized by means of a <wizard> in the self-service user interface, and the machine service provider process is fully standardized in order to manage customer expectations. Consequently, the service variability level is considered: "medium-low". In the third interaction-type, human service provider to machine customer, service inconsistencies, in the context of *super-services,* also have a tendency to be medium, since the machine service provider aims for developing a catalogue of standard services or a service configurator in order to facilitate itself the delivery of different services as they are needed by the human customer. Thus, the service variability level is considered: "medium-high". Lastly, in the fourth interaction-type, machine service provider to machine customer, services inconsistencies tend to be very low, as the *automation* of a service delivery process requires the standardization of the service itself. Hence, service variability level is considered: "low".

**Table 6.** Inconsistency (variability) in service provider – customer interaction-types

| | Passive | Active |
|---|---|---|
| Passive | M2M<br>(low variability in autonomous-services) | H2M<br>(medium-high variability in super-services) |
| Active | H2M<br>(medium-low variability in self-services) | H2H<br>(high variability in human-services) |

### 3.5 Involvement

Based also on the service provider – customer interaction nature, human involvement in the service creation and service delivery process can be classified as: "low, medium, or high". In the first interaction-type, human service provider to human customer, the *human* nature of the *service* makes essential the human involvement of both parties, hence, human involvement is considered: "high". In the second interaction-type, human customer to machine service provider, due to the *self-service* approach in the service delivery, only the human customer is needed, thus, human involvement is considered: "medium". In the third interaction-type, human service provider to machine customer, because of the *super-service* approach in the service delivery, only the human service provider is needed, therefore, human involvement is considered: "medium". Lastly, in the fourth interaction-type, machine service provider to machine customer, *autonomous- services* make human involvement unnecessary, and therefore, human involvement is considered: "low" or "null".

**Table 7.** Involvement in service provider – customer interaction-types

| | Passive | Active |
|---|---|---|
| Passive | M2M<br>(low involvement in autonomous-service) | H2M<br>(medium involvement in super-services) |
| Active | H2M<br>(medium involvement in self-services) | H2H<br>(high involvement in human-services) |

## 4 Discussion

The level of usage of *digital technologies* in a *service delivery process* influences the *characteristics of services.* Such influence is in some cases is "positive" and, in others, "negative". For instance, as the level of usage of digital technologies increases in a service delivery process, the degree of *service intangibility* increases (see Subsect. 3.1), since the physical interaction between the human customer and the human service provider gets reduced. On the contrary, when it comes to the *service inseparability* (see Subsect. 3.3), the level of usage of digital technologies in a service delivery process decreases this characteristic, since technology makes possible to separate the customer from the service provider by using technology as an interface between them.

Furthermore, the influence exerted by the *digital technologies* in a *service delivery process,* and as a consequence on the *characteristics of a service,* is mediated by the type of interaction that is established between the customer and the service provider. For example, although *service inconsistency* (see Subsect. 3.4) decreases as digital technologies are used in a service delivery process, due to the process standardization, it decreases more quickly in the case of *self-service solutions* because the process is directly controllable by the service provider to ensure its effectiveness.

Again, the influence of *services characteristics* resulting from the different levels of usage of digital technologies in the four types of *service provider – customer interactions* in turn impacts on the organisation and management of a *service delivery process.* Such impacts are briefly reported as follow: (i) When it comes to *service* *intangibility,* digital technologies increase this characteristic, and involve shifting the service physical evidence from humans (e.g. the technician uniform) to technology (e.g. computer interfaces); (ii) When it comes to *services inventory (perishability),* digital technologies can reduce the problems that traditionally affect the variability of services demand, including their design and availability management, as digital technologies can create "virtual buffers", and offer "elasticity" of digital resources (e.g. cloud ICT-infrastructures). However, particular attention must be paid to balancing the capability and capacity of a service delivery process; (iii) When it comes to the *inseparability* of the *service provider – customer,* the attention of the service provider shifts from being focused on the front-office activities (i.e. H2H) to the back-office activities (i.e. H2M), up to concentrating only on support activities when both customer and service provider are excluded from the service delivery process in a machine service provider to machine customer context (i.e. M2M); (iv) When it comes to *services inconsistency (variability),* its reduction in a service deliver process involves an increased "standardization" of overall service system (i.e. processes, competencies, and resource involved); and (v) When it comes to the *human service provider* and/or *human customer involvement,* the reduction of participation of humans in a service delivery process reduces the necessary efforts to make tangible "the intangible", because human customers are not interested in participating in the service delivery process, but they could still be interested in participating in the "service co-design [11] ".

## 5 Conclusions and Further Research

This research work introduced a study aimed at understanding how *digital technologies* influence *services characteristics* in *service delivery processes.* To do so, it proposes a novel classification of *service provider – customer interactions* supported by digital technologies with two dimensions: (a) the presence and the role of the service provider in a service delivery process, and (b) the presence and the role of the customer of the service in a service delivery itself. The achieved results underline that digital technologies modify both the characteristics and delivery processes of services. Moreover, the degree of influence of digital technologies can be amplified and/or mitigated by the level of involvement of a customer and/or a service provider in a service delivery process. In other words, the planning and managing of the processes, competencies, and resources involved in a service delivery depends on the different types of service provider – customer interactions (viz. H2H, H2M, and M2M).

We believe that this work can have interesting managerial implications as it helps service managers and practitioners understand how to design/manage service delivery processes for different types of service provider – customer interactions. However, this research work presents some limitations. First, it is based exclusively on a theoretical evaluation and a position that arises from the considerations of a group of researchers and practitioners[1]. Therefore, it would be necessary to deeply study the feasibility of

[1] IFIP WG5.7 SIG on "Service Systems" – https://www.ifipwg57.org/special-interest-groups/

the considerations that emerge when assessing whether services characteristics change in relation to the different types of service, customer, and industry. Moreover, empirical explorations should be carried out to analyse how different digital technologies impact on the different components of a service delivery process (viz. activities, resources, skills, infrastructure, measures) as well as to highlight their implications on the whole service lifecycle, from the interpretation of customer needs to the measurement of achieved results.

Further research should include the influence of *digital technologies* in *service quality determinants,* and in the structure of *service delivery processes* in reference to their *service blueprinting elements* (viz. customer actions, front-stage, back-stage, support processes, physical evidence, inventor, and line of visibility) [12].

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# Capability-Based Implementation of Digital Service Innovation in SMEs

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**Abstract.** In order to be successful in the market in the long term, enterprises must not only continuously optimize their operations but also constantly innovate. It is necessary to develop radically new digital services which disrupt their existing business model. For small and medium-sized enterprises (SMEs), it is a major challenge to put the generated solutions into practice. They have to cope with digitalization while having limited resources. The presented paper starts by examining the challenges for SMEs in the context of digitalization. Thus, an analysis of the approaches used in practice for implementing digital services in 36 SMEs is carried out. Essential differences between start-ups and established SMEs are identified. On this basis, a capability-based, agile methodology is presented which supports enterprises in advancing newly developed, digital services from prototype status to the customer's environment. Finally, the methodology is put into practical application within an innovation project in an SME.

**Keywords:** Service development · Innovation · Capability-based · Digitalization

## 1 Introduction

In the context of digitalization, new service-based business models are developed that confront established market actors with major challenges [1]. Physical products are transformed into digital services that adapt to the customer's individual context. In order to remain competitive, established enterprises must succeed in digitally transform their product portfolio and transfer the resulting changes into an operational business. This includes the deep integration of people and technology as well as high customer involvement [2]. Most challenges usually arise during the transition from the first demonstrators to the operating service system at the customer's site [3]. Small and medium-sized enterprises (SMEs) have to face these challenges with a lack of financial resources and competencies. For this reason, they have to be particularly efficient in the application of their resources [4]. The objective of this paper is to present a methodology for advancing digital services of SMEs from prototype status to the live production environment. As a research methodology a design science approach is applied. First, the problem is formulated in chapter two. Then, a capability-based methodology is invented


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and finally applied and reflected in a first use case. This paper describes just the first iteration. The methodology will be continuously developed in future projects [5].

## 2 Digital Service Innovation in SMEs

In order to be able to examine the processes of the implementation of digital service innovation in SMEs more closely, the necessary terminology must be defined first. A service is a process in which resources (e.g. goods, knowledge and skills) are applied for the benefit of others or oneself. Thus, the focus is no longer on the physical product, but on the benefit achieved [2]. Innovation is a phase of technical ontogenesis. It starts with cognition, the scientific investigation of unknown natural phenomena. If the inventions based on this are technically implemented and brought onto the market, the term “innovation” can be used [6]. The term ‘digital’ covers gathering, storing, processing, providing and using information electronically with the help of information technology (IT) [2]. Important methodologies for the implementation of digital service innovations are for example agile approaches like Scrum [7]. In this paper, the implementation of the innovation is examined in particular. Technical aspects, as well as the requirements of employees and customers, are considered. The process of invention and the actual market launch are not taken into account.

### 2.1 Analysis of Digital Service Innovation in SMEs

The approach presented in this paper focuses on SMEs which act as digital service providers. SMEs can be characterized as enterprises with fewer than 250 employees and a turnover of less than 50 million euros [8]. They have considerably fewer resources to implement service innovations. SMEs lack investment capital, which leads to increased pressure to succeed in innovation projects. Besides, they frequently do not have the competencies required for the realization of digitalization projects [4]. For a more in-depth analysis, it is necessary to examine the current methodology of SMEs. Therefore, the following section analyzes how SMEs are currently dealing with the challenges in the implementation and introduction of digital services. It is based on an analysis of the funding measure “Industrie 4.0 Testbeds for SMEs”, which offers the opportunity to advance existing inventions towards market maturity with the help of short-term testing and development activities in research institutes. In 2018, a total of 36 SMEs who participated in the funding measure were interviewed in a semi-structured manner about their processes in service innovation. The SMEs belong to the information and communication sector (13), the manufacturing sector (10), the scientific and technical services (8) and other sectors (5). The main differences in the implementation and introduction procedures can be observed between start-ups and enterprises that have been established on the market for a long time. In the following, these differences are further detailed. The results are summarized in Table 1.

**Start-Ups.** 14 out of the 36 analyzed enterprises can be characterized by the fact that they are operating on the market for less than five years. All of them are very focused on the development and operation of just a single service innovation. The implementation is very methodical. Based on an elaborated business model, agile approaches (e.g. scrum) are used in eleven of the start-ups for operational implementation of user stories. If there are existing contacts, lead customers are strongly involved in the development activities in ten of the enterprises. However, most start-ups are technology-driven. The know-how required for implementation is systematically built up. Development and operations of the product are supervised by the same people, which makes an internal product launch unnecessary.

**Established SMEs.** The SMEs of this group have been on the market for an average of 23 years. They have already well-established physical products and services. Only six of the analyzed enterprises are developing a completely new range of services. 16 of the 22 enterprises are trying to further develop their existing range of products to digital services. The implementation of the strategy and the development process in all enterprises are strongly driven by the managing director and are not explicitly planned. Mostly, a rough and technology-based vision was formulated, which addresses a clearly defined customer need. Based on this, a first prototype is developed. Customer feedback only takes place at the end of development. (Waterfall model) Generally, only little methodical support was applied in the investigated enterprises of this group. The execution is mostly carried out by the R&D department. The projects are realized in groups of two or three employees. Only five projects involve employees from operations. Often, the necessary competencies for development are only available at partners like research institutes or software companies.

**Table 1.** Comparison of development approaches for digital service innovation.

| Criteria | Start-up | Established SME |
|---|---|---|
| Product range | Focus on a single service | Wide product range in operations ties development capacities |
| Strategy implementation | Difficulties to find customer needs, based on a business model | Based on a rough vision, more focused on technology |
| Methodology | Agile approach | Waterfall model |
| Operations involvement | Same people in development and operations | To limited extent |
| Customer involvement | Early involvement aimed at | Involvement in tests after development phase |
| Knowledge building | Built up systematically | Mostly covered by partners |

## 2.2 Requirements for a Methodology to Implement Digital Services

In summary, there is a clear difference between established enterprises and start-ups. Start-ups follow agile approaches to identify customer needs and develop digital service innovation. In this way, they are continuously approaching customer needs. Established companies have deficits in their methodology. However, through their experience and deep inside to customer processes, they are able to identify highly relevant customer issues. What they need is an approach that supports them in formulating their digital service innovations clearly understandable and adaptable to the fast-changing customer requirements. To support such an agile approach, a central communication element is necessary, which meets the requirements of both, operations and development. Therefore, it has to be understandable without background knowledge, but also offer space for detailed considerations. Capability-based approaches can meet these requirements. Since they are not technology-oriented, but based on specific goals and benefits, capabilities link strategy, development and operations holistically. Thus, a capability-based solution approach will be pursued in the following.

## 3 Capability-Based Implementation of Digital Innovations

In this section, initially, the term capability is defined shortly. A detailed discussion can be found in [9]. Afterwards, a methodology for the development of digital service innovation in four steps is presented.

### 3.1 Capability Definition

Business capabilities are abilities or capacities that a business may possess or exchange to achieve a specific purpose or outcome [10]. Ability refers to the level of available resources like people, hardware and software needed for the performance of a process [10, 11]. The capacity of a capability describes the scale of the outcome [12]. In order to model capabilities based on this definition, they are regarded as a system in the following. This results in an inner and an outer view to describe capabilities.

The outer view describes the relationships among the capabilities of the value creation system. This includes the capabilities of the own enterprise, but also those of partners and customers. In this black-box description, it can be distinguished between input, output and context. The input describes the form and the type of the required variables for generating the capability. (e.g. information, materials). The output describes reliability, accuracy, scale and form of the results of a capability. (e.g. the regular provision of specific information via a defined interface) The context describes the boundary conditions under which the capability is realized. This might include a specific customer environment, a defined time frame or the available financial resources. In summary, the outer view defines the required capability performance. This definition can be made by describing specific scenarios or by a collection in a table.

Moreover, capabilities have an inner structure. This can be described on the one hand by decomposing capabilities into sub-capabilities. On the other hand, they are characterized by a process which is enabled by resources. Basically, a distinction can be made between the resources people, software and hardware. Each of them is linked to the process. Figure 1 summarizes the elements of capabilities. Further capability-based approaches can be found in the information systems literature [9]. Another approach can be found in military research [13]. A major hurdle in both approaches is their large scope. This makes it difficult to implement them in SMEs.

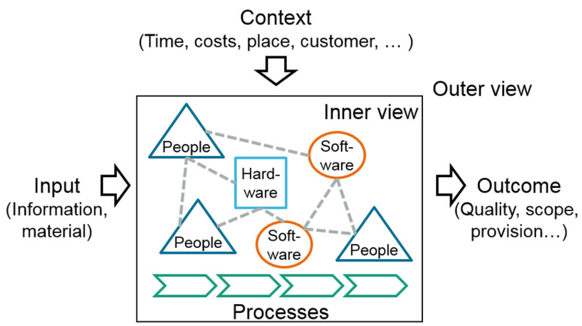


**Fig. 1.** Structure of capabilities

### 3.2 Implementation of Capabilities

The presented approach is based on existing agile procedures which enable a rapid response to changes in the environment such as new customer or employee requirements [14]. It consists of four steps, which are performed iteratively. First, the required capabilities are derived from the aspired service innovation and collected in a backlog. This is followed by the steps 'finding ideas', 'prototyping' and 'testing'. Figure 2 gives an overview of the approach. The individual steps are described in detail in the following.

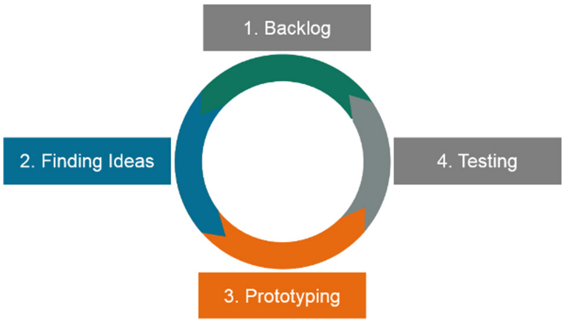


**Fig. 2.** Approach for capability-based service innovation

**Backlog.** The aim of this step is to identify the individual capabilities and their objectives. As described above, this paper starts after the invention of a new digital service. Ideally, the idea is detailed in a business model and translated into the required business capabilities. A comparison with the capabilities already available in the company follows to identify capability gaps. Missing capabilities and their requirements are documented, for example in a table. It is crucial that the outer view is first elaborated for each capability. This forms the boundary conditions under which the capability can later be used operatively. Moreover, the objectives, as well as the reliability and accuracy with which the capability must be performed, are defined.

Furthermore, the timeframe of the capability deployment and the required capacity of each capability are defined. This includes a description of the extent to which the capability must later be implemented and what financial resources are available for it. The results for each capability are stored in the backlog.

**Finding Ideas.** The aim of this step is to generate and select implementation alternatives for capabilities. Therefore, the capabilities are taken from the backlog. First, it must be analyzed whether it is sufficient to adapt to existing capabilities. If this is not possible, new capabilities have to be developed. Therefore specific resource combinations are stored. Creativity techniques such as brainstorming are used. A capability can be generated in different ways. For example, a different degree of automation can be set. The generated capability alternatives are compared using a cost-utility-analysis, which enables a joint consideration of costs and benefits. A suitable capability alternative is selected. The other proposals are documented for later iterations.

**Prototyping.** The aim of this step is to quickly create capability prototypes by implementing the resources. These prototypes are developed in several iterations of finding ideas, prototyping and testing. In the first iterations, this can be done for example by simple storytelling or mock-ups. Requirements for people, hardware, software and interfaces can be further detailed. In later iterations, the prototypes are implemented with simple hardware, such as Arduinos or Raspberry PIs, to carry out the tests quickly at low costs. In the last step, the capability is converted into practicable hard- and software. At the same time, the competencies of the employees are gradually being developed. Therefore, education activities are systematically planned based on the required business capabilities.

**Testing.** The aim of this step is to test the previously generated capability prototypes with the intention to quickly generate feedback. Thus, the prototypes are immediately tested by employees and customers. Holistic feedback must be requested and all those people who are affected by the capability must be involved. Tests can be executed in different ways. One possibility is the use of test beds which is a realistic environment at a research institute. Another possibility is to test the solution together with a lead customer. The aim is to move forward step by step towards the operative application of the capability. For this purpose, the capability can be used initially for certain customers or smaller operational scenarios.

## 4 Validation

In the following, the approach presented above is applied to a service innovation project. Innovation provider is a consulting company that wants to offer an innovative consulting service, based on the exact recording of processes and times in the manual assembly of large-volume products. The objective is to create transparency and to identify optimization potentials in assembly, data-based. A comprehensive description of the technical development can be found in Kärcher et al. [15].

First, the target capabilities are identified, by analyzing the aspired business model. The capabilities ‘data acquisition’, ‘data processing’ and ‘information provision’ are defined. For each capability, requirements are deposited. For example, the data acquisition for large components must take place with an accuracy of 0.5 s and an accuracy of 99%. The data acquisition must be possible within a period of 7 days without interruption. The aim of the capability is to generate total process times. For this purpose, the start or end of an assembly process must be detected. The capability requirements are collected in a table which is used as a backlog. Now ideas for the implementation of the capabilities are generated. The consulting company already has the capability to record times paper-based. However, since it is not possible to sufficiently develop this capability further, the development of a new capability is aimed at. There are different possibilities. The recording is possible with the help of an app which makes the data immediately available in real time. With a higher level of automation, data can be captured with the aid of sensors (e.g. RFID, camera, sensors on components). Based on the cost-benefit analysis, the company decides to implement sensors on the components. In order to get the first feedback quickly, storytelling is used for first prototypes. For this, the procedure of the capability is presented to several stakeholders from the assembly in a workshop. In the second step, the implementation of prototypes takes place with the help of simple sensors. Only in the last step, own sensors are developed. Testing is first carried out in a test environment at a research institute where a demonstrator is set up. At the same time, competence requirements for employees were recorded. It was determined that the consultants on site needed additional knowledge in configuration and bug fixing in order to implement the capability. Appropriate training material is created and tested with the first version of the system. In the second step, the solution is introduced into the customer's assembly in small projects.

**Discussion.** The advantage of the approach presented in this paper is that customers and employees from the operations are involved in the development process at an early stage. By using capabilities, the development is less technology-driven and strongly geared to the benefit. This led to numerous new ideas in the presented project. In addition, the components of the service innovation were developed independently of each other. As a result, these can be reused in further service innovation projects. An important hurdle was the application of the concept of capabilities, as this was often misunderstood. Thus, a training concept should be developed.

## 5 Summary and Outlook

This paper presents a capability-based approach to implementing digital services in SMEs. The challenges of SMEs were first examined in the context of a literature search and a short study. This showed that especially established SMEs have great difficulties in implementing solutions in operations. Based on this, an agile, capability-based approach was examined in more detail and applied on a practical innovation project. A major advantage of the approach was the detachment from specific technologies. It shows how SMEs can gradually implement solutions. Through the use of capabilities, they remain focused and receive a holistic overview of the necessary adjustments. In addition, capabilities can be used to holistically map a situation and the customer benefit generated by the service. The application has shown that while the method is very simple to use, it is limited to smaller projects. Very complex digital service innovations, as they occur in large enterprises, can only be mapped roughly without creating too much complexity. Further work is to apply this approach to a larger group of companies. In addition, elements of change management should be integrated. For example, the approach could be broadened by the strategic planning of change.

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# Digital Servitization: The Next "Big Thing" in Manufacturing Industries

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**Abstract.** Manufacturing firms increasingly produce and provide services along with their traditional physical products. This process, better known as servitization, is a mature theme in the literature, flourishing in recent years. Digital disruption is propelling manufacturers to move on towards digital transformation and deliver digital services. Prior research investigated the impact of servitization measured by the traditional services. However, the role of digital technologies in manufacturing is neglected. This paper intends to shed light on the impact of digital service portfolio antecedents on firm performance. Our analysis used the Serbian dataset of 240 manufacturing firms from the European Manufacturing Survey conducted in 2018. The empirical results show that, in manufacturing firms, digital services can significantly increase the turnover ratio. Results indicate that management in manufacturing companies should utilize digital services such as Web-based services for customized product design and Web-based offers for product utilization to maximize firm's turnover ratio and upgrade current service business model.

**Keywords:** Digital services · Servitization · Financial performance

## 1 Introduction

A paradigm shift in business models is occurring in the manufacturing industry [1]. Durable goods manufacturers choose to innovate their offerings by providing services to accompany their existing products throughout the life cycle [2]. However, with the advent of new technologies (i.e. information technologies), traditional services such as maintenance and repair [3] are not enough. Digital disruption is propelling manufacturers to move on towards digital transformation and deliver digital services. For example, latest report from McKinsey shows that manufacturing firms are introducing on average eight digital services [4]. However, this number varies widely by country. The literature has looked at the impact of servitization measured by the traditional services on performance [2], [5–8], however the role of digital technologies in service business transformation is under-investigated [9]. This paper investigates and offers an understanding on how digital services affect the turnover in manufacturing firms.

This study relies on a unique dataset from the European Manufacturing Survey (EMS) with a sample of 240 industrial firms from Serbia. Our analysis shows that digital services have positive influence on firm's turnover ratio. Two out of five digital


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services (i.e. web-based services for customized product design and web-based offers for product utilization) positively affect firm performance.

## 2 Background and Related Work

### 2.1 Digital Manufacturing Services

In the literature, service strategy has a long presence through wide terminology such as servitization [10], servicizing [11], product–service systems [12], or even open service innovation [2], et cetera. Today, the presence of digital technologies has brought the transformation of service business models [9] and formed something that is called digital services. The provision of digital services, or 'Digital servitization', has become a sub-stream of service business model [13]. Digital servitization is defined as "the provision of IT-enabled (i.e. digital) services relying on digital components embedded in physical products" [13]. Digital services are different from traditional since the marginal cost of digital services is near zero and they are substitutes for traditional products [14].

Digital technologies such as Internet of things, cloud computing and predictive analytics [9] are considered a key elements of the fourth industrial revolution [15]. Cambridge Service Alliance provided research regarding servitization with the participants from Capital Equipment Manufacturers and academics [16]. They identified top five service technologies in manufacturing sector and all of them are digital based services: predictive analysis, remote communications, consumption monitoring, and two aspects of mobile communication platform [16]. Furthermore, the all of these digital services are in line with digital services presented in this study. For instance, Digital McKinsey [4] report shows that two thirds of manufacturing firms worldwide say that digital solutions in manufacturing are one of their highest priorities. Technological development potentially offers a variety of benefits for firms able to utilize it and seamlessly embed them in business models and products to improve market competitiveness [15] and provide more accurate information sharing inside and outside the boundaries of the firm [17]. While broadening the perspective from product-related services to digital services is fundamental to the servitization debate, its impact on a firm's performance remains in question. This is partly due to the fact that the possibility to charge for digital services that had previously been free represents a challenge to managers [18].

Certainly, the concept of servitization could enhance the competitiveness of a manufacturing firms while simultaneously advancing economic conditions, resulting in a higher turnover from selling digital services [19]. Studies that deal with the assessment of whether adding additional services, even digital, improves the financial performance of a firm are scarce and more empirical research is needed in this area [2, 20, 21]. To shed more light on this important area of production research, we investigate how specific digital service portfolio choices influence firm's financial implications.

### 2.2 Research Questions

Based on literature review, the following research questions were proposed in attempt to identify the different effects of digital services on manufacturing firm's turnover:

- RQ1: The deployment of digital services will positively impact firm's turnover ratio?
- RQ2: Which digital services, if any, increase firm's turnover ratio?

The digital services presented in the model were identified based on exploratory interviews with practitioners and group discussions with experts in the field. All EMS consortium members were involved in this process which resulted in a universal transversal list of digital services so that all manufacturing sectors can apply it regardless of the product offered. Identified digital services are: (1) Web-based offers for product utilization, (2) Web-based services for customized product design, (3) Digital (remote) monitoring of operating status, (4) Mobile devices for diagnosis, repair or consultancy, and (5) Data-based services based on big data analysis. Consequently, these digital services were included in the EMS questionnaire. We use the turnover ratio as our dependent variable. In the same manner, early studies show that share of turnover was defined as the share of company turnover in the market [8, 22, 23]. Moreover, the turnover ratio was defined as the annual turnover of the firm in the year 2017 divided by the annual turnover of the firm in the year 2015 [24].

Figure 1 depicts the proposed research framework.

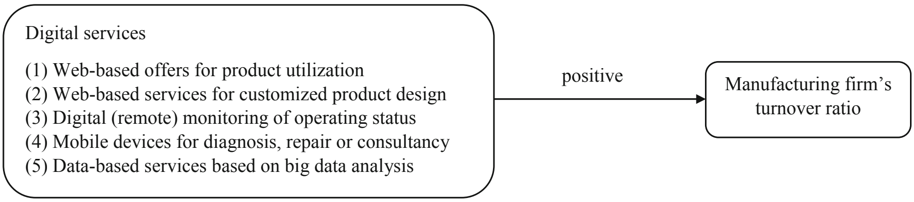


**Fig. 1.** Research framework.

## 3 Data and Methodology

Data for this empirical study derive from the European Manufacturing Survey, a survey on manufacturing strategies, application of innovative organizational and technological concepts in production, and questions of digital servitization in the European manufacturing industry [25]. The EMS is administered by the Fraunhofer Institute for Systems and Innovation Research [26]. The objective of this regular, triennial questionnaire is to systematically monitor the innovation behavior of European manufacturing enterprises at the firm level. The concepts, constructs and questions are well-tested and have been agreed upon in the EMS consortium. The six-page questionnaire includes questions on innovation activity, firm and industry characteristics, and general firm data. The survey is sent out repeatedly to senior managers of firms with 20 or more employees and designed to be representative of all regions, industrial sectors covered, and enterprise sizes. The survey is conducted among manufacturing firms, addressing manufacturing sites (NACE Rev. 2 codes from 10 to 33). A non-response analysis is conducted to ensure that the sample is representative of the population. The analytical dataset includes 240 observations of manufacturing firms from Serbia. The dataset in our research is from the 2018 survey edition. The comparison of data regarding firm size and industry sector distribution between Serbian subsample, and those of other EMS countries (e.g. Croatia, Germany, Lithuania, Slovakia, Slovenia) shows no significant size bias.

With regard to descriptive statistics, the sampled firms report, on average, a firm size of 124 employees (SD = 207). In total, 110 companies are small firms (fewer than 50 employees), 103 companies are medium-sized (between 50 and 249 employees), and 27 firms are large enterprises (more than 250 employees). Firms belonging to the food products (39 firms), fabricated metal products (36 firms), and rubber and plastic products (21 firms) sectors account for the most prominent observations in the sample. Tables 1 and 2 depict the sample distribution regarding size and industry sector.

To analyze the relationships between digital services and financial implications we employed a multivariate data analyzes.

**Table 1.** EMS database – distribution of firms by size.

| Firm size | n | % |
|---|---|---|
| 20 to 49 employees | 110 | 45.8 |
| 50 to 249 employees | 103 | 42.9 |
| 250 and more employees | 27 | 11.3 |
| Total | 240 | 100.0 |

**Table 2.** Classification on manufacturing sectors according to share on total sample.

| NACE Rev. 2 | Manufacturing industry | Share on total sample (%) |
|---|---|---|
| 10 | Manufacture of food products | 16.3 |
| 25 | Manufacture of fabricated metal products | 15 |
| 22 | Manufacture of rubber and plastic products | 8.8 |
| 27 | Manufacture of electrical equipment | 6.3 |
| 28 | Manufacture of machinery and equipment | 6.3 |
| 14 | Manufacture of wearing apparel | 5.8 |
| 16 | Manufacture of wood and of products of wood and cork | 4.6 |
| 23 | Manufacture of other non-metallic mineral products | 4.6 |
| 29 | Manufacture of motor vehicles, trailers and semi-trailers | 4.2 |
| | Others | 28.1 |

## 4 Results and Discussion

Table 3 presents linear regression model, for a dependent variable (turnover ratio), used to test research questions.

**Table 3.** Results of linear regression.

| Digital services | Model parameters |
|---|---|
| Web-based offers for product utilization | .481$^{+}$ |
| Web-based services for customized product design | .532$^{*}$ |
| Digital (remote) monitoring of operating status | −.434 |
| Mobile devices for diagnosis, repair or consultancy | .108 |
| Data-based services based on big data analysis | .083 |
| R | 0.627 |
| $R^2$ | 0.393 |
| F | 3.782 |
| Sig. | 0.002 |

*Note:* $^{*}p < 0.05$; $^{+}p < 0.1$.

In the regression model that tests both research questions, the overall model was significant, $R^2 = .393$, $F = 3.782$, $p < .01$. One predictor had a significant coefficient – Web-based services for customized product design ($B = .532$, $p < .05$), thus supporting the idea to include them in the service portfolio to increase the turnover ratio. The influence of Web-based offers for product utilization on turnover ratio was not significant at $p < .05$, but marginally significant at $p < .1$ ($B = .481$). Hence, manufacturing firms should also include them in the digital service offering. However, manufacturing firms focusing on the development of digital services such as Digital (remote) monitoring of operating status ($B = -.434$, $p > .1$), Mobile devices for diagnosis, repair or consultancy ($B = -.973$, $p > .1$), and Data-based services based on big data analysis ($B = .083$, $p > .1$) show no statistically significant effect on turnover ratio. For RQ1 (*The deployment of digital services will positively impact firm's turnover ratio?*), regression model was tested. In the model that estimates the effect of digital services on firm performance it is shown that the impact is significant and positive. Furthermore for RQ2 (*Which digital services, if any, increase firm's turnover ratio?*) only Web-based services for customized product design and Web-based offers for product utilization into the model show the positive effect on firm performance, providing support to RQ2.

As a major finding, our research indicates that the deployment of specific digital service portfolio choices will exhibit distinct financial performance. For instance, our results indicate that manufacturing firms should provide *web-based services for customized product design* and *web-based offers for product utilization* as digital services to increase firm's turnover ratio. It is not clear from our data, however, whether the success of the two digital services is due to the additional managerial focus these firms received, or if, as we assume, cultural practices of customers in emerging market. These results are in line with previous studies [15, 27, 28].

## 5 Conclusion

This study examines digital servitization strategies of manufacturing firms. Consequently, this paper provides theoretical and practical implications on how and in what way digital services impact the manufacturing firm turnover. The empirical results indicate that two digital services significantly or marginally influence a firm’s turnover ratio. Today, many manufacturing firms are evolving their business strategy from the traditional focus on product offerings toward a new direction, so that business models based on digital services can bring higher performance [29, 30]. Our results indicate actionable insights for managers of manufacturing firms to expand their understanding of how to increase turnover with provision of digital services. Specifically, managers in manufacturing firms should provide digital services such as *web-based services for customized product design* and *web-based offers for product utilization*, to maximize the firm’s turnover. Moreover, this findings, support prior study which shows that the framework is applicable to a wide variety of engineered products, especially those that can benefit from customer input during the early stages of the product realization process (i.e. mechanical or electrical engineering) [31]. However, managers should be aware that not all digital service provisions will lead to a service business model. Furthermore, it’s very important to find which digital services make the best effects on manufacturing firm performance according to type of industry.

Our sample was collected from all manufacturing industries, and, perhaps due to the industry specificity, results could differ. Also, there are various aspects that should be taken into consideration for the assessment of digital service impact on a firm’s turnover (e.g. type of customer served, seasonality, and promotion). This research is limited only with dataset considers in Serbia. Prior study shows important of organizational and innovation concepts in developing countries [32]. For further research, authors could make comparison of results between developing and developed countries in part of digital servitization. Furthermore, EMS consortium must deeper investigate the manufacturing sector in the next data collection round, because of the extremely important topic of digital servitization in development of the Industry 4.0. Moreover, further research is necessary to assess the experience and challenges of firms with a focus on one industry (i.e. the manufacture of fabricated metal products) and to consider different challenges in measuring the impact of digital services provided by manufacturing firms. Development of these ideas could prove especially useful for firms facing the challenges of a particular industry, showing that specific digital services can improve their financial performance [2].

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# Organization of Sales for Smart Product Service Systems

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**Abstract.** Many industrial companies face their digital transformation. In addition to an existing portfolio of products and services, new digital services are being developed to offer a portfolio of smart product service systems (Smart PSS). While the development of new digital services is rarely a problem for the companies, the organization of sales and distribution of Smart PSS in particular is a key issue. The sales of Smart PSS differs considerably from the sales of only products or services and must therefore be designed differently in order to meet customer requirements and successfully commercialize the developed Smart PSS. This paper therefore describes how the sales organization of Smart PSS should be designed successfully in various forms. The network thinking methodology is used in combination with a case study research approach to describe the connection between the offered portfolio, the customer requirements and the different elements of a sales organization. Furthermore, four different types of a sales organization for Smart PSS are described. This paper gives a recommendation for companies on a design of their sales organizations on which practical implications may be developed.

**Keywords:** Smart product service systems · Sales organization · Sales management · Network thinking · Case study research

## 1 Introduction

Many industrial companies today already use a service business to differentiate themselves from competitors in the product business. They use the combination of products and services to offer systems that provide the customer a solution. Research literature refers to this as *product service systems* [1–4]. In addition, companies start to develop digital services [5, 6]. Digital services use data as a central resource, e.g. data from the sensors of machines [7–10]. Manufacturing companies are trying to avoid the strong price competition in traditional product markets by offering digital solutions in addition to services, such as condition monitoring, remote services or value-added services [3, 11, 12]. The interplay between physical products, services and digital services is shown in the shell representation of Smart PSS (Fig. 1) [13]. For many manufacturing companies, the physical product is still at the center of the portfolio. This is accompanied by a complementary business of spare parts and an expanded product range.


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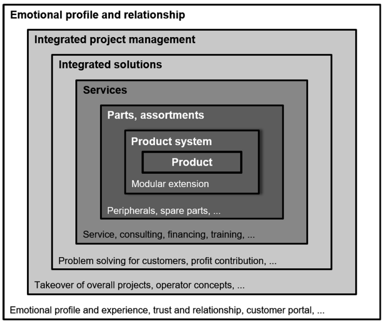


**Fig. 1.** Shell illustration of product service systems [13]

In the fourth shell, classic services are added, which complement the product business to form a product service system. Although the following shells only describe a deeper integration of the system, many of the digital solutions make it possible to establish the deep integration to offer a Smart PSS [13–16].

However, many companies struggle to sell Smart PSS. Studies about companies, which offer only product service systems, show that even they struggle to sell the solutions properly [17]. Referring to case studies we conducted for this paper, companies also struggle to sell Smart PSS properly. A first indicator of why these companies have problems is provided by a study showing that 39% of the surveyed top performing companies set up their own sales department to sell digital services [18]. Although this step seems logical at first in order to transfer the speed from the development process into sales, problems arise during integration with sales for existing products and services [19]. The design of Smart PSS follows the same principles as for PSS [20]. This includes the integration of the system in order to create synergies [21, 22], and the one-face-to-the-customer principle, which describes that there should be a single point of contact for every customer [16]. The current division of the sales departments into products, services and digital solutions leads to a one-sided focus in which each department optimizes itself and to individual customer contact persons for products, services and digital solutions [18].

This gap between the design principles and business practice is the motivation for this paper. Many companies invest large sums in the development of Smart PSS, but seem to have problems in the distribution of those systems. Due to the lack of research in this area, we aim to provide new insights in this paper to describe the relevant elements of a sales organization and to describe possible characteristics for different types of Smart PSS. In order to achieve this, the paper addresses the following research question: *How can the sales organization of smart product service systems be designed successfully?*

To answer this question we first briefly summarize the theoretical background of the relevant literature. Second, we describe the research methodology that was used to identify the elements of a sales organization for Smart PSS. Third, we present the results of the developed model with regard to the research question. Fourth, we conclude with the key contributions of this work to the field of sales organizations for Smart PSS.

## 2 Research Background

### 2.1 Smart Product Service Systems

The term ‘smart product service systems’ is quite new to research literature and therefore has to be described in detail before dealing with it in the following. Chowdhury et al. deliver an in deep systematic literature review on the term of Smart PSS [23]. They present in detail, that most of the work done in the field covers product service systems, but little effort was put in conceptualizing the ‘smart’ aspect of the PSS. The ‘smart’ aspect is often implied in the definition of these systems, but there a no distinct answers given to how PSS can be enabled to get ‘smart’. Valencia et al. describe three general types of PSS: result-oriented, use-oriented and product-oriented. Furthermore, they answer to how PSS are getting ‘smart’. “Smart PSSs are ‘smart’ because they carry some of the characteristics of smart products, such as the capacity to transform data into knowledge to perform more effectively” [20]. There is not one sole definition covering all aspects necessary for a satisfying characterization. However, as Chowdhury et al. deliver the most recent definition, it is likely the most sophisticated. The basis for their definition are the interactions of smart technologies, physical products, services and business models. Common to all previous literature the main goal is to satisfy the customers’ needs [14, 20, 23]. This satisfaction is reached through functional integration of digital services [34, 35].

### 2.2 Sales Organization

The sales organization is a functional department of a business that is responsible for the sale of the portfolio offerings and the design of the distribution channels. Therefore, it may be seen as a tool of the distribution policy. Further, a comprehensive and complete task description is harder to conceptualize, because of the different scope in each individual business [24]. Most literature is dealing with characteristic approaches to sales of products alone. On the one hand, there are approaches, which may be transferable and applicable for Smart PSS. On the other hand, the Smart PSS alter from the common approaches in a way that these concepts have to be revisited and thought through again [25]. The sale and distribution of Smart PSS have a strong focus on business-to-business markets. Thus, customers are mostly businesses as well, which leads to other characteristic behaviours compared to Business-to-customer customers [26].

## 3 Methodology

The design of the sales organizations for smart product service systems followed an iterative five-step approach, which is based on the methodology of *network thinking* as shown in Fig. 2 [27, 28]. Designing a successful sales organization for Smart PSS is a complex problem. A tool for mastering this complexity is the method of networked thinking. The goal of networked thinking is to describe cause-effect relationships in systems in such a way that the behavior of the system becomes predictable under changed conditions. In particular, the method makes it possible to map and analyze the type, intensity and time behavior of the interrelationships between the individual system descriptive characteristics [27–30].

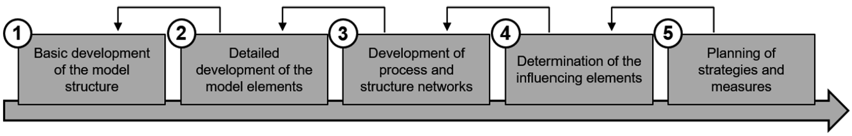


**Fig. 2.** Approach of network thinking for the development of sales organizations

The research in this paper is limited to steps 1 and 3 of the process. For this purpose, the basic model elements were described by means of a case study research approach. This method is suitable whenever a theory for a so far unknown phenomenon is to be built [31, 32]. Case study research ensure that the achieved results are closely connected to the everyday reality of companies. To record the case studies a standardized interview was conducted with managers from the sales and product management departments. In Table 1 all recorded use-cases are listed. The number of case studies examined for this paper is limited to five, as the elements of the developed model and the different types of sales organizations were the same for all companies. Even though the focus of this paper is on machine manufacturers, we also included cases from neighboring industries in the study to gain a holistic view of the sales organization.

**Table 1.** Overview of selected cases

| Industry | Employees | Turnover | Sales organization | Type |
|---|---|---|---|---|
| Agricultural machinery | 11.500 | € 3.7 bn | Integrated | OEM |
| Equipment manufacturer | 6.000 | € 1.5 bn | Separated | OEM |
| Machine manufacturer | 13.500 | € 3.5 bn | Integrated | OEM |
| Equipment dealer | 3.000 | € 1.1 bn | Integrated | Supplier |
| Equipment manufacturer | 1.700 | € 280 mio | Separated | OEM |

# 4 Sales Organization for Smart Product Service Systems

In this section, the results of the case study research are presented. First, the typical elements of a sales organization for Smart PSS and their connection will be discussed. Afterwards, different types of sales organizations and their effects on the aspects of the organization will be presented.

## 4.1 Elements of a Sales Organization for Smart Product Service Systems

Based on the conducted interviews from the case study research with five companies the following basic model of a sales organization for Smart PSS was derived through network thinking (Fig. 3). The model is based on the interviews and the connections between the different elements. The interrelationships were collected with the help of networked thinking. The model is divided in four main sections, which are interconnected with each other.

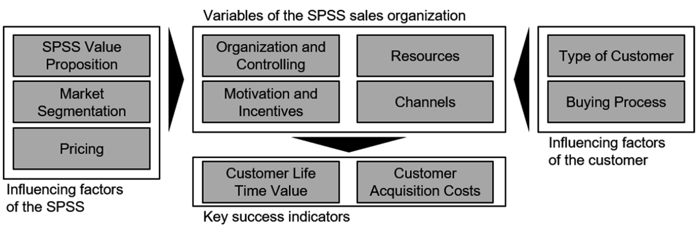


**Fig. 3.** Basic model elements of a sales organization for smart PSS and their connection

The variables of the sales organization of a Smart PSS are at the center of the model, which includes ‘organization and controlling’, ‘resources’, ‘motivation and incentives’ and ‘channels’. These elements are also described in the literature as typical elements of a sales organization [25, 26]. Two sections are influencing these variables of the sales organization. This is on the one hand the influencing factors of the Smart PSS itself with the elements ‘Smart PSS value proposition’, ‘market segmentation’ and ‘pricing’ and on the other hand, the influencing factors from the customer side with the elements ‘type of customer’ and ‘buying process’. To measure the success of the Smart PSS sales organization companies use the key success indicators ‘customer life time value’ and ‘customer acquisition costs’. These two indicators already show that companies want to minimize the costs to convince a new customer of the Smart PSS and try to increase the perceived value of the Smart PSS during a longer time following the long-term principle of PSS [16].

This basic model already shows the complexity of the design of a sales organization for Smart PSS. Especially the two influencing sectors have in combination a huge impact on the sales organization. The Smart PSS portfolio is usually developed independently from the sales organization and different types of market segments and types of customers want differently be addressed by a sales organization [24], which is also acknowledged in the next chapter by the description of different types of a sales organization for Smart PSS. The complexity of the model arises from the interaction of the individual elements, since they are of different intensity and time behavior. The change in the organizational structure, for example, can be changed quickly, while the culture and cooperation of the employees are rather slow elements.

### 4.2 Different Types of Sales Organization for Smart Product Service Systems

The case studies show that, depending on the current Smart PSS portfolio and the company's customers, there are different types of sales organization. A total of four of these types are shown in Fig. 4. In the first type, the offering is divided into three categories (product, service, digital), of which all are sold separately. The second type integrates the respective service and digital departments, as both work from a customer-centric perspective [18]. The third type offers Smart PSS for the first time, but as a bundle with individual revenue models [13, 16]. The last stage represents a subscription model for the entire Smart PSS, where the entire service is sold via a subscription model in the digital ecosystem [33].

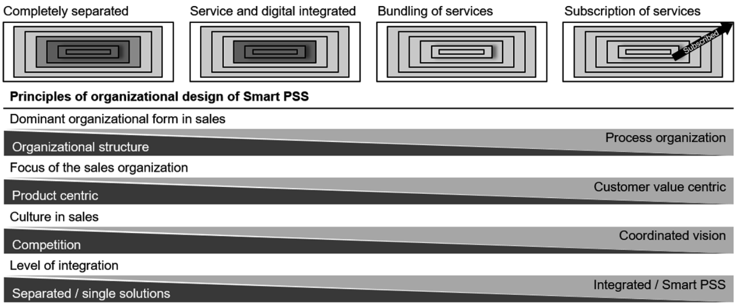


**Fig. 4.** Different types of sales organizations for Smart PSS

The fundamental aspects of a sales organization are changing. These include the dominant organizational form, the focus of the organization, the culture and the level of integration. All four aspects are changing from a rather separate and non-integrated to an organization whose aim is to jointly sell Smart PSS. In addition to the mere organization or processes, softening factors such as the culture of the employees are also a decisive changing factor, which show the complexity of the whole research and application field. The sales organization must be able to fulfill all four characteristics, as the case study research shows that there are customer groups for each type of business model. This finding, together with the already prevailing complexity described in the previous section, shows that the sales organization for Smart PSS needs to be completely rethought and -designed to ensure successful sales and to respond to the needs of customer groups of Smart PSS.

## 5 Contribution and Discussion

The literature examined show that companies have few problems with the technical development of Smart PSS, but the sale leads to major problems. This happens due to the high complexity, which Smart PSS as well as different customer groups put to the sales organization. The contribution of this paper is a model that illustrates the complexity of sales organizations by presenting the individual elements in a first draft model. In addition, the demand is shown that the future Smart PSS sales organization is designed by different types in order to successfully serve various customer groups.

The results of the paper provide an initial contribution to understanding the complexity of the sales organization, which lead to recommendations for companies for the optimal design of their sales organization. Nevertheless, this paper can only provide a basic model for the sales organization, but is the first of its kind to focus on the sales organizations while other authors usually focus on the portfolio or development of Smart PSS [36]. Next steps are to detail the individual elements and to gain a deeper understanding of the intensity and time relationships of the elements described in Fig. 3. Based on the resulting dynamic model of the Smart PSS sales organization, influencing variables can be determined that could be changed better or worse. Based on these influencing variables, recommendations for action can be developed, which transfer the findings of the theoretical model of a sales organization for Smart PSS into design guidelines applicable for companies. In order to carry this out, both extensive research on Smart PSS, as well as the inclusion of further case studies is necessary.

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# Operations Management in Engineer-to-Order Manufacturing

# Exploring Logistics Strategy in Construction

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**Abstract.** The purpose of this research is to explore logistics strategies in construction. There are very few studies on logistics and SCM practices in construction, especially when it comes to the long-term strategic work of construction companies. Therefore, this research takes a contractor's perspective and addresses logistics strategy based on the empirical examination of two case companies in the construction industry. The main focus is the contents of the strategy and possible components of the logistics strategy are identified through a literature review. Also the process of the strategy is treated through exploring logistics strategy in two case companies exemplifying two strategic approaches to construction logistics. However, the approaches differ, implying a spectrum that at one end responds in a standardized manner to a pre-determined design solution and at the other reveals a re-configurable modular approach. The main contributions of this study lie in exploring logistics strategy in construction and providing examples of how construction companies work with logistics strategies, adding empirical knowledge to the field of construction logistics.

**Keywords:** Logistics strategy · Construction management · Case study

## 1 Introduction

Construction is essentially a complex industry due to the large number of participants and interactions (Winch 2010). Where traditional manufacturing industries can work long-term and strategically in a stable and process-oriented environment, the construction industry is typically characterized by one-off projects, tendering and procuring sub-contractors and suppliers on a short term-basis each time a project is launched (Dubois and Gadde 2000; Kristiansen et al. 2005). This leads to a situation where projects are managed locally, in a tactical manner, becoming disconnected from the strategic company level (cf. Dubois and Gadde 2002; Kristiansen et al. 2005). This in turn affects how logistics and supply chains are managed within construction companies, where it is uncommon to find logistics strategies defined at the company level that are implemented as logistics plans at the project level. Recent research has demonstrated that the principles of supply chain management, particularly when focused on logistics, offer a potential means of overcoming this complexity and improving productivity (Vrijhoef and Koskela 2000), yet achieving this in practice is far from straightforward. While some progress has been made, the nature of the


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industry and the scale of relationships involved cause barriers to progress (Meng 2013). This indicates the need for a 'big picture' view of construction logistics and supply chain management, one that is more strategic than operational in nature.

The purpose of this research is therefore to explore how logistics strategies can be developed in construction companies, and how they can be a platform for developing effective logistics plans for individual projects. There are very few studies on logistics and SCM practices in construction (Bankvall et al. 2010), especially when it comes to the long-term strategic work of construction companies. This research takes the perspective of the contractor and focuses on the empirical examination of the contents of logistics strategy in the construction industry. In so doing, the following research questions are addressed:

1. What are the typical components of a logistics strategy?
2. What constitutes logistics strategy in construction?

Building on these research questions the following section describes the research design. Thereafter the literature review is introduced, with a focus on investigating research question 1. Research question 2 is then addressed through case studies followed by case analysis and discussion. The paper is then concluded, and possible further research is identified.

## 2 Research Design

There is a lack of studies on logistics strategies in construction, therefore this study is explorative, using a case-based research method. The research design is divided into two phases. The first phase is a literature review taking a stance in the traditional logistics and operations management literature, searching for suitable factors for describing and defining the contents of a logistics strategy.

The second phase of the research is based on an empirical study focusing on two case studies representing construction companies that have developed logistics strategies for their operations. One of the case companies has a logistics strategy that is standardized and deployed for all of the company's construction projects, whereas the other case represents a construction company employing a modularized logistics strategy that forms the basis of configurable specific logistics plans for individual projects. As such, we use two contrasting cases to identify and describe critical variables (Stuart et al. 2002). Contextual variables and project specific characteristics are identified and coded to facilitate the use of pattern matching and logical models (Yin 2014) for a cross-case analysis, and for contrasting the case studies with the results from the literature review. The main sources of data are: archival records (logistics strategy statements, internal reports, project documents, master's thesis reports) and semi-structured interviews (strategists, logistics managers, project managers).

## 3 Literature Review

### 3.1 The Construction Industry Setting

The productivity in the construction industry is considered relatively low (Abdel-Wahab and Vogl 2011; Fulford and Standing 2014; Josephson and Chao 2014), but the construction industry also faces unique settings that to some extent can explain the low level of productivity and the high costs. This uniqueness is characterized by the construction site that creates a temporary factory around the product (Bygballe and Ingemansson 2014), since these products are typically large and immobile, meaning they must be built on the site of use. Therefore, construction work is carried out in temporary organizations with temporary supply chains (Behera et al. 2015). Typically, a construction project is dependent on many, often small, firms acting as subcontractors (Dubois and Gadde 2002; Miller et al. 2002). As a result of the construction industry setting, many studies report on poor performance that originates from poor logistics management (Meng 2012), e.g. high costs (Hwang et al. 2009), waste (Josephson and Saukkoriipi 2005), and waiting time (Thunberg and Persson 2013). This is one of the reasons why some authors (e.g. Bankvall et al. 2010; Department for Business Innovation and Skills 2013; Thunberg and Persson 2013; Vrijhoef and Koskela 2000) argue that many of the problems in construction could be mitigated through better managed supply chains and better logistics management.

### 3.2 Logistics Strategy

There are surprisingly few clear definitions of what a logistics 'strategy' is, even outside of construction in its more traditional domain of manufacturing. According to the Financial Times Lexicon, a logistics strategy is "the set of guiding principles, driving forces and ingrained attitudes that help to coordinate goals, plans and policies between partners across a given supply chain." (Financial Times Lexicon, n.d.). Seeking their categorization, Autry et al. (2008) defined logistics strategies as "…directives formulated at the corporate level … used to guide more efficient and effective logistics activities at the operational level of the organization". This establishes the important separation of logistics as a strategic activity at the company-level, compared to its implementation at an operational, or in construction's case, project-level (see Fig. 1). Figure 1 also shows that logistics strategy is divided between the strategy contents and the strategy process. The main focus of this study is the strategy content, including how the contents are transferred into detailed descriptions of logistics components in logistic plans for each individual project. However, the empirical part of the study also includes the strategy process, including parts of the formulation and implementation of the strategy when the strategy is realized into logistics plans at the project level. As such, the unit of analysis is the logistics strategy content and process, taking a contractor's perspective.

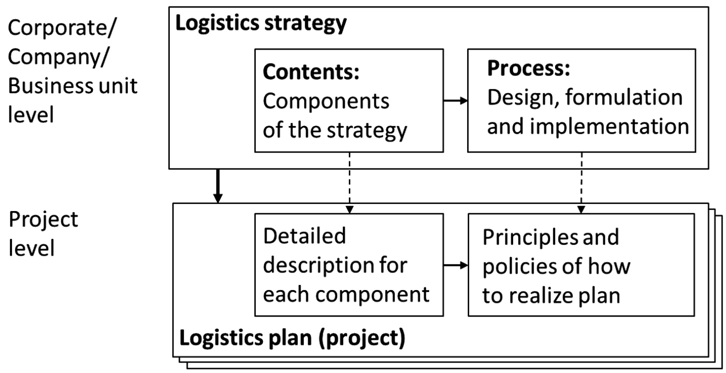


**Fig. 1.** Logistics strategy and plans divided into content and process aspects of strategy.

### 3.3 Components of Logistics Strategy

Bowersox and Daugherty (1987) established the first logistics strategy classification, identifying three distinct bases for logistics development: process-based/functional, focusing on cost-reduction; market-based, focusing on customer service; and information/external-based, focusing on coordination and collaboration. McGinnis and Kohn (1990) similarly investigated forms of logistics strategies. Throughout this strand of research into logistics strategy has been a continual questioning of the detail of what such a proposition contains (Clinton and Closs 1997). Relying on the division between the contents and the process of a strategy, it is possible to identify a set of logistics components that make up the strategy content and some examples of this from the literature review is presented in Table 1.

The identified components reveal a list of areas where strategic logistics decisions must be made and executed as logistics plans and decisions, these components help companies to work actively to define logistics strategies. McGinnis et al. (2010) identify that companies working intensively with their logistics strategy show significantly better performance than more passive companies, especially when it comes to logistics coordination effectiveness and customer service commitment. These performance indicators, in turn, are argued to positively affect overall company competitiveness (McGinnis et al. 2010).

## 4 Case Studies

The two case companies, referred to as company A and B, operate mainly in the Swedish market. Company A, a commercial construction company, shows a construction logistics ‘strategy’ that is focused upon a narrow ‘product-type’—commercial office buildings in dense, urban areas of Sweden. Their projects are mostly new-builds, with some renovations, and typically have budgets up to 500m SEK (US$53.8m at March 2019). Utilizing traditional construction methods, the company only undertakes a handful of projects at one time. Company A's logistics strategy is highly standardized in order to meet the pre-defined demands of these projects.

**Table 1.** Examples of components of the logistics strategy contents identified in the literature.

| Traditional logistics textbooks[a] | Autry et al. (2008) | Sing (2016) | Oakden (2016) |
|---|---|---|---|
| Customer service policy | Customer service | Customer services | Customer service policy |
| Supply network design (nodes) | Procurement (incl. supplier selection) | Channel design | Inventory location policy (Supply Network Nodes) |
| Transport and distribution (links) | Coordination & Collaboration activities | Network strategy | Transport and distribution policy (Supply Network links) |
| | Transport management | Transport management | |
| Inventory policy | Inventory & Order management | Warehouse operations | Inventory policy |
| | Operational controls | Materials management | Cost plan |
| IT, information sharing and communications | Technology/Information System | Information technology | IT and communications capability |
| | Storage | Policies & procedures | |
| Logistics organization structure | Strategic distribution planning | Facilities & Equipment | Logistics organization structure |
| Logistics targets and metrics (KPI) | Order processing | Organization & Change management | Logistics targets and metrics |
| | Logistics social responsibility | | |

[a]This is a summary of the components mentioned in the most common textbooks on logistics and supply chain management. Due to the page limit it was not possible to include them all.

Company B, a larger construction company than A, undertakes projects all over Sweden in urban and sub-urban locations. The projects that they have developed a logistics strategy for are residential in nature and almost exclusively new-builds. The structures are built using a mix of traditional and prefabricated methods, with a typical cost between 50m–300m SEK (US$5.4m–$32.3m at March 2019). Being a large company, they have many projects running concurrently around the country.

As for the contents of the logistics strategies, both company A and B have clearly defined the components of their strategies. Company A demonstrates that a clearly defined logistics strategy can be put in place that responds to a fixed ‘product’ through a pre-defined, standardized logistics approach at the project-level. Company B’s logistics strategy has created a reconfigurable ‘modular’ approach, meaning that components of the strategy are defined and then a range of solutions within these components are defined for selection based upon the nature of the specific project’s context when logistic plans are developed. A summary of the logistics strategy components for the case companies is provided in Table 2.

**Table 2.** Summary of components making up the logistics strategy content for the two cases.

| Company A | Company B |
|---|---|
| Long-term strategic suppliers and sub-contractors—development of relationships for continual improvement | Long-term relationships with suppliers and development of these relationships |
| Use of a Construction Consolidation Centre (CCC)—a centralized distribution center to help manage material flows | The use of Construction Consolidation Centre (CCC) or Distribution Terminals |
| Integrated Planning Process—clear and related production and delivery planning | Planning of transport and distribution activities |
| Planning Roles—dedicated organizational management roles for: transport co-ordination, in-bound co-ordination, and IT co-ordination | Delivery planning and scheduling |
| Dedicated IT System (Cloud-based)—All project participants must use this system (contractors, suppliers, transport companies etc.) | Understanding the detailed design requirements of a project from a logistics perspective |
| On-site Materials Handling Team—Dedicated and specialized team for efficient materials movement and task planning | Site logistics planning solutions |
| | Marking and labelling of goods |

Overlaps between company A and B appear in the content of these strategies. However, rather than focusing on the content (that is specific to each company’s business model), instead the two approaches reveal distinct ways of approaching a logistics strategy and its implementation at the project-level. Company A has a standardized logistics strategy, where the logistic plans are strictly based on what is defined in the components of the strategy contents. Basically, all logistics plans look the same, since the strategy is adjusted to the narrow focus of the projects that company A is bidding for, with the only variable being the site conditions. Company B uses the components of the strategy contents as decision-making areas that must be dealt with when developing their logistics plans for their different projects. Since the projects vary so much in location, design, structure, size, etc., company B’s strategy must be more flexible and can be seen as a modularized strategy, where the modules (components) are adjusted to the contextual factors as logistics plans are developed.

## 5 Discussion

Case studies A and B demonstrate that construction logistics strategies emerge in response to specific contextual factors. This context extends beyond the physical construction site and includes factors that are related to the specific business models of the companies themselves, responding to their technical platform (construction method), product offering (type of building), and target market (customer profile or budget), in line with Brege et al's. (2014) definition of construction business models. Case Studies A and B reveal the possibilities of a strategic approach to construction logistics. These approaches establish a spectrum that at one end responds in a standardized manner to a pre-determined design solution (as in A) and at the other uses a reconfigurable modular approach (as B shows).

The main contribution of this study lies in establishing an exploration of logistics strategy in construction, drawing attention to logistics as a strategic activity for contracting companies. Furthermore, this study provides examples of how construction companies work with logistics strategies, identifies that a spectrum of approaches exists, adding empirical knowledge to the field of construction logistics. Relating to the two research questions, a possible set of components of the logistics strategy contents have been listed in Table 1 (RQ1) and examples of what constitutes logistics strategies in construction (RQ2) have been provided through the case studies, especially through Table 2.

The research presented here is exploratory and a starting point to research logistics strategy in construction. There are a number of ways to continue this research, of which some are: to extend the literature review to further define the logistics strategy components; to increase the number of cases and also the number of projects within each case organization where logistics plans, anchored in logistics strategies at corporate level, have been implemented; and to extend the cases to countries outside of Sweden.

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# Architecture for Digital Spare-Parts Library: Use of Additive Layer Manufacturing in the Petroleum Industry

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**Abstract.** Spare parts management (SPM) is a typical challenge in the offshore and onshore petroleum industry. SPM consumes a significant amount of operational expenses that are attributed to maintaining the integrity of production and process facilities (P&PFs) at the anticipated level. Productive SPM approaches are essential for maintaining integrity; in particular, ageing P&PFs and legacy assets exacerbate the challenge of maintaining integrity at the anticipated level. This manuscript firstly provides an overview of how additive layer manufacturing/three-dimensional (3D) printing has been effectively utilized by different manufacturers to produce equipment, which resembles the equipment used in the petroleum industry. Then, it discusses the potential use of a digital spare parts library and the optimal strategy to mitigate current challenges pertaining to SPM. Finally, it proposes an architecture for a digital spare-parts library.

**Keywords:** Spare parts management · Petroleum industry · Three-dimensional printing · Digital spare parts library

## 1 Introduction

Additive layer manufacturing (ALM) {or the buzz term ‘three-dimensional printing’ (3DP)} was originally used for prototyping; however, it is now more and more applied to manufacturing end products [1, 2]. It has been estimated that ALM has the potential to generate an economic impact of $230 billion to $550 billion per year by 2025, through direct manufacturing and the use of 3DP to create tools and molds [3]. In some cases, ALM has been considered a supplement to conventional production technologies. In other cases, it is the only means through which complex products can be fabricated [1]. A further distinguishing feature of ALM is its distribution nature. On-site manufacturing for maintenance becomes an important application of ALM. While traditional manufacturing mostly takes place at a centralized facility, with the resulting parts distributed to end users, ALM has the potential for implementation at the point-of-


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use. It enables innovations in manufacturing value chains, many of which are still being realized [4]. In particular, the petroleum industry seems to have benefits when it comes to preserving the integrity of legacy assets. Especially, unprecedented levels of mass customization, smaller and cheaper supply chains, and the 'democratization' of manufacturing, enable the integrity of legacy assets to be maintained (i.e. particularly by allowing clients to print their own spare parts) in the petroleum industry. Hence, it is essential to investigate how to integrate ALM into petroleum-industry-related activities, to transform the effectiveness of upstream supply chains, as well as to bring new markets and sources of revenue to the downstream businesses.

The technology for ALM has been advanced through a coordinated development focusing on three areas (Fig. 1): 3D printers and printing methods [5], software for product design and print [6], and the development of materials for ALM [7]. The use of ALM in the digitalized and automated process chains of spare parts in petroleum industry seems to be one of the most significant opportunities (Fig. 2).

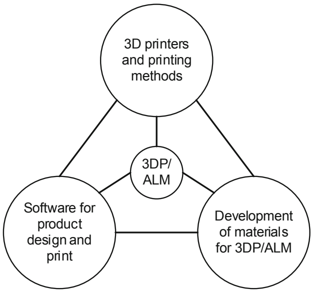


**Fig. 1.** Three areas of 3DP/ALM.

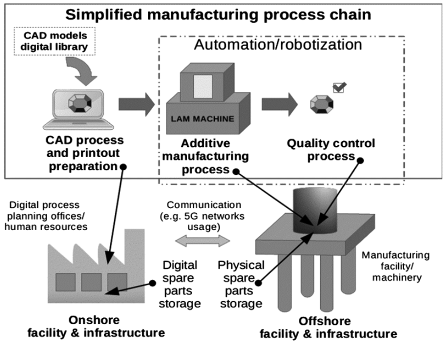


**Fig. 2.** On-site implementation of ALM.

This paper focuses on investigating how the petroleum industry should plan for the widespread adaptation of ALM, focusing on spare parts. In this context, it discusses whether to go for in-house manufacturing or to outsource it to ALM service providers, as well as examining the impact of ALM on the traditional supply chains vs. the potential for having digital and/or more refined supply chains. It also proposes a framework to reinforce decision-making related to the use of ALM in the petroleum industry.

## 2 Challenges Facing Application of ALM in Petroleum Industry

It is a significant challenge to manage all assets effectively in a predictive manner within the petroleum (i.e. oil and gas), power, energy and process industries, including utilities, petrochemicals and metals and mining [7]. A recent survey reveals that, out of 83 respondents, 53% report that it is necessary to reduce operational expenses and 40% state that dealing with ageing assets and infrastructures poses a challenge [7]. The aforementioned survey also reveals that it is important to invest in technology to enhance the management of maintenance projects [7].

The primary objective of a maintenance project is to enhance asset reliability and performance and to minimize the non-productive downtime. In this context, project performance plays a key role, as better project performance reduces the duration of the shutdown of equipment for complex and routine work [7]. It has also been revealed that there is a 6% increase in the shutdown duration in complex maintenance projects, whilst budgetary restrictions prevent asset owners spending on the upgrade or repair/replacement of equipment. The situation has been further exacerbated in the context of maintaining ageing equipment.

In particular, the parts related to legacy assets cause a significant challenge when the manufacturers are no longer in business. In this context, ALM offers the opportunity to print parts that are required to maintain and/or replace equipment as it becomes legacy [8]. Furthermore, the inherent characteristics of ALM provide significant benefits to the petroleum industry, especially when it is necessary to manufacture complex parts that use expensive materials and are required to be made in small batch sizes [8]. Moreover, ALM has an interesting potential for the offshore petroleum industry, as it can mitigate some of the challenges pertaining to the remoteness of offshore from machine shops and skilled labor. For instance, one of the long-term holy grails of ALM is the potential to manufacture parts on site as needed, instead of having to order and wait for delivery when equipment breaks, and spare parts are not available (refer to Fig. 2).

Spare part management and holding inventory increase operational expenses; as 3DP/ALM requires no complex tooling, it is possible to bring the manufacturing nearer to the ultimate consumer, something which is referred to as ‘distributed manufacture’ (i.e. “migration of manufacturing from the centralized factory to more localized distributed factories”) [9]. Moreover, 3DP/ALM reduces many stages of the traditional supply chain, making it leaner via a reduction in the need for haulage, warehousing, logistics and unnecessary expenses on disposable packaging [9].

## 3 ALM: Offshore Petroleum Industry Opportunities

Table 1 illustrates the pros and cons of ALM in industrial applications [9, 10].

**Table 1.** Pros and cons of ALM.

| Pros | Cons |
|---|---|
| **Economical product customization:**<br>• Permits cost-effective production of very small batches<br>• Allows every single product to be tailor-made to the customer's exacting specifications (i.e. significantly difficult with traditional production processes, as it is necessary to have expensive tooling and molds, whilst redesign becomes expensive) | **Limited product dimensions:**<br>• Limits the maximum dimensions of the final product due to relatively small 3D print bed sizes<br>• Need to manufacture large products by other technologies |
| **Freedom of design:**<br>• Allows for freedom of design because standard CAD software can be used to design and redesign products<br>• Allows a CAD model to be printed directly into a physical part, whilst allowing redesigns to be implemented with ease<br>• Permits designs to be created by anyone skilled in computer-aided design | **Reduced choice of materials:**<br>• The limited number of raw materials that can be used for 3D printing limits the choice of materials, colors, and surface finish, compared to subtractive technologies |
| **Complex product manufacturing:**<br>• Enables relatively easy manufacturing of products that were hard or even impossible to produce in the traditional way<br>• Allows printing complex products as a single entity at once, resulting not only in less waste and in lighter products but also in time savings with improved performance<br>• Reduces overall manufacturing time for complex products, due to the ability to consolidate several machining steps into a single manufacturing step | **Lower accuracy level:**<br>• 3DP/ALM technologies have not yet reached the same level of parts' accuracy associated with other technologies |
| **Decentralized manufacturing:**<br>• Allows the products designed in standard CAD software environments to be produced anywhere around the world, provided that compatible 3D printers are available (AM-platform, 2014)<br>• Brings the manufacturing process physically closer to clients, as 3D printers are spreading around the world<br>• Reduces time-to-market and/or lead times, as it is possible to outsource manufacturing for globally dispersed 3-D printing service providers | **Limited strength:**<br>• Due to the layered additive process, products have limited strength, restrained resistance to heat and moisture, and compromised color stability |

In the petroleum industry, there are unique challenges, especially in relation to maintenance and spare parts' management. Figure 3 illustrates different aspects of spare parts in relation to ALM and the corresponding pros and cons.

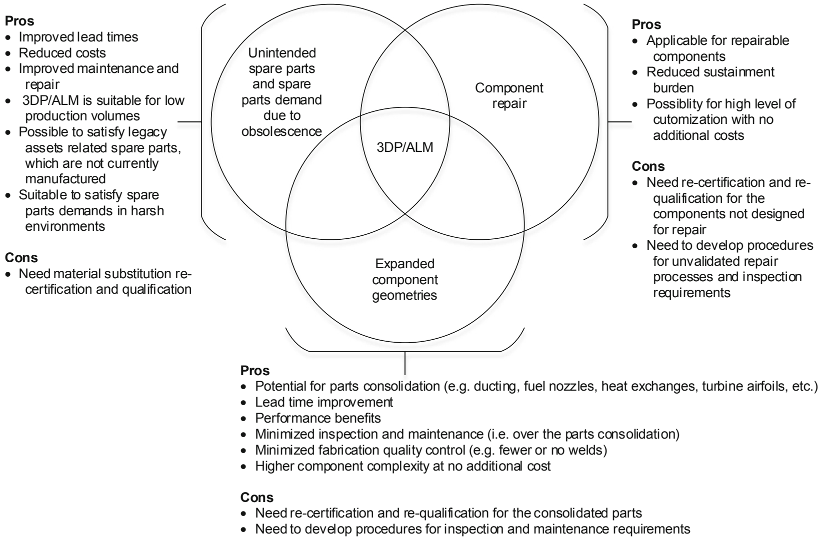


**Fig. 3.** ALM vs. maintenance and spare parts.

Besides maintenance and spare parts' management challenges, another significant challenge is the dearth of additive manufacturing standards, due to which companies conduct their own testing to ensure the integrity of equipment, processes and products [4]. Costly and time-consuming testing deters the wider application of additive manufacturing, underscoring the need to develop standards from design to part build to operation. Hence, one of the most serious hurdles to the broad adoption of additive manufacturing of materials in the petroleum industry is the qualification and certification guidelines for additively manufactured parts. Some of the challenges related to qualification and certification of ALM processes and components are [4]:

- There is a lack of information related to material properties, and we have much less experience and scientific knowledge of ALM processes than of conventional manufacturing.
- Risk assessment based on the statistics of large-volume history data does not apply to ALM production as it does for conventional manufacturing.
- The ALM process has a more disintegrated processing route, compared to conventional manufacturing. Hence, a global traceability solution, enclosing multiple ALM and supply chain locations, will be needed more than ever.
- Secrecy about technology and software/algorithm sources is an obstacle. Since software plays an important role in product quality, it is a subject of concern for certification.

- Directionality and heterogeneity of ALM products can bring challenges for certification and testing.
- Lack of product reproducibility and uncertainty of quality control still exist.

## 4 ALM vs. Technology Qualification

The renewal and/or extension of existing technologies and the ability to take advantage of new technologies play a major role in remaining competitive and improving system efficiencies in the petroleum industry [11, 12]. In this context, it is a challenging task to confirm that new technological solutions are fit for purpose and that a system will perform as intended during its service life without potential failures [13]. In such situations, the concept of technology qualification identifies opportunities to improve system design, minimize schedule risk, reduce cost risks during operations by reducing uncertainties and increasing reliability, and identify failure modes and necessary design changes at an early stage [14–16]. Therefore, it is of prime importance to implement a technology qualification process when there is: limited experience about new technology; limited records of accomplishment of novel technologies; absence of classification rules, statutory requirements and industrial standards; and challenges with new and harsh environments [14, 16]. The core idea of the technology qualification process is to identify potential failure modes and the risk of potential failures at an early stage, prior to utilizing a new technology. Hence, it is possible to use recommended practice – DNV-RP-A203 – for qualifying ALM applications in the petroleum industry [15, 17].

## 5 Framework for Petroleum Industry: A Digital Spare Parts Library

The competitiveness of the petroleum industry is directly or indirectly affected by the productivity of the maintenance strategy that has been employed. In this context, having a preventive maintenance program (PM) is vital to minimize major repairs and abrupt stoppages of production and to sustain the continuous workflow [18]. Spare parts play a significant role in implementing a PM program, and the previous sections in this manuscript have revealed that ALM has a higher potential to cater for spare-parts-related challenges. However, it is also essential to investigate the manufacturing operational challenges such as ‘parameter design’ [19]. In this context, the ‘parameter design’ involves investigating the optimal parameter combination that provides the required output performance in the ALM process. The aforementioned is crucial for ALM, due to its inherent suitability, such as the manufacturing of complex parts that use expensive materials with small batch sizes together with a high level of customization. It is impossible for the ALM machine manufacturer to develop a user manual, which caters for different product manufacturing demands. For instance, [20] demonstrated an investigation of the process parameter effects on the dimensional accuracy of parts produced by the Polyjet Direct 3D printing process. Hence, it is possible to use an engineering robust design approach, as indicated in [19], for

3DP/ALM ‘parameter design’, in order to align with lean manufacturing philosophies (i.e. minimization of waste in relation to time and other resources). It is possible to make the transition from a physical spare parts inventory to a digital spare parts library with 3DP/ALM capabilities [17]. In this context, it is vital to develop a group technology (GT) based coding system to retrieve spare-parts-related information from a digital library for performing ALM work *just-in-time* [18, 20, 21]. Figure 4 illustrates an architecture for a spare parts library, focusing on ‘prioritization of spare parts’, ‘parameter designing’, and ‘group technology’ (GT), for effective exploitation of ALM in the petroleum industry.

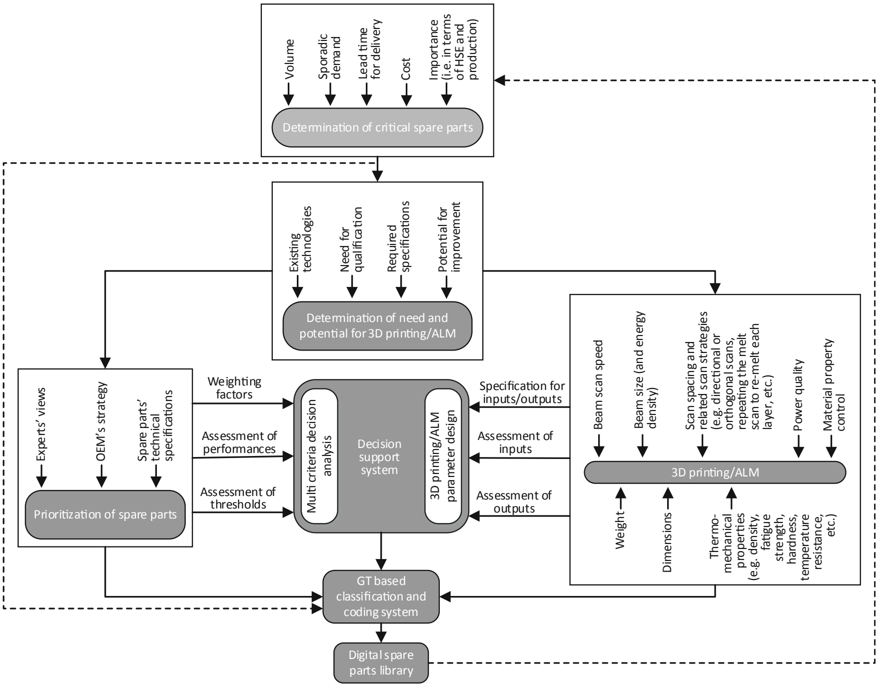


**Fig. 4.** Architecture for digital spare parts library.

For instance, [18] have proposed a GT-based approach to optimize the inventory of spare parts, using a “failure similarity coefficient (FSC)”, which “defines the relationship between pairs of equipment/machines with respect to their needs for PM based on the type of failures they encounter”. In addition, [21] demonstrated the use of GT-based classification and grouping according to the principle and structure of the new equipment and new spare parts. Moreover, [22] have demonstrated the use of the “Vector Perturbation Approach” for addressing the aircraft spare parts’ grouping problem.

## 6 Conclusion

The study presented in this manuscript has demonstrated the role of ALM and its potential for use in the offshore petroleum industry. It showed the importance of the development of three areas: 3D printers and printing methods, materials for ALM, and software for product design and print. It also presented the need to invest in technologies to better manage maintenance projects and the role of ageing equipment (requiring additional maintenance). In addition, it explained how ALM fits within advanced manufacturing performance, as well as focusing on mitigating maintenance and spare parts' challenges. Furthermore, the potential use of a technology qualification process for assuring the use of additive layer manufactured parts has been explained. Finally, it proposed an architecture for a 'spare parts library', demonstrating the interrelationship among: 'determination of critical spare parts', 'prioritization of spare parts', 'parameters involved in 3DP/ALM', 'determination of need and potential for 3DP/ALM', 'GT-based classification and coding system', and 'multi-criteria analysis for decision-making accompanied by parameter design' for enhancing the potential use of ALM in the petroleum industry.

Future research shall be carried out to investigate the effective use of risk-based prioritization of spare parts, accompanied by artificial intelligence/machine learning supported group technology, focusing on developing methodologies for effective parameter designing, to enhance the use of ALM, mitigating spare-parts-related challenges.

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# IPD Methodology in Shipbuilding

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**Abstract.** This paper proposes an Integrated Project Delivery methodology in shipbuilding from the perspective of design function, to validate with limited design knowledge whether the project can satisfy unified project goals. This is achieved by aligning real-time information flow with the design development process. The methodology is built on a systematic, multidisciplinary theoretical analysis and triangulation of methods and principles from ship design, lean construction, the collaborative BIM software, and multi-stage thinking from decision theory.

**Keywords:** Integrated Project Delivery · Ship design · Design uncertainty · Lean construction

## 1 Problem Description

This paper considers engineer-to-order (ETO) shipbuilding, where the project delivery complexity is defined by frequent design changes throughout the project execution, and concurrent activities to reduce time to market [14]. This is leading to continuous disturbances and updates, altering activities to be performed and their sequencing, not only changing the duration of predefined activities [27]. Traditional project risk management approaches with disconnected functions, and buffering around statistically describable uncertainty under fixed design [18, 19], often fail in this context [2,27]. The implication of disconnected design and planning functions is that of design information fragmentation. This is leading to frequent changes in technical specifications, schedules that fail to consider the design uncertainty [13], and potentially complex and costly updates throughout the project delivery [27].

With many projects characterized by high and difficult to quantify levels of uncertainty, and model based planning that fails to adequately handle the complexity [2,8,24], new approaches to project delivery, building on collaborative processes, are emerging. One is Integrated Project Delivery (IPD), a relational contracting approach that early aligns project objectives with the interest of key stakeholders through shared risk and reward [3]. The aim of IPD is to


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achieve team integration in order to improve procurement and the project delivery process [22], and to overcome problems caused by information fragmentation. IPD creates an organization able to apply the principles of lean project delivery [20], arguing for project phases being intertwined by a common cause, and not separable as commonly done in traditional approaches. Lean project delivery aims to effectively involve downstream stakeholders in front-end loading (or pre-project planning), through cross functional teams, to e.g. pursue objectives that may change during the course of the project, and to integrate this knowledge into plans and strategies [4,6]. Construction Industry Institute defines front-end loading as the process of developing sufficient strategic information with which stakeholders can address risk and make decisions in order to maximize the potential for project success [12]. Front-end loading may add a certain amount of time and cost to the early project phases, but reduces the impact of disturbances.

While the number of professionals supporting the advancement of IPD is increasing [3], the number of projects using IPD is limited [7]. There are several reasons to this. Stakeholders' hesitation to share key technical and market information is one reason. A second is that, to fully leverage on the benefits of integrated approaches, a collaboration and information sharing solution is needed, such as Building Information Modelling (BIM) [3]. BIM is a digital model of construction bringing design activities closer to the customer and production, serving as a collaboration platform across stakeholders and disciplines, allowing full information transparency [22], and assisting the management of construction projects [10]. The integration of lean principles with BIM functionalities (like 4D scheduling into the Last Planner System of planning and control to enhance workflow reliability [9]), enables cost effective exploration of alternative design and construction models in early project phases. When IPD and BIM are used in conjunction, the expectations for the project to be completed successfully are increased [16]. BIM requires software interoperability [15], which is a challenge in shipbuilding due to the many heterogeneous applications in use, along the dynamics and adaptability needed to operate in this sector [1]. A third reason is related to enabling a collaborative design and planning process to prove (or disprove), with limited design knowledge, whether the project can satisfy unified cost, time and risk requirements [17]. A such validation process requires allowing multiple values of design parameters, that are selected or down-selected at key decisions points. One example is the Toyota set-based development approach [26], which differs from point-based design where decisions are iterated and modified over a fixed design. See [25] for the difference between point-based and set-base design. While the value of such real options is recognized, it is less clear how to operationalize them in planning and project delivery. Lean construction has justified its implementation by significant improvements in time, cost and quality estimates, and its organizational integration approaches help identifying how to structure to project delivery to make it more flexible [4,23]. But its Last Planner System has not explicitly addressed options for flexibility [5], apart from advising that master control schedules are kept at the level of milestones between project phases, and planning in greater detail as time for execution approaches [4]. This may explain why projects in dynamically changing environments struggle with lean and IPD customization to their uncertain context.

Given the quantified impact of design changes on project performance [27], and the third challenge for IPD implementation listed above, this paper addresses the following research question: *How to achieve a collaborative design and planning process under limited design information to enable IPD in shipbuilding, and to enable late changes with least disturbance.*

The research approach is briefly described in Sect. 2, the IPD methodology and exemplification of concepts in Sect. 3, and conclusion in Sect. 4.

## 2 Research Approach

The research is built on a systematic, theoretical analysis and triangulation of methods applied to the design and development of uncertain project, *and* an active engagement in the shipbuilding industry in Norway with interview based studies. The methodology offers the theoretical understanding for the choice of methods and best practices that can be applied to the shipbuilding case. While particular methods are industry specific, the developments apply to ETO projects at large. The research is multidisciplinary, building on principles from ship design, lean project management, multistage thinking from decision theory, and collaborative BIM principles.

## 3 IPD Methodology—A Design Planning Perspective

This section describes the IPD methodology to enable a collaborative design and planning process under limited design information. This is done by aligning the design model development and validation process to real-time information throughout the project delivery. The validation process builds on a unified project value – the owner's business case within the stakeholders' allowable time, cost and quality constraints, and within acceptable level of risk–, and requires a systems-oriented design workflow, where all aspects of the project lifecycle are embedded into design management. This calls for a shift in ship design, from that of the sole domain of naval architects and design engineers, to incorporate stakeholders into pre-planning, before the commencement of design.

For integration and validation under limited design, we triangulate lean concepts and the LPS terminology of [4] "should-can-will-did" with multi-stage thinking in decision theory, to address the following elements in front-end planning:

– Design information fragmentation and the minimal information needed to make design and planning decisions at important points in the project delivery. This refers to what information 'should' be enabled and when.
– Stakeholder capabilities to deliver requested minimal information. This is related to what 'can' we have as compared to 'should'.

– A collaborative design planning and project delivery process that is aligned with 'should' and 'can', and enables design updates with least disturbance. This is connected to the design management and build strategy, i.e., the commitment of what 'will' be done.

### 3.1 Design Information Fragmentation

Knowledge on the minimal information needed to make or update design decisions at important milestones is developed by applying the *Level of Details (LoD)* concept, adopted from the EUBIM Task Group [15] to the *SFI coding and classification system for the maritime industry* [21].

The LoD concept, building on design engineering and implementation constraints and advanced simulation of design variance, establishes a non-static design boundary, used for the assessment of design quality and maturity, information availability and accessibility of critical components at key phases.

The SFI system provides a functional subdivision of technical and financial ship information, progressively detailed through subdivisions.

The combined LoD-SFI concept provides planners with necessary knowledge on what level of information (we call it minimal information) is needed for a 3D, 4D or 5D model of the vessel to satisfy unified project goals. The concept is exemplified by Fig. 1 for a simple case of cargo space development on a cruise vessel, with hull structure, hull materials and high grade steel decisions. The dotted lines represent alternative design paths (i.e., the solution space) at concept-, basic- and detail design phases. The SFI technical and financial components where alternatives are allowed are concretized.

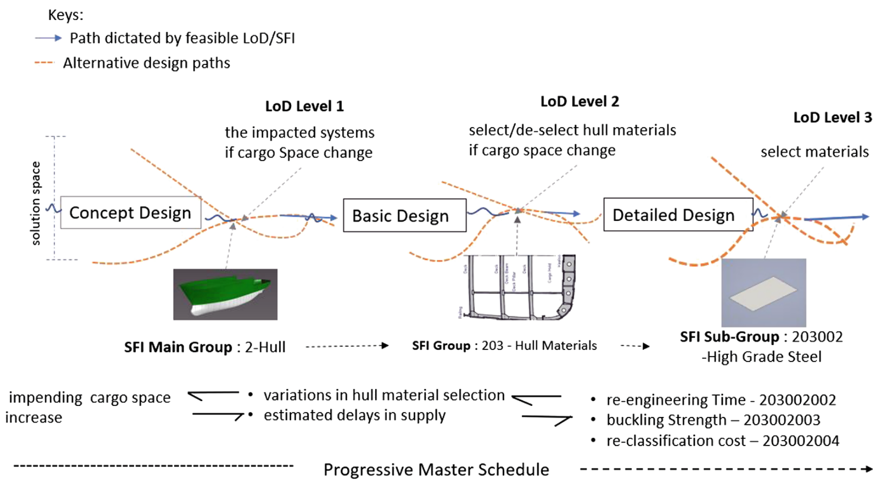


**Fig. 1.** LoD-SFI embedded project timeline

### 3.2 The Design Model Development and Validation Process

To ensure the collaborative project validation process under limited design information, the project control workflow on Fig. 2 is developed. This is illustrated for the concept phase, and to be replicated for subsequent phases.

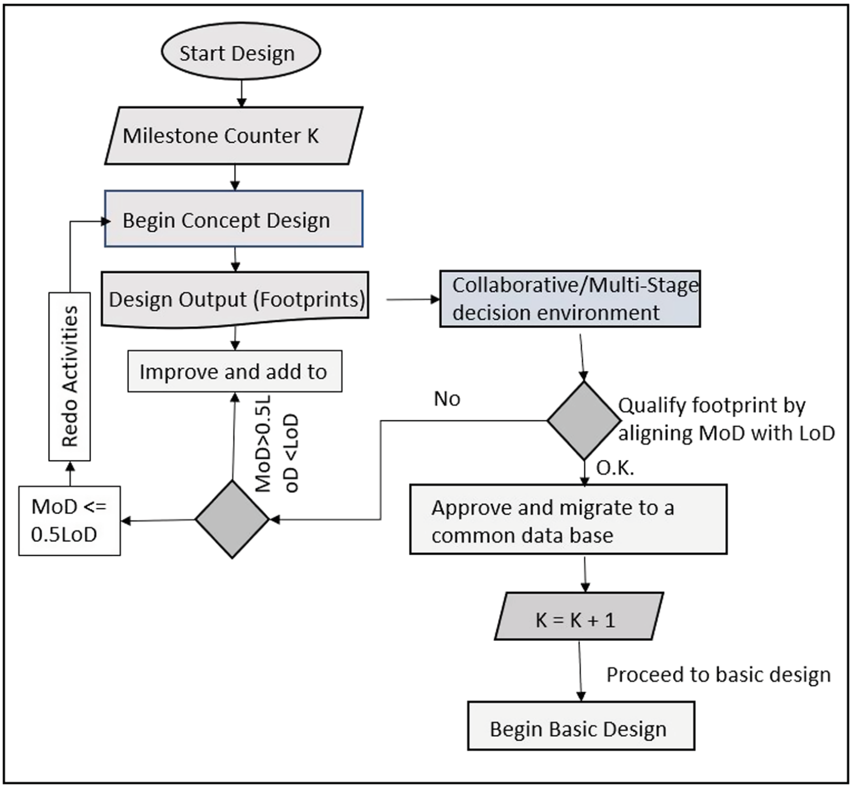


**Fig. 2.** IPD collaborative design workflow

In this process, the design task begins and concept design commences. The combined LoD-SFI concept drives the minimal information to be requested for validation. The collaborative design workflow enables comparing and validating the design model maturity (call it MoD) against the pre-established LoD information (as illustrated on Fig. 1). For comparability of MoD to LoD we apply a 0–1 scale, where: Value 1 reflects full alignment of model maturity to what is expected; Values between 0–0.5 suggest a low level of alignment, where major revisions in project goals and/or alternative design solutions are needed; Values between 0.5–0.99 suggest partial alignment where multiple design alternatives are to be managed simultaneously. As the project progresses, the design management process is increasingly difficult as more subsystems and their interdependencies must be addressed simultaneously.

The control flow dictates decision-making based on real time information, and facilitates collaboration for a multi-layer validation process. If the design model outputs, after evaluation, do not support the information flow from the client and main stakeholders, decision makers revert to initial condition (concept design here). This ensures that only value-generating work is accepted.

### 3.3 Variation-Order Control

To effectively manage design changes, a responsive plan is needed, i.e. a proactive approach where alternative designs can be selected/down-selected based on real-time information. To identify points in time and activities where alternatives are needed, a front-end uncertainty assessment is required. With the difficulties to predict changes in advanced shipbuilding (often on the edge of known technology), a front-end assessment of change probabilities has limited value. An alternative approach is to assess the impact of potential changes on the system, disregard the probability of occurrence. This mitigates the need to deal with probabilities.

For the scope of this research, the impact and criticality of activities is assessed as follows. In first step, the *Design Structural Matrix* [11] is applied to the *SFI system of coding for ships* [21], to identify interdependencies and influences between SFI subsystems. In second step, *lifecycle* costing of these interdependent systems is performed. By exposing the criticality of activities from a system perspective, this approach serves as decision support to identify places in the design process where the limited uncertainty management resources are to be focused. For example, by keeping the design solution space open and allowing multiple parameter values. Advanced simulation, such as the virtual twin technology, allows to further explore these concepts, by varying parameter values and identifying alternative design alternatives and implementation paths. Because of space limitation, we omit the exemplification of this concept.

## 4 Conclusion

High design uncertainty in ETO projects triggers a move away from traditional point-based design, with selection of a final alternative as soon as possible, to strategies that consider multiple alternative designs in parallel and postpone the choice of a final alternative to as late as possible. The proposed collaborative methodology aims to enable project validation under limited design knowledge, by delaying design decisions and managing alternatives in parallel throughout the shipbuilding project delivery. The paper addresses neither the costs of design changes throughout the project, nor the quantified benefit of options to effectively handle these. For that we refer to existing literature.

The proposed IPD methodology incorporates concepts from lean project delivery, Building Information Modelling and multi-stage decision making (with stages defined by feasibility and information availability), into the ship design process.

While the developed concepts are demonstrated by small examples, future large-scale implementation is needed for further validation. This opens up for a discussion on both the software maturity within naval architecture, where traditional approaches are still dominating, and on the organizational and behavioural prerequisites to enable a collaborative design and project development culture.

The contribution of this paper is placed within a wider context of management of project uncertainty.

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# Changing Markets: Implications for the Planning Process in ETO Companies

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**Abstract.** This article focuses on project planning within an ETO context using shipbuilding as an empirical case. The aim of the research is to understand how a change in market from offshore to cruise affect the planning processes. The article adopts qualitative methods to understand the involved actors strategies and choices to execute a new type of build. The research shows how long-terms association with one market, caused a certain flow of work. This allowed the involved actors to rely on routine activities, which made the actual process of planning fade into the background. A new market comes with new challenges and demands, which disrupted this workflow. The article analyses what caused the lack of focus on planning and its consequences. It argues for a danger of companies confusing structure with content, and calls attention to the importance of the context of planning. In this case, the context of market.

**Keywords:** Project planning · ETO · Market change

## 1 Introduction

In a recent research project studying the planning process in Engineer-To-Order (ETO) companies, an interesting observation surfaced during a discussion at a shipbuilding company. One of the participants stated that some years ago, they had invested significant resources in establishing structures to ensure a good planning process, but these seemed to have deteriorated with time. In the following discussion, the participants seemed to agree this was related to a long-term commitment on building ships for one specific market. This approach resulted in developing a certain flow in their work processes, which made the planning process fade into the background. Faced with a new market situation, the company acknowledged that the project planning process seemed poorer and a different focus was necessary if they were to achieve better project management and control. The situation is not unique for this company since many other similar shipbuilders encounter a shift towards other market segments. Following this observation, the main research question in this study is: How does market changes affect the planning process in an ETO environment?

The industrial context of this study is shipbuilding, an industry characterised by ETO strategies. Since the 90's, many Norwegian shipbuilding companies have been focused on delivering offshore-specialized vessels (OSV) dedicated to activities within


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the oil industry. However, low oil prices during the last few years led many shipbuilding companies to adapt to producing new types of vessels, mainly for the cruise market. The significance of this change to new markets, that this research focuses on, is illustrated in Fig. 1, [1] that depicts the types of vessels produced by three of the main Norwegian shipbuilding companies between 2010–2016. Out of 160 vessels produced in that period, none of them was a cruise ship or related to the cruise market. The area that is developing fast nowadays is the market for smaller cruise ships that could sail in more demanding environments (e.g. arctic waters). Since these vessels are comparable in size and tonnage with some of the OSVs, most OSV shipbuilders decided to enter the cruise vessels market.

| | Yearly number of ships delivered | | Ship types | | | |
|---|---|---|---|---|---|---|
| Yard | 2010-2016 | Total | PSVs | AHTSs | Other OSVs[1] | Other types[2] |
| A1 | 3; 2; 4; 2; 3; 1; 3 | 18 | 10 | 4 | 3 | 1 |
| A2 | 2; 1; 2; 5; 4; 0; 2 | 16 | 1 | 3 | 8 | 4 |
| A3 | 4; 4; 3; 4; 4; 1; 0 | 20 | 18 | 0 | 2 | 0 |
| A4 | 1; 3; 5; 3; 3; 3; 1 | 19 | 7 | 8 | 4 | 0 |
| A5 | 4; 3; 3; 4; 1; 1; 2 | 18 | 8 | 1 | 7 | 2 |
| B | 2; 4; 4; 5; 2; 3; 2 | 22 | 12 | 1 | 8 | 1 |
| C1 | 5; 4; 5; 5; 5; 5; 3 | 32 | 11 | 6 | 13 | 2 |
| C2 | 4; 2; 2; 1; 3; 2; 1 | 15 | 5 | 2 | 5 | 3 |
| Total | 25; 23; 28; 29; 25; 16; 14 | 160 | 72 | 25 | 50 | 13 |

PSV, platform supply vessel; AHTS, anchor handling tug supply vessel.

[1]Other OSVs include offshore construction vessels, seismic research vessels, subsea construction vessels, diving support vessels, pipe layers, and cable layers.

[2]Other types include windmill support vessels, fishing vessels, yachts, and naval ships.

[3]In this case, gross tonnage is used as a differentiator, because the compensated gross tonnage factors are not very robust for OSVs.

**Fig. 1.** Types of vessels delivered from 2010 to 2016 [1]

Embarking on such restructuring demands a new type of thinking. While this presents a challenge, some key defining features of the industry speaks positively to their ability to make this transition. According to [1], among this industry's strengths are: (1) Norwegian shipbuilding companies are effectively organized and have long traditions in producing advanced vessels. (2) They count on skilled and multidisciplinary workforce that build its knowledge and experience through generations of seafaring and craftsmanship. (3) Flat and informal organizational structures with short distances between workers and managers, as well high worker autonomy.

A significant change from OSV projects to the cruise market is the primary focus within our project. In most OSV projects, the customers concern with details principally focused on the technical capabilities of the components installed on the vessel. Here the shipbuilders have a certain slack within the decision process. On the cruise projects, the technical part is expected to hold a certain standard, but the focus in the dialog with the shipyard is on the details of the interior, a vital element for customers' competitive edge on this market. This change in focus represents a change concerning which areas of the building process yards are allowed some (if any) slack. The new situation potentially redefines work processes and provides new coordination challenges. These changes are necessary to see in relation to the ETO context. In [2], ETO is defined as a production approach where each customer requires significant changes to the fit, form and function of the product so that it meets a specific purpose. This causes a potentially high level of variability from project to project even if, at the surface level, products might seem similar to one another [3]. It is necessary to understand how project planning changes with a shift in market in an ETO context.

## 2 Theoretical Background

ETO companies deliver complex multilevel products that often contain parts that are engineered to order [4] challenging the process of delivering exactly the required product. The demand for customized products is increasing and that results in a growing number of ETO companies [5]. Yet, development of theories or paradigms is slower and according to [6], there is a lack of research devoted to this environment. This statement is reinforced by [7], who revealed that literature on product development has been published for decades, while the majority of ETO literature has been published within the last ten years. Thus, our study aims to contribute to the existing literature on ETO and management of such challenging projects.

ETO products are delivered through a project-based approach where planning is an essential activity and most teams apply management ideas from the project management literature. Planning is the process of defining goals and establishing the procedures to accomplish them and becomes effective only when it is intertwined with the process of controlling activity execution [8]. Even though most project managers agree that planning is important for a successful project, the process of planning a is not really understood [9]. According to [10] there are several major flaws of project planning: **Focus** (scheduling is overemphasized while planning process is neglected). **Role** (control overshadows action planning). **Process** (proper decision-making gets all the attention, while the necessary steps prior to the following it are ignored).

In [10] the conclusion is that such traditional project planning approach results in a situation where "*instead of the advanced formal planning setting the course of action, it is its execution that shapes the so called formal plan"* (p. 263) [10]. Furthermore, the PMBOK®[1], state that the project team should take into consideration the contextual perspective of each project (cultural, social, political, etc.), however, most of the project management literature rarely discuss the project context, or how to act, react or interact within different contexts [11]. Hence, a more effective planning process needs a change in methods, modified strategies, expectations should be adjusted (e.g. attitude to uncertainty) and the overall philosophy of project management should be reconsidered [10]. Through focusing on market shifts, this study will contribute to this call for increased attention to context.

To deal with challenges within the planning process, lean construction community developed a planning tool called Last Planner System (LPS®) that recommends four

[1] Project Management Body of Knowledge – the guide published by Project Management Institute.

planning levels that would function as an arena for communication between project participants [12]. The first planning level is the master plan containing milestones and phase durations. The next level is phase scheduling where activities form the previous level become more detailed showing conditions of satisfaction between processes within phases. The third level is the lookahead plan which role is to identify and remove, five to eight weeks in advance, eventual activity constraints so each activities can be completed as planned. The fourth level is week plan where activities are quite detailed and project teams make reliable promises and make sure that activities to be completed in the following two weeks are not constrained. Eventual constraints are dealt with during weekly meetings and measures are taken to solve the problem as soon as possible, and teams affected by delays get the information on time [13].

LPS® has been implemented in many types of project-based industries including shipbuilding. Several Norwegian companies report different approaches to its implementation: some developed a three level plan, others developed only two levels, while a third type used all four recommended levels. However, the main idea is that all these companies use LPS® as a tool to inform project teams about the status of the project activities. While the LPS® recommend a certain planning structure, the issue addressed in the beginning of this paper, turns the attention once again to the importance of context. As a company shifts from one market to another, it might be necessary to make significant changes in regards to the content of this structure (hence, what is focused on). This article aims to contribute to the LPS® literature by drawing attention to the danger of companies confusing planning structure with planning content.

## 3 Case Company

During the years producing OSVs, most shipbuilders focused on developing and implementing improvements for many of their working processes with a scope to reduce lead time and total cost of their products. One of these processes was the planning approach to such projects. Our case company designs and builds several types of highly customized vessels for both OSV, fishing, cruise markets, etc. About ten years ago, the company introduced parts of LPS® concept and developed an own structure of their planning process. They adopted four planning levels: project-, lookahead- and week plans, and then assigned a specific type of planning meeting to address each of these levels, that respectively provides information to a certain planning level.

The first level was the project plan meeting where the project manager, dedicated coordinators (purchasing, technical, production) and project planner discussed issues regarding the project status and identified solutions for some of the problems at management level. In addition, some of the key sub-contractors were invited when relevant. The second level was a lookahead planning meeting where discipline coordinators from several technical and production specializations as well as some of the most relevant sub-contractors discussed project issues that needed solutions at this level. The third level was production meetings where own and sub-contractors' team leaders from all disciplines (steel, welding, machinery, etc.) discussed production issues.

These planning structures worked quite well for our case company while producing OSVs. Both central management and head of planning were confident in their ability to use such planning structures as a good tool to ensure flow in the work process. Project teams developed a good understanding of their roles and attributes. Coordination of these projects was based on trust and a certain slack within the decision process. A consequence of the positive flow of coordinating these activities was that meeting facilitators seemed to gradually lose focus on the planning aspect, as things were working quite well. It became a background activity performed mostly by the planners. Case in point was the decision to move the planning manager to another department during a fall in the market. This fall led also to layoffs and contract termination for own employees and some of the sub-contractors.

When the company decided to produce vessels for the cruise market, they assumed that most planning structures would remain more or less the same and little attention was given to the processes needed to make them work. All three meetings were now focused more on firefighting and solving problems that the project team was not prepared for. The activities listed in the plan were largely according to the intended meetings in terms of timespan. Yet, in the discussion about coordination issues, activities had to be delayed or even done earlier and people often changed dates in the plan from a qualified guess, which they were prepared to change again if necessary, rather than a real root cause analysis of the situation. Thus, addressing the coming weeks' activities, particularly long-term, was seldom discussed at these meetings. The participants seemed well oriented about each other's activities, and it was clearly a good information flow in the project. The problem was that the plan seemed to stop being most relevant point of reference to know what needed to be done and when. No one seemed to expect that the dates in the plan were accurate and seemed to think that the necessary adjustments were more important to do elsewhere. This lack of confidence in the plan become a self-fulfilling prophecy that can also explain why these meetings turned into an arena for day-to-day coordination more than planning meetings.

When presented with these reflections, the company commented that they appeared to have lost focus on the planning process. A key reason was the previously mentioned slack that had been developed because of similarities between previous projects. Another reason, was that layoffs and retirements in the same period meant that many of the key personnel involved in the work of putting planning on the improvement agenda was gone. Thus, they questioned if this meant that the current project organization did have the same understanding of the philosophy behind the structure of the planning meeting. Although this is a single case study, [14] argues this can be the start of a multiple-case study and in our research we intend to develop a more comprehensive analysis on how similar product categories can affect the planning processes within ETO environment.

## 4 Methodology

The aim of this study is to understand how change in market affect project planning in ETO companies. Qualitative methods are thus best suited, as we need in-depth understanding of the involved actors strategies and choices [14]. The data material consist of data from document analysis and 22 semi-structured interviews with relevant representatives from the case company and its subcontractors. Moreover, the researchers have conducted participant observation of seven project planning meetings at all the levels presented above. The selection of candidates for the interviews has carefully considered different roles and disciplines involved in the project to ensure a complementary picture of the process of building the ship. A snowball method for data gathering has been adopted. Initially, a list of relevant interviewees where drafted. Additional people have been recruited, made relevant from topics that came up in the interviews or through suggestions from the interviewees. Moreover, preliminary findings were discussed with the project steering group on three occasions. The group consist of relevant management from technical, sales and production departments, a key sub-contractor and representatives from two research institutions. Discussing the preliminary findings with this group have further enhanced our understanding of the addressed issues.

## 5 Findings

During the interviews done for our research project, one common theme resurface continuously: known, well established processes and procedures are affected by the change of the market. The problem amplified because of the flow that have developed in the work processes and made the company lose track of the planning part of their planning structures. Since this was working, it seems reasonable to assume that these meetings slowly were redefining into long-term and short-term coordination meetings. Thus, the company failed to reassess the current planning process suitability for a new market. There were several signals that necessary adjustments were called for.

OSVs were relatively easier to produce while cruise vessels demand a very different type of thinking that most employees were not aware off. The three types of structures for project meetings functioned well due to aspects like: (1) Project teams have established a mutual understanding of the activities to be executed and everybody knew when these could be done. (2) Customers trusted shipyards' expertize and that resulted in a certain amount of slack in regards to the decision process. (3) Most of the sub-contractors have developed long-term relationships with the shipyard and that contributed to a good understanding of the flow within the shipbuilding process. (4) Planning was performed by the shipyard in collaboration with the most relevant sub-contractors. Consequently, they achieve a certain level of trust where problems were solved "on the floor" by people involved in the project. Planning meetings were an arena for discussing activities for the next period and measures needed to solved eventual problems. (5) Most coordinators were employees with experience and they were part of the team who developed the three planning structures.

When changing the type of market, the company observed that the three planning structures were challenged in an unexpected way. Among the reasons could be: (1) Activities within cruise projects were much more detailed and the main focus was on the accommodation part as oppose to the technical part as with OSV projects. Thus, the mutual understanding of project activities was challenged and needed a total review. (2) Customers buying cruise vessels have a different approach to collaboration and project management. Because most of these customers have never built vessels with these shipbuilders, there is a lack of trust that can only be built over several projects. Consequently, most decisions are discussed at several levels affecting the execution of the planned activities. (3) Many of the sub-contractors used in OSV projects are not prepared to deliver in cruise projects. This implies that the shipyard had to find new sub-contractors meaning that the mutual understanding of the project problems was no longer existing. Moreover, some of these sub-contractors gain more negotiating power if the customer imposed them to the shipyard. (4) Planning was performed by the shipyard, however, through a different collaboration with sub-contractors. More focus on contractual issues between the parts resulted in a different collaborating frame. Planning meetings were no longer an arena for preparing the next period activities, but a place to discuss most demanding issues. (5) New coordinators did not get enough training in leading these meetings and even though the old planning structures are still used, their focus is no longer the same.

This article started initially with the observation that a good flow in the work process had caused a lack of focus on the planning process. By good flow, we here refer to a tacit coordination of work tasks, where participants know what to do, and what others are meant to do, as a result of having worked together on several similar projects. In our case, the argument can be made that good flow shifts the understanding of such meetings from planning to short- and long-term coordination. This becomes problematic because one can lose sight of the strategic potential of evaluation planning structure when the context of work changes. The situation shed light on a real dilemma: good planning can be a very important requisite to facilitate good workflow, but when one achieves good workflow, it can become harder to keep focus on the importance of the content of planning.

## 6 Discussion

The case presented here is another confirmation of the need for more effective planning methods as argued by [10] and to adapt project management approach to the context of the project as argued by [11]. It also sheds light on the fact that planning needs to take into consideration the relationship between the work processes that have changed from one type of project to another while the structure remained the same. One might think that using the same employees and the same type of thinking, the planning process can be performed in the same way.

The purpose of this paper is twofolded and brings to attention the importance of adapting the planning process to the context of the project. For the practitioners, the findings presented above shows that projects need different approach to planning when embarking on unfamiliar markets and that needs to be established before the start of the project. Using LPS® is an approach that can improve the planning process, however, ETO companies need to continually adopt its structures to the context and the specific challenges within each project. Moreover, planning meetings should address planning issues and include real root cause analysis for the encountered problems. For the theoretical contribution, this paper brings into discussion the need for developing better understanding of the project planning process in ETO environment. The case presented her is not unique. We have had several projects within similar companies and planning challenges remain a constant issue.

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# Purchasing Strategies, Tactics, and Activities in Engineer-to-Order Manufacturing

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**Abstract.** This paper presents a six-step method for matching strategic purchasing goals with relevant tactics and operationalizing them through specific activities. The paper provides some of the observations from three Norwegian engineer-to-order companies that are currently working on implementing the proposed method. This paper contributes to purchasing and supply chain management research by providing and testing a method that helps companies to develop strategic goals for different segments of their purchasing portfolios and to match them with relevant tactics and specific activities.

**Keywords:** Supply chain management (SCM) · Purchasing · Engineer-to-order (ETO)

## 1 Introduction

*A supply chain is managed, link-by-link, relationship-by-relationship and the organizations that manage these relationships best will win* [1].

Manufacturing strategies usually relate to the point where a particular product is linked to a specific customer. A common strategy is to make the distinction among make-to-stock (MTS), assemble-to-order (ATO), make-to-order (MTO), and engineer-to-order (ETO) production [2]. ETO companies can be identified by their characteristics of supplying high-value, customized products and having a deep and complex structure, and the general view is that the ETO supply chain is where the “decoupling point” is located at the design stage [3].

In the past, researchers built their theories on the assumption that companies competed with one another. This thinking was later replaced by the idea that supply chains, not individual companies, competed with one another. More recently, this understanding has evolved further due to the realization that companies often have similar supply chains and share many of the same suppliers. This means that companies compete on managing the links or relationships in their supply chains [1].

Therefore, successful ETO manufacturing depends on the effective management of supply chain relationships. The purpose of this paper is to describe the method for ETO companies to develop purchasing strategies, tactics, and activities based on the analysis of their purchasing portfolios in order to improve supply chain relationship management.


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## 2 Theoretical Background

Various scholars [3–9] have described ETO characteristics and operations as inherently different from those of mass production. This paper's scope emphasizes the complexity of ETO manufacturing, derived from three characteristics.

First, ETO manufacturing produces capital goods that are typically high-value due to their uniqueness and complexity, and they are delivered as projects [7, 8, 10, 11]. Therefore, supplier networks are built temporarily and torn down after project fulfillment.

Second, ETO manufacturing combines non-physical activities, such as design and engineering [4, 7, 12], with physical activities, such as component production, assembly, and installation [5]. The non-physical activities are often geographically dispersed, separated from physical activities, and executed by individual entities. Consequently, the company that manages the overall project executes only a small part of the project that is performed by its own personnel and in its own production facilities.

Third, ETO manufacturing often executes engineering and production concurrently because not all design details and drawings are finalized when the procurement of long-lead items and the production of the components start. Accordingly, design changes affect component production at all supplier tiers, making it difficult to align and control production and engineering activities. Quality issues may arise, requiring rework [3, 13–16].

Therefore, successful ETO manufacturing depends on the effective management of supply chain relationships. Among the most known frameworks for managing supply chain relationships are the ABC analysis and different varieties of purchasing portfolio models originated by Kraljic [17]. The ABC analysis is a well-known tool for differentiating between important and less important purchases, but it merely focuses on the financial value of each purchase [18].

A wide variety of purchasing portfolio models inspired by the Kraljic matrix can be utilized to execute a purchasing portfolio analysis (PPA). However, all of these models are very similar to the original Kraljic matrix in that they use almost the same dimensions and suggest similar tactics [18]. This is why, in this paper, the PPA implies, in line with the original Kraljic model, the classification of purchased items into four categories in a $2 \times 2$ matrix: *strategic, bottleneck, leverage,* and *noncritical.* In contrast to the ABC analysis, the PPA is based on two dimensions: supply risk and financial impact [18]. This more balanced approach to differentiating a company's purchases is the reason why this study applies the PPA. The PPA allows ETO companies to analyze and understand their purchasing portfolios, thus setting them in a position to develop purchasing strategies and tactical initiatives.

A purchasing strategy can be described as a strategic approach related to the purchasing department [19–22]. The purchasing strategy can be defined in the form of strategic priorities, such as costs, flexibility, and innovations. Purchasing tactics, or what is called "sourcing levers" [21], comprise a set of tactics used to operationalize the purchasing strategy as a combination of activities in a purchasing category. Purchasing tactics directly address the actions that decision makers can take to achieve the desired outcomes. The tactics can be divided into two groups: *transaction-oriented tactics,* which focus on capturing the existing value, and *relationship-oriented tactics,* which emphasize creating value in collaboration with other actors [21] (Table 1).

**Table 1.** Purchasing tactics [21]

| Transaction-oriented tactics | Relationship-oriented tactics |
|---|---|
| Volume bundling | Product optimization |
| Price evaluation | Process optimization |
| Extension of supply base | Optimization of supply relationships |
| | Category-spanned optimization |

Once the tactics are identified, they are further broken down into a set of specific activities to realize the strategic goals [21].

## 3 Research Methodology

Case studies are widely used in operations management research to test, develop, and extend theories [23, 24]. This paper applies a multiple case study approach as it is likely to build a more robust and testable theory than a single case would. The empirical basis for this study is based on multiple representative case studies involving three Norwegian ETO-manufacturing companies [25, 26]. Company A produces customized, capital-intensive, and advanced products for the maritime industry; company B produces one-of-a-kind, highly technical, and complex products for the global oil and gas industry; and company C produces customized hydraulic products for a broad range of market segments and industries. Although these companies operate in different market segments, all of them have their own production facilities in Norway, and over 60% of the costs of their final products come from purchased items and services.

Consequently, the three ETO companies in this study are involved in different ongoing research projects focusing on the improvement of delivery time and delivery precision through better supply chain relationship management. The main data was collected from workshops, focused interviews, and observations, as well as from discussions and site visits over a 14-month period. The data analysis was carried out by three researchers in close cooperation with key personnel of the three case companies. Application of ideas and best practices from the review of relevant literature (in particular [19–22]) and resulting active discussion with three case companies, allowed the conceptualizing of a six-step methodology.

## 4 Developing Strategies, Tactics, and Activities

Based on the discussed literature and the empirical investigation, this paper suggests a six-step method to develop purchasing strategies, tactics, and activities (Fig. 1):

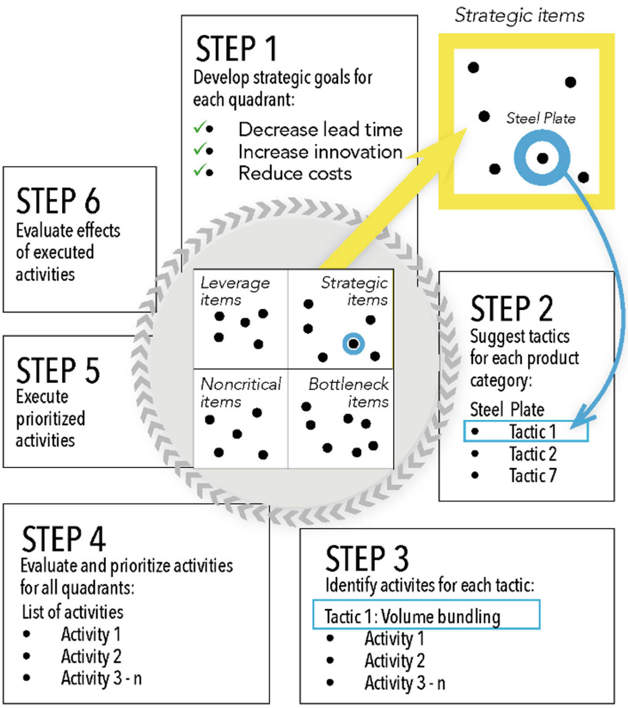


**Fig. 1.** Six-step method for developing purchasing strategies, tactics and activities

1. Develop strategic goals for each quadrant in the PPA.
2. Select the relevant tactics for each product category.
3. Identify the activities for each tactic.
4. Evaluate and prioritize the activities.
5. Execute the prioritized activities.
6. Evaluate the effects of the executed activities.

The proposed method implies that a company has already performed the PPA. It is worth mentioning that this methodology can easily be adapted to fit the output of other ways of categorizing a company's purchasing portfolio, such as the ABC analysis. The following sections provide a more detailed description of these steps.

## 4.1 Develop Strategic Goals for Each Quadrant in the PPA

As explained earlier, purchasing strategies are defined in the form of strategic priorities, such as costs, flexibility, or innovations. In step 1, the goal is to agree on one or more strategic goals or priorities for each quadrant in the matrix (strategic, bottleneck, leverage, and noncritical). A strategic goal/priority could be reduced costs, reduced lead times, increased delivery performance, increased innovations, and so on. For example, a company could select a strategic goal of 10% cost reduction for all purchasing categories in the *noncritical* quadrant, 95% delivery precision for all purchasing categories in the *strategic* quadrant, and 20% lead time reduction for all purchasing categories in the *bottleneck* quadrant.

### 4.2 Select the Relevant Tactics for Each Product Category

Step 2 involves selecting the relevant tactics for each product category in each quadrant. The strategic goals/priorities determined in step 1 should guide the choice of relevant tactics, as listed in Table 1. For instance, a company may choose the *volume bundling* and the *price evaluation* tactics to underpin its strategic goal of 10% cost reduction for the *sealing rings* purchasing category in the *noncritical* quadrant of the matrix.

### 4.3 Identify the Activities for Each Tactic

In step 3, a company identifies the activities for each of the tactics chosen in step 2. Following the example in step 2, the specific activities aimed at operationalizing the *volume bundling* tactic for the *sealing rings* purchasing category could be *concentrating the volumes on suppliers X and Y* and *bundling several requests into a package with a large volume*.

### 4.4 Evaluate and Prioritize the Activities

As the activities can vary significantly in terms of time, cost, ease of execution, risk, and so on, it is necessary to evaluate all activities for all product categories and prioritize those activities that should be executed (step 4). Depending on the purchasing portfolio, some companies can end up with several hundred activities. The process of evaluating and prioritizing can be tedious and challenging. Therefore, the authors suggest that a structured set of evaluation criteria is needed, and more research on this matter is welcome.

### 4.5 Execute the Prioritized Activities

Step 5 entails the execution of the activities, following the prioritization in step 4.

### 4.6 Evaluate the Effects of the Executed Activities

In the final step, a company should evaluate the effects of the executed activities on the strategic goals defined in step 1, as well as on the positioning of specific purchasing categories in the matrix, as it is likely that some of them could move to another quadrant due to changes in their *supply risk* and *financial impact* scores. In addition, as ETO-manufacturers work in project-based environment, each new project introduces several new purchasing categories in the company's purchasing portfolio. Therefore, at this point, it is natural for the loop to start again, beginning with adjusting the strategic goals for each quadrant, all the way through to executing the newly prioritized activities, evaluating their effects, and so on. As a result, this approach forces a company to continuously work on its purchasing portfolio by developing and adjusting its strategic goals, selecting the relevant tactics, prioritizing and testing specific activities, and evaluating their effects.

## 5 Discussion

This section briefly discusses some of the observations from the three case companies that are currently working on implementing the proposed method described in Sect. 4. At the time of writing this paper, the current project status of each case company is somewhere between steps 2 and 3 of the proposed method.

In step 1 (develop strategic goals for each quadrant in the PPA), it was common for all of the companies to focus on *reducing purchasing costs, increasing the delivery precision,* and/or *reducing the lead time* for all quadrants in their PPAs.

In step 2 (select the relevant tactics for each product category), all of the companies selected a combination of both transaction-oriented and relationship-oriented tactics (see Table 1). For example, one of the companies chose *volume bundling*, *process optimization,* and *optimization of supplier relationships* as the common tactics for each of the purchasing categories in the *strategic* quadrant. However, the same company used a more tailored approach to selecting the relevant tactics for each of the five purchasing categories in the *bottleneck* quadrant. *Price evaluation* was a common tactic for all of these purchasing categories, but selection of other tactics, such as *process optimization* and *volume bundling*, differed.

In step 3, the selected tactics are currently being operationalized by connecting them with specific activities. For instance, one of the companies has selected the *test delivery from supplier Z* activity for the *toothed ring* purchasing category to operationalize its selected tactic *extension of supply base*, underpinning its strategic goals of reduced purchasing costs and increased delivery precision for the purchasing categories in the *strategic* quadrant.

As mentioned earlier, the lists of activities by each case company will likely include several hundred lines. A structured approach for prioritizing which of the activities should be executed first is needed.

## 6 Conclusion

To improve the supply chain relationship management in ETO manufacturing, a method for developing purchasing strategies, tactics, and activities was designed. The method was developed in cooperation with three Norwegian ETO companies.

This paper contributes to purchasing and supply chain management research by providing and testing a method that helps ETO companies to develop strategic goals for different segments of their purchasing portfolios and to match them with relevant tactics and specific activities.

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# Examining Circular Economy Business Models for Engineer-to-Order Products

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**Abstract.** Realization of the circular economy (CE) and its full potential requires firms to rethink their supply chains and business models. Although several frameworks in the literature propose circular economy business models (CEBMs) to redefine how companies create and capture value while adhering to CE principles, there has yet to be an examination of CEBMs in engineer to order (ETO) context. To address this gap, this study maximizes the depth of the phenomenon under investigation by leveraging a case study of a Norwegian company that deals with a large number of small ETO projects. Our findings increase knowledge of how ETO products can adapt to CEBMs.

**Keywords:** Circular economy · Circular economy business models · Engineer-To-Order products

## 1 Introduction

Victor Hugo's infamous quote, "you can resist an invading army; you cannot resist an idea whose time has come", is what possibly best encapsulates the concept of circular economy (CE) being the idea, that needs to replace the current production and consumption system – take-make-dispose linear model [1]. Most would agree that CE has become mainstream. It would be hard-pressed to find a firm that has not at least started a recycling initiative or engaged in some kind of community development project, even if the efforts were sparse. Auspiciously, many firms have gone far beyond, overhauling products and processes and looking outwards at system-wide innovation, and CE initiatives that promise to radically reshape their businesses now and in the future [2]. As more firms begin to recognize the potential of this novel approach, the CE quickly moves from theory to practice and the demand for businesses to embrace it strategically and operationally, and for the governments to establish a consistent set of rules for CE [3] is growing accordingly. More importantly, CE calls for novel business models that will simultaneously ensure the creation of environmental quality, economic prosperity, and social equity to benefit current and future generations [4]. This is understandable since a business model is the essence of a firm, representing the architecture through which firms create value, deliver value to their customers and capture value for


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themselves. Thus, if the role of the firm is vital for a successful transition to CE, then the implementation of new business models is warranted.

The extant literature addresses related topics, including a framework that integrates circular economy business models (CEBMs) and circular supply chain management [5], the development and application of a circular business experimentation framework [6], and a visualization tool to map CEBMs [7]. Although the literature provides useful insights, further research is still required on how firms can implement CE practices for value creation and capture [8]. This is crucial because CE implementation strategies are mainly associated with individual products [9]. As such, in this paper we use product as a unit of analysis when examining CE implementation strategies. Since CEBM implementation largely depends on individual products, with the assumption that varied products might require varied manufacturing plants, settings and strategies, and business models, the present study focuses on engineer-to-order (ETO) products. Against this backdrop, this study seeks to empirically identify the characteristics of specific ETO products and examine their appropriate CEBMs. To the best of our knowledge, no study has specifically investigated the CEBMs for ETO products and considering the uniqueness and relative complexity of ETO products, insights from this paper should be of interest to scholars, practitioners, and policy makers.

The paper proceeds as follows. We commence by reviewing literature related to CEBMs and production of ETO products. We then provide a framework that shows the general applicability of CEBMs for ETO products, which is followed by a methodology section and presentation of the case study. Finally, we discuss the findings and provide an outline for further work.

## 2 Circular Economy Business Models (CEBMs)

Before discussing CEBMs, it is important to understand the business model concept and its implications. A business model is defined as "the design or architecture of the value creation, delivery, and capture mechanisms [a firm] employs. The essence of a business model is in defining the manner by which the firm delivers value to customers, entices customers to pay for value, and converts those payments to profit" [10]. In operational terms, a business model includes a value proposition (product and service; customer needs; geography), a revenue model (pricing logic; channels; customer interaction), and a cost model (core assets and capabilities; core activities; partner network). To be successful, these components must be coherent and internally aligned [11].

A CEBM can be defined as "the rationale of how an organization creates, delivers, and captures value with and within closed material loops" [12]. Studies on CE have addressed the design of CEBM in light of CE principles, and approaches to reconfigure and realign business model components according to CE practices [e.g., 8, 12]. Such models embrace cyclical material flows, renewable energy sources and cascading-type energy flows [13]. Put succinctly, to be regarded as 'circular', a model does not necessarily need to close material loops by itself within its own internal system boundaries; it could also be part of a larger system that together close a material loop echoing the Industrial Ecology thinking.

Studies by Stahel [14], and Bocken et al. [15], describe three key strategies for CE, from the resource perspective. (1) *slowing* loops, which extend a product's life to slow down resource usage (e.g. through repair); (2) *closing* loops between post-use and production through recycling, resulting in a circular flow of resources; and (3) *narrowing* loops, which aim to use fewer resources per product (e.g. through efficient manufacturing processes). Clearly, each of these strategies requires a different configuration of the value proposition, the revenue model, and the cost model, i.e., the business model. An intriguing question, then, is how to implement these for ETO products? Before addressing this question, the next section sets the scene by presenting ETO production.

## 3 Production of ETO Products

ETO refers to a strategy whereby design, engineering and production is based on specifications provided by a specific customer order. As such, the customer order's decoupling point for ETO is at the design stage such that each order is tied to the design phase of a product [16]. Given the product-process characteristics of this type of environment, the products are highly customized, produced in low volumes (often one-of-a-kind), and customer specific; also, the processes are labor intensive, usually non-repetitive, and often demand highly skilled labor [17]. The entire execution of the ETO product is often organized as a project particularly for capital goods. Since companies are generally unaware if and when a customer will place an order, accurately forecasting demand, ordering materials and producing products in advance are very challenging [18].

Drawing on Willner and colleagues' [19] ETO matrix, products can be produced using four ETO archetypes (complex, basic, repeatable, and non-competitive), depending on the number of units sold per customer order, the existence of repetitive customer orders and the engineering hours needed to produce the product. Given these four ETO archetypes, CE strategies for ETO products will plausibly vary according to the type of ETO production.

The subsequent section examines the appropriate CEBMs in ETO context.

## 4 Examining Appropriate CEBMs for ETO Products

CEBMs require the appropriate reconfiguration of value creation, delivery and capture, activities according to the nature/type of the product. We provide a framework, which shows the general applicability of CEBMs in ETO context (see Table 1). The framework proposes four major CEBMs for all ETO products (circular supplies, product life extension, product value extension and resource value). We further divide these major CEBMs into sub-CEBMs and describe them along four business model dimensions (value proposition, value delivery, value creation and value capture). This is derived from major frameworks such as business model canvas [20] and widely accepted conceptual analyses [11, 21]. This alignment is essential in ensuring that ETO companies can understand and apply these CEBMs.

**Table 1.** Circular Economy Business Models (CEBMs) and Circular Economy (CE) practices related to Engineer-To-Order (ETO) products. The highlighted rows - major CEBMs, the column under each major CEBM = reviewed CEBMs, which are further divided into sub-CEBMs.

| CEBMS | CE practices related to ETO products | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Value proposition** | | **Value delivery** | | **Value capture** | | **Value creation** | |
| | Products | Services | Target Customer | Value delivery Processes | Revenues | Costs | Partners and stakeholders | Value creation Processes |
| Circular supplies | | | | | | | | |
| Industrial symbiosis (IS) [15, 22]. | Waste as production inputs | Cost and supply risk reductions; synergistic partnerships; third party waste reduction. | Manufacturers; B2B suppliers. | Sharing communal services (e.g. maintenance, recycling); set up geographically proximate collaborations (e.g. eco-industrial parks). | Additional revenues through new IS products/component s; new revenue potential through green image. | Reduction of waste disposal costs; reduction of material and energy costs; reduction of transportation costs. | Manufacturers; B2B suppliers | Physical exchange of materials, energy, water; using own waste and/or third party's as inputs for production. |
| Product life extension | | | | | | | | |
| Classic long-life model [15]. | Long-lasting products | Repair; maintenance; upgrading | B2B customers (Quality- and cost-conscious) | Offering long-lasting products & corresponding repair/ maintenance services; upgrading services. | Price premium for longevity & high quality of products; additional revenue through extended usage | Long-term service & product warrantee cost | After-sales service agents. | Designing long-lasting products; repairing & upgrading of products and/or components. |
| Repair and maintenance [24]/ Reuse & Redistribute [23]. | Repaired components; spare parts; Reusable components/parts. | Securing uptime & lifespan of products; shipping/installation; maintenance; repair; customer education; facilitate collaboration. | Quality-conscious (those willing to pay more for quality services); cost-conscious customers (those with constrained budgets) | Providing (product-based) services & results; Making reused components accessible & affordable; take back used components. | Additional revenues from the services provided; additional product or component revenues. | Reduction of material costs (through reusing/repairing components/parts); increase of labor and logistics costs | B2B customers (shipyards & ship owners); after-sales service engineers; manufacturers. | Components upgrading or upcycling; reselling and/or taking back components Maintaining or repairing products & components |
| Refurbishment and remanufacturing [24]. | Repaired, refurbished products; used components as inputs; remanufactured components; | Upgrading; shipping and installation, warranties (auxiliary services). | Cost-conscious/B2B customers; B2B suppliers. | Providing used components, materials; taking back used components. | Additional product/component revenues. | Reduction of material costs (through upgrading); transportation, logistics. | B2B customers; manufacturers; After-sales service engineers. | Restoring the functionality of components; upcycling and taking back components. |
| Product value extension | | | | | | | | |
| Extending product value [15]. | Used products or components in as-new quality; repaired products. | Taking back used components. | B2B customers. | Taking back used components; selling used components. | New revenue potential from retaining material ownership. | Reduction of material costs; increase of labor and logistics costs. | Collaborations with B2B customers; after-sales service engineers. | Repairing or remanufacturing own components. |
| Product as a service [22]. | - | Leasing; renting; product maintenance, repair & control. | B2B customers. | Specifying functionality, retaining product ownership, | Leasing fee; rental fee. | Product longevity; product maintenance costs; material costs reduction. | Manufacturers; B2B suppliers; B2B customers. | Using products longer; maintaining, repairing & controlling product. |
| Resource value | | | | | | | | |
| Recycling and waste management [23, 24]. | Reusable/recyclable production inputs; components based on recycled waste; | Waste sorting; waste recycling; take-back management. | Some key customers (B2B) interested in using such waste as production input (downcycling) | Providing used components, materials, waste; taking back used components, waste. | Additional product/component revenues | Waste handling processing; resource inputs; logistics; transportation. | Key customers; municipality | Components recycling; upgrading or upcycling of components; taking back components. |

‘Circular supplies’ are business models based on industrial symbiosis in which the residual outputs from one process can be used as feedstock for another [22]. Through it, ETO companies may replace linear resource approaches and phase out the use of scarce resources while reducing waste and removing inefficiencies. Whereas, ‘product life extension’ business models aim to extend the lifecycle of products through engineering solutions including repair, maintenance and/or upgrade [22, 23]. With this model, ETO companies can help ensure that products stay economically useful for as long as possible and that product upgrades are done in a more targeted way (e.g., fatigue/obsolete components are replaced instead of the entire product). Moreover, ‘product value extension’ business models offer product access and retain ownership to internalize benefits of circular resource productivity [15]. This model would be attractive to a few ETO companies with high cost of operation for their products and that have skill advantage relative to their customers in maintaining the products, hence, giving them an advantage in selling services and recapturing residual value at end-of-life. ‘Resource value’ business models for these ETO products, is built on mostly ‘recycling and waste management’ [24], and generally, they can take different forms, thus, upcycling (which creates higher quality materials and improved functionality) and downcycling (e.g., the conversion of used materials into materials of lower value). This model is a good fit for most ETO companies especially where waste material from products can be reclaimed through take-back management and reprocessed cost effectively.

Nevertheless, for a CE to function these different types of CEBMs will need to interact and work together. For example, in the case of an advanced equipment to maritime industry, the ‘product value extension’ business model implies the equipment manufacturer either takes back used components of the products or retains ownership of the products, and is incentivized to repair/refurbish/upgrade the equipment over time to maintain maximum efficiency. However, the full circular benefit is only realized if the business models would allow for product and process design change, so that the products/components are repairable, upgradable and disassemblable to reduce the use of virgin materials [3]. Based on a CE, these ETO firms have the opportunity to expand their services they offer or collaborate with others to maximize value. For instance, a firm which bases their CEBM on refurbishing and remanufacturing their components may need to partner with a ‘tracking facility’ provider so they can monitor the whereabouts of their products, and then work with a logistics company or some of their B2B customers to ensure the end of life components are returned (take-back management).

Next, we present key methodological choices for the present study.

## 5 Research Methodology

Our study explores an emerging phenomenon – CEBM, hence an embedded single-case design was deemed appropriate since single case design is suitable for revelatory purposes [25]. We selected a company (hereafter company X) that manufactures and supplies propulsion systems to shipyards and ship owners. With more than 1000 engineering hours per unit and 120 bespoke units sold annually, the propulsion system is a perfect example of an ETO product. We used three data collection approaches: face-to-face semi-structured interviews; direct, non-participant observation and document review. The next section describes company X and its ETO product characteristics, which are then matched with CEBMs identified in the developed framework.

## 6 The Case Company, Its ETO Products and Suitable CEBMs

Company X's business concept is to design, manufacture, market and service complete systems for the propulsion, positioning and maneuvering of larger vessels. Products are highly customized, manufactured on-site, and are manifested through a project organized execution model covering engineering design, procurement and production, which are done in-house to ensure quality in integration of systems. Most of the equipment is designed to meet the demanding requirements of North Sea offshore standards and is used on different types of vessels (e.g. offshore, fishing, cruise, coast guard). In general, company X creates value by understanding customer requirements, translating them into specifications at the product and component levels, and integrating components and subsystems into products. Table 2 presents company X's ETO products characteristics and their descriptions.

**Table 2.** Company X's ETO product characteristics and their descriptions

| ETO product characteristics | Description |
|---|---|
| Low volume | On average, 120 units are produced and sold annually. This varies significantly year by year, depending on the condition of the market, etc. |
| High degree of customization | The products have high-engineering complexity (i.e. more than 1000 h per unit) and are engineered per precise customer specifications |
| Project-based environment | The ETO operations are typically project-oriented, thus, the customer is exposed to the lead-time that encompasses the entire project duration |
| Product design | Each product is engineered/designed according to specific requirements, which vary from one customer to another |
| Customer involvement/Customer specific | Customer orders drive production. Each project is highly customer-specific and requires over 1000 engineering hours. The main drivers are different propulsion system requirements, regulations imposed by class, authorities and customer preferences (shipyards and ship owners) |
| Labor intensive/high-skilled labor | Given the complexity of the products, the manufacturing process is labor intensive and often demands highly skilled labor |
| Type of modularization | There is a slight product modularization. Its design elements are split up and assigned to modules based on a formal architecture or plan |

## 7 Appropriate CEBMs for Company X

From Table 1, we propose two major CEBMs that are appropriate for company X's propulsion systems: 'product life extension' (which builds on 'repair and maintenance', 'reuse and redistribute', and 'refurbishment and remanufacturing'), and 'resource value' (that builds on 'recycling and waste management').

'Repair and maintenance' business models are part of product sales and stand-alone services for company X; they are more about offering superior product experiences and engaging customers in co-creation (e.g. following maintenance schedules), than they are about selling products [2]. These models are addressing almost all the business model dimensions, indicating how issues, such as customer-centric services, fast learning and problem-solving capabilities, and up-to-date product expertise, are essential and of high value to company X. Since company X provides these services itself, there may a reduction in the costs for virgin materials.

Given the nature of the propulsion systems, 'reuse and redistribute' business model is the most relevant; there are only a few components and/or parts that are/can be reused. Instead of having used components flow (back) to company X directly or via an intermediary for repair and replacement, the company's aftersales service engineers typically decide whether components can be reused (whilst in the field with customers), depending on their level of wear or fatigue. The same applies to the 'refurbishment and remanufacturing' business models, which require that company X establishes the necessary reverse logistics to have access to used components [26]. It should be noted that, in this type of industry, buying back used components by contacting customers directly is challenging; it is extremely time-consuming to trace customers all over the world, and it is even harder to identify them after ship ownership changes. More so, buy-back method would involve high logistics costs. Since the products are located under the waterline, there is also the practical difficulties involved of obtaining the components except when the vessel is up for the 5-year class and maintenance dockings.

Considering 'recycling and waste management' business model, company X pays much attention to the downcycling of very few components such as electrical and electronic equipment. This is because recycling is quite challenging as most components have material grades and material mix adapted to the specific requirements, which over time changes due to technological improvements and most components degrade in seawater rendering them slowly less and less attractive for reuse or upcycling.

Put succinctly, these identified CEBMs would therefore allow company X greater control of their resource streams, innovation through the supply chain and enhanced collaboration within the supply chain amongst all actors.

## 8 Conclusion and Further Work

Most ETO manufacturers stand to benefit more from the multifarious collaborations that can be built based on these CEBMs and from component take-back to complex industrial symbiosis networks. CEBMs for ETO products mostly address one of the three key CE strategies: the *slowing* resource loops. There is, nonetheless, a need to convince manufacturers to adapt *narrowing* and *closing* loops strategies to retain product and material value, respectively, if they are to successfully transition to CE; to do so, companies must rethink their supply chains and how they create and deliver value.

We have noticed that a recycling business model for ETO products is greatly underutilized partly due to the complexity of the product. Hence, further work may elucidate distinctly how ETO manufacturers should design a collection and recycling infrastructure for such a recycling business model, and how they may capture value from it.

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# Digitalized Manufacturing Logistics in Engineer-to-Order Operations

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**Abstract.** The high complexity in Engineer-To-Order (ETO) operations causes major challenges for manufacturing logistics, especially in complex ETO, i.e. one-of-a-kind production. Increased digitalization of manufacturing logistics processes and activities can facilitate more efficient coordination of the material and information flows for manufacturing operations in general. However, it is not clear how to do this in the ETO environment, where products are highly customized and production is non-repetitive. This paper aims to investigate the challenges related to manufacturing logistics in ETO and how digital technologies can be applied to address them. Through a case study of a Norwegian shipyard, four main challenges related to manufacturing logistics are identified. Further, by reviewing recent literature on ETO and digitalization, the paper identifies specific applications of digital technologies in ETO manufacturing. Finally, by linking manufacturing logistics challenges to digitalization, the paper suggests four main features of digitalized manufacturing logistics in ETO: (i) seamless, digitalized information flow, (ii) identification and interconnectivity, (iii) digitalized operator support, and (iv) automated and autonomous material flow. Thus, the paper provides valuable insights into how ETO companies can move towards digitalized manufacturing logistics.

**Keywords:** Engineer-to-Order · Digitalization · Manufacturing logistics

## 1 Introduction

The need for coordination of material and information flows in ETO operations is significant [1] and tailored approaches are required for an effective and efficient management of manufacturing operations [2]. Several studies have been aimed at addressing the challenges related to manufacturing logistics in different ETO cases, however, the aspect of digitalization has not yet been sufficiently addressed in this type of manufacturing environment [3].

The new, digital technologies within Industry 4.0 has the potential to change the manufacturing industry by enabling new and more efficient processes. Concepts and developments such as the Internet of Things (IoT), Cyber-Physical Systems (CPS), augmented reality, artificial intelligence and big data analytics are expected to lead to a paradigm shift in industrial manufacturing [4]. Digitalization emerges as a way of managing complexity, and is introduced as one of the main areas for future research in


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complex ETO manufacturing [3]. With the high complexity in these manufacturing environments, there is a need to investigate how digitalization can improve manufacturing logistics performance. Therefore, this paper aims to identify how digital technologies can be applied in order to address the challenges in ETO manufacturing logistics.

The remainder of this paper is structured as follows. Section 2 presents and describes the characteristics of ETO manufacturing logistics. Thereafter, a case study serves to identify specific manufacturing logistics challenges. Applications of digital technologies in ETO is then identified through reviewing literature, before digitalization and manufacturing logistics challenges are linked in Sect. 5. The paper ends with the conclusions, limitations and further research in Sect. 6.

## 2 The Characteristics of Complex ETO Manufacturing

Manufacturing logistics concerns the coordination of the operations related to the flow of materials through the manufacturing departments up to the production of the end product [5]. Achieving cost-efficient manufacturing logistics in ETO is challenging due to the characteristics of the manufacturing environment [6]. With the ETO approach the activities of design, engineering, as well as the actual production processes, are performed after an actual customer order has been received. The customer order decoupling point is located at the design stage, with actual customer orders driving the production [7]. The large degree of customization, the product structure complexity, and the overlapping of manufacturing and design activities are reasons for a very high complexity of the internal ETO supply chain [8].

The most complex type of ETO manufacturing, which is the main focus of this paper, is the production of one-of-a-kind products [9]. Producing unique products every time has major implications for the manufacturing logistics processes, such as production control, as it creates a dynamic, uncertain and complex manufacturing environment [10]. Table 1 presents the main characteristics of complex ETO manufacturing.

**Table 1.** Main characteristics of complex ETO manufacturing.

| |
|---|
| Product characteristics:<br>• Big-sized, complex products with deep product structures [3, 11]<br>• High level of customization [9]<br>• High product variety and low volume on product level (one-of-a-kind products) [2, 9] |
| Process characteristics:<br>• Manufacturing carried out as large projects in fixed position layouts [9]<br>• Frequent changes [11]<br>• Highly integrated and overlapping activities [12]<br>• Focus on flexibility [11] |
| Market characteristics:<br>• Customer order decupling point located at the design stage [7]<br>• Fluctuations and uncertainty in mix and sales volume [10]<br>• Uncertainty in product specifications [10] |

## 3 Manufacturing Logistics Challenges in Complex ETO

To get empirical data on how the characteristics of ETO manufacturing are affecting manufacturing logistics, a case study of the Norwegian shipyard Ulstein Verft AS (UVE) was conducted. Case data was collected through semi-structured interviews, observations at the yard and background data on the company from several years of research collaboration. This section includes a brief description of the case company and its manufacturing logistics.

UVE is part of Ulstein Group ASA, a Norwegian industrial group with activities in ship design and shipbuilding. The group's main business consists of designing and building highly customer-specific vessels, typically advanced offshore vessels such as supply vessels, anchor-handling vessels, offshore construction vessels and seismic vessels, in close collaboration with the customers. In recent years, they have also started building expedition cruise ships, yachts and passenger ships, in addition to ships for the offshore wind industry and developing designs for fishing vessels. UVE is the shipyard responsible for outfitting the ships delivered by the group. The hull production is carried out at a foreign yard, before the hull is towed to UVE in Ulsteinvik, Norway.

The production at UVE is a highly complex ETO production and the characteristics of the production environment at UVE bear a close resemblance to the ETO characteristics presented in Table 1. In general, there is a highly complex material and information flow related to outfitting activities at UVE, with non-repetitive and non-routine work processes. This is a result of the complex production of one-of-a-kind products, and a high uncertainty in process specifications. Moreover, processes are prone to disruptions due to changes occurring after the outfitting activities has started. This affects the planning, scheduling and sequencing of tasks, the supply of materials and the supporting documentations needed by operators to perform jobs. It is today challenging to achieve the tight integration of IT systems needed for efficient outfitting of the ships.

Paper-based documentation of product models and drawings are critical sources of information for operators in this type of manufacturing. Operators have a particularly important role in performing the outfitting activities at UVE, as standardization and automation of processes is difficult due to the non-repetitive type of work. Many operations are thus manual, including production processes, material handling and internal transportation of materials. Providing the required information to operators is further complicated when changes occur, as models and drawings then must be updated accordingly. Furthermore, it is difficult to have an overview of the yard from a manufacturing logistics perspective as operations are spread across a vast area. Materials, tools and equipment are thus geographically dispersed, and operators spend a considerable amount of time walking to collect or search for them.

From this, four main manufacturing logistics challenges at UVE are derived:

- IT system integration and sharing of up-to-date information
- Localization of materials, equipment and tools
- Complex and information demanding work for operators
- Manual material handling and irregular and disrupted flows.

## 4 Digital Technologies in ETO Manufacturing Logistics

Digital technologies emerge as promising means for managing complexity. While the technical developments of these technologies are rapidly advancing, applications in ETO still lags behind and requires research focus [3]. To have a structured overview of the available technologies and their features, eight technology groups were identified by integrating the technology clusters of smart manufacturing [13] and the nine advances in technology forming the foundation for Industry 4.0 [14]. This is shown in Table 2.

**Table 2.** Overview and description of digital technologies.

| Tech. group | Description |
|---|---|
| Autonomous robots | Automatic Guided Vehicles (AGVs), Autonomous Mobile Robots (AMRs), and Collaborative robots (COBOTS) for material handling and performing logistics operations |
| Integration of IT systems | Horizontal and vertical integration of IT systems for production management (PLM, ERP, MES) |
| Internet of Things | Objects equipped with sensors and actuators, enabling storing and exchange of information through network technology |
| Cyber security | The secure and reliable protection of industrial production systems from cyber threats |
| Cloud manufacturing | Cloud-based solutions for sharing and exchange of data between systems, sites, and companies |
| Visual technology | The visual representation of an object, in the form of augmented reality (AR) through superimposing a computer-generated 3D image in the real world, creating a virtual reality (VR) or projecting 3D images as holograms |
| Data analytics | Transforming data into knowledge and actions within a manufacturing system. Big data for analysis of large sets of real-time data, artificial intelligence, machine learning and advanced simulations are all part of this group |
| Additive manufacturing | 3D printing of objects layer by layer, based on 3D models or CAD files of the objects |

Reviewing recent literature on ETO manufacturing and digitalization has identified a range of possible applications of these technologies. These are described in the following paragraphs of this section.

Several different IT systems are used at the different levels of today's manufacturing systems, but these are often not fully integrated [14]. However, the current technological developments in ICT increases the opportunity of achieving such an integration. Also in one-of-a-kind production, fully integrated, digitalized factories are possible through integrated sensor networks and supporting information systems [15]. Enhancing integration between modeling, scheduling and monitoring processes is particularly relevant for ETO [16]. Eventually, everything should be connected to a cloud-based solution and also taking the aspect of cyber security into account [17].

Digital technologies can be applied to assist operators to become smarter [18], and this is particularly relevant considering the high operator density in complex ETO. Visual technology such as Augmented reality [19] is one example of operator support that can enable schedules, product models and work instructions to be displayed on tablets or AR-glasses. Integration of such mobile devices with higher-level enterprise systems enables rapid sharing of updated information to the production floor. Such digital interfaces will also enable updating status of tasks through mobile devices, thus digitalizing progress reporting. Building Information Modeling (BIM) for information sharing through “BIM kiosks” is another means to provide operators with fast access to digital product models available from the PLM system [20].

Several papers have investigated the use of RFID for identification, localization and tracking [15, 19, 21]. Tracking and localization technology for automated data capturing of materials movement can enable real-time planning and control [15] such as real-time monitoring of assembly processes [22]. Furthermore, the integration of e.g. RFID, GPS and GIS technology with AR technology allows operators to get information on the location of materials, tools and equipment on mobile devices such as smart glasses or tablets. Drones is another possible application for localization purposes, as they can be utilized for inspection of the overall status of the shipyard [23]. Combining drones with 3D photography can then be used to provide 3D footage of the yard.

Although 3D printing mainly concerns production technology, such applications are also relevant for manufacturing logistics as it provides an ability for suppliers to send part designs to the yard for printing at the yard [23]. Moreover 3D printing can be used for printing of tools and equipment on the spot [23], hence it can reduce the time operators spend walking to acquire the tools and equipment necessary to perform a job.

Automated solutions for material handling are however the most promising developments to reduce time spent walking, waiting and searching. Automation of production processes, material handling and transportation of materials and equipment on the production floor has traditionally been difficult in complex ETO. However, with the increased flexibility of automated solutions today, the possibilities to automate such activities are increasing, exemplified by the use of AGVs, mobile robots, collaborative robots and automated material handling and feeding [24].

## 5 Features of Digitalized Manufacturing Logistics in ETO

Having identified various applications of digital technologies in ETO, it is now possible to link these to the manufacturing logistics challenges. Each of the identified challenges are here linked with a feature that can be provided by digital technologies.

The close integration between engineering and production in ETO manufacturing requires integrated IT systems for the efficient control and execution of manufacturing logistics activities. Moreover, with product changes occurring after production has started, it is necessary to provide operators with updated product drawings and models. Efficient information sharing is also required in the opposite direction, from shop floor to higher level IT systems, e.g. status and progress reporting from the production floor. With these challenges, there is a need for a *seamless, digitalized information flow*, where all subsystems at the various levels of the manufacturing system are integrated. Information should flow continuously from the production floor via MES system up to higher-level IT systems, such as the ERP system. This gives access to real-time information for planning and controlling operations.

The complexity of ETO products, with their deep bill of materials, makes it challenging to maintain an overview of all materials, equipment and tools necessary to perform operations. They are geographically dispersed across the facility, and workers often spend time searching for these assets, as well as walking over significant distances to acquire them. These challenges related to localization of materials, equipment and tools requires that *Identification and interconnectivity* is provided through digital technologies. It is now to a large extent possible to identify and interconnect objects in a facility through the utilization of new technology, and this will enable a highly integrated way of managing operations. Identification technology, networking technology and equipping products with sensors are keys to create a connected factory.

Operators in ETO manufacturing facilities such as UVE's shipyard must perform a range of highly complex, manual and non-routine tasks, as products are one-of-a-kind. Information about products, assemblies, processes etc. are therefore critical for the operators for them to be able to perform the scheduled tasks and activities. Digitalized manufacturing logistics should therefore include *digitalized operator support*. Human workers will still be important in a digitalized shipyard, and digital technologies should therefore be utilized to provide enhanced support for them, giving rapid and easy access to required and up-to-date information about the processes and activities.

With the manual material handling and irregular and disrupted material flow, there is a need for a more *Automated and autonomous material flow*. Products, components, tools, equipment and other objects can then be transported more efficiently, and with less human intervention. In manufacturing logistics, digital technologies can bring autonomy and automation to the physical flow of materials.

Figure 1 shows the manufacturing logistics challenges identified from the case study, and their corresponding required features of digitalized manufacturing logistics.

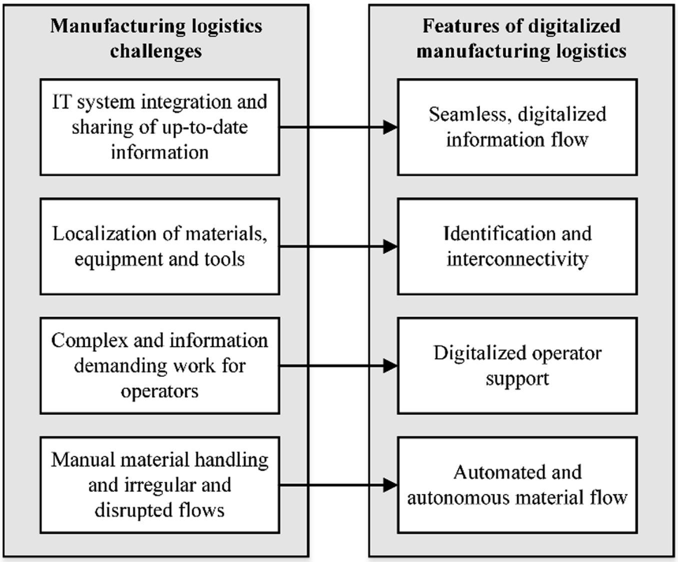


**Fig. 1.** ETO manufacturing logistic challenges and corresponding required features of a digitalized manufacturing logistics system.

## 6 Conclusions, Limitations and Further Research

This paper has identified a number of manufacturing logistics challenges in ETO manufacturing. It has further linked these to a set of required features of a digitalized manufacturing logistics system, outlining the needs that should be met by digital technologies. To be able to address the manufacturing logistics challenges in ETO there is a need for seamless, digitalized information flow, identification and interconnectivity, digitalized operator support, and automated and autonomous material flow. Digital technologies can enable these features, and there is a range of possible applications also in ETO. For digitalized manufacturing logistics in ETO several of the technologies should be applied and combined. Although there is still a lack of research on digitalization in ETO manufacturing [3], this paper identifies a range of digital technologies that has been applied or described conceptually for this type of manufacturing.

Further work related to this research will focus on developing more concrete descriptions of how the digital technologies can be implemented in the case company, and estimate the benefits in terms of relevant and measurable performance indicators such as time, cost, flexibility and quality. Future research should also include case studies of ETO manufacturers with similar characteristics as the case company in this paper, in order to generalize the findings.

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# Aspects for Better Understanding of Engineering Changes in Shipbuilding Projects: In-Depth Case Study

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**Abstract.** Engineering changes are driving forces of product development and improvement in any company. In shipbuilding projects, engineering changes are introduced throughout the project duration and cannot be planned or introduced to the next production run since products are only made once and never repeated. A lot of research exists on engineering changes and their management in general, but the focus of this study is to increase the awareness and understanding of the engineering changes specifically in shipbuilding projects. In this study, an in-depth investigation of engineering changes and aspects having influence on engineering change implementation performance in Norwegian shipbuilding company was performed. The findings indicate that engineering changes and their implementation performance are related to such aspects as market segment, supply chain network, design maturity, overlapping project stages, and timing of EC occurrence in the project. These aspects, their influence on the number of ECs, and EC implementation and performance, are described and analyzed in the paper, and future research plans are presented.

**Keywords:** Engineering change · Shipbuilding · Engineer-to-order · Case study

## 1 Introduction

There is a fair share of standardized shipbuilding in the world, but European, and particularly Norwegian shipbuilding industry, is still producing highly customized products in short series, or even volumes of one. Their products are designed and built as separate projects. Typical strategy for this production environment is engineer-to-order [1]. Engineering changes (ECs) are common and unavoidable in this production environment [2]. As opposed to make-to-stock environment, where ECs are batched and implemented before the start of production, ETO companies have to be able to implement changes at any stage of the project duration [3]. In this study ECs are defined as modifications to structure, behavior and function of a technical artefact that has already been released during the design process [2, 4]. Even though ECs are implemented in order to improve the product or adapt it to the new requirements and needs, they often result in project cost overruns and delays [4]. Extensive amount of the literature suggests strategies, practices and tools for improved management of ECs.


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However, different contextual conditions of production environments and industries are not always explicitly staged in the studies. Hence, the aim of this paper is to investigate what aspects have moderating effects on EC implementation process, cost and time of ECs, as well as number of occurring ECs, in shipbuilding companies.

The paper begins by presenting a brief theoretical background in Sect. 2. Section 3 outlines a research methodology used in this study. In Sect. 4, case company is introduced, followed by the case study findings in Sect. 5. Section 6 concludes the paper and describes further research agenda.

## 2 Theoretical Background and Research Motivation

There is a vast amount of research dedicated to ECs and their management. It is outside of the scope of this paper to provide overview of all the ECM strategies, practices and tools available in the literature. Those interested might refer to the most comprehensive literature review on ECM conducted by Hamraz et al. [2] and further continued and complemented by Ullah et al. [5]. In addition to that, studies conducted by Huang et al. [6] and Storbjerg et al. [7] provide excellent overviews of ECM strategies, practices and tools. The authors of this paper conducted a literature study on this topic as well and identified that is seems that research on ECs up to date has concentrated heavily in the engineering design domain and there is almost no research studying influence of ECs on production, logistics, and supply chain and vice versa. Exceptions are such studies as Wänström et al. [8], Ho [9], and Lin and Zhou [10]. In addition to that, most studies on ECs still do not differentiate between the different production environments, even though back in Eckert et al. [11] suggested that future ECM practices and tools should be developed considering such factors as production volume, the degree of customer involvement in customization, the degree of internal and external uncertainty, and the inherent product complexity.

This study explores if these research gaps are worth studying; are there moderating aspects of the specific production environment that differentiate it from other environments when it comes to ECs and their management? How do these aspects affect EC implementation performance? This study goes outside the design domain to explore production, logistics and supply chain aspects of EC implementation.

## 3 Research Methodology

In Fig. 1, the basic research framework is outlined, which shows the relationships between the studied constructs. When EC occurs, it is analyzed and implemented using engineering change management (ECM) processes, procedures, and tools. ECs come at a cost of course; money and resources are spent on their implementation. This study hypothesizes that both number of occurring ECs, how they are managed, and cost and time of their implementation will be influenced by the moderating aspects specific for the shipbuilding environment. No specific hypotheses as to exact relationships between these aspects and EC implementation were formulated prior to conducting the study. Therefore, an inductive research approach was chosen [12]. In-depth case study in

Norwegian shipbuilding company was conducted. The case study method was chosen because of its suitability for theoretical development, where constructs are not defined or only partially defined [13, 14]. In addition to that, case study method allows for a more comprehensive understanding of the nature and complexity of a phenomenon studied [13, 14]. This paper presents part of the findings from the performed case study.

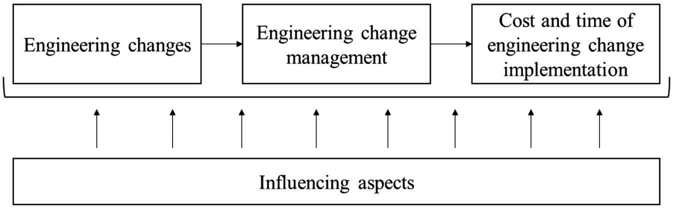


**Fig. 1.** Research framework

The data was collected over three years' time span and several visits to the case company, ranging from 1 to 5 days in duration. Several meetings and semi-structured interviews were conducted with deputy CEO, deputy managing director, business analysts, project managers, design and engineering managers, and production planners. The interviews consisted of two stages. At a first stage, ECM processes in the case company were mapped and ECM practices and tools used by the company were identified. At the second stage, interviewer went through the whole ECM process with the interview participants and asked what aspects were contributing to the way ECs are managed at each stage of the process, the number of occurring ECs, and finally their cost and time of implementation. Since no data on exact EC implementation time and cost is available in the company, qualitative measurement was used, - interview participants were asked to describe the degree of a given aspect's effect on EC implementation performance. In addition, documents related to ECs were collected, including descriptions of EC management procedures, change evaluation sheets, company presentations, publicly available information, and reports on the previous research projects conducted with the case company by the research group.

For data analysis, recommendations of Eisenhardt [14], and Miles, Huberman and Saldana [15] were followed. The NVivo software was used to store, transcribe, code and analyze the data. First, interviews were transcribed, and a narrative description of the case history was created, ECM processes were described, ECM practices and tools were identified. After that, a two-stage coding was performed. At the first stage, descriptive codes were assigned to data chunks to detect reoccurring patters in all interviews and the documents available in an inductive way. From this, at the second stage of coding, similar codes were clustered together to create a smaller number of categories (pattern codes). The results of the coding were tabulated to compare findings across different interviews. The researchers iterated repeatedly between the data and emergent theory until a strong match between theory and data was reached. Several main aspects were identified, but due to the limited length of the paper, only five (most mentioned by the interview participants) aspects are presented.

## 4 Case Study

The study was conducted in a Norwegian shipbuilding company (further called "N"). Typical shipbuilding project consists of following stages: design (concept, contract and basic), engineering, production, procurement, commissioning, and after-sale [3]. N performs several roles in shipbuilding industry, both as a ship designer, a shipyard, and a main equipment supplier. N is a part of global shipbuilding supply chain. This supply chain generally consists of four main actors: ship designer, shipyard, main equipment suppliers and shipowner (customer). In addition to that, classification organizations are involved; they establish and check technical standards for the construction and operations of ships. A simplified N's supply chain is presented in Fig. 2.

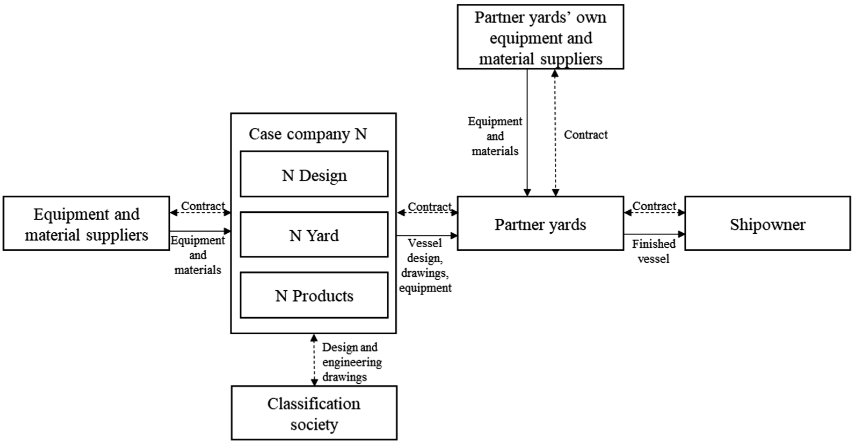


**Fig. 2.** Shipbuilding supply chain

First, N Design and ship owner develop and negotiate on vessel details. N designs vessels and delivers design to the own yard or sells to the external yard, depending on the customer preferences. Contractual relationships are established between the shipowner and the yard, meaning there are no contractual relationships between the designer and the shipowner. Detailed engineering is performed by the engineering team at the yard. Even though partner yards buy designs from N and carry contractual responsibility for delivering the vessel to the shipowner, both the designer and the yard share responsibility since the customer will receive a vessel with the designing company's brand name on it. Most often ship designer coordinates the engineering and procurement of the main equipment, however sometimes this equipment is procured by the yard or customer. In this case, designer does not have a direct contact with suppliers. In cases when the vessel is built in N yard, the hull is produced at external yards to cut shipbuilding costs. After the hull is towed to N yard, it is outfitted with main equipment, pipes, cabling, and HVAC in the dry dock. After that, the vessel is moved outside the dock, where final outfitting is done on the water. Procurement (especially procurement of main equipment) and production usually starts before the engineering is finished, which, according to the company, shortens project duration by up to 12 months. Project delivery time is around 2 years.

## 5 Aspects Affecting EC Implementation in Shipbuilding Projects

In this chapter, we provide five aspects that affect ECs and their implementation in the case company with some real-life examples.

**(1) Market Segment.** For a long time, main case company's specialty was building offshore support vessels (OSVs), but they have recently moved into a new market segment – cruise vessels. Here, professional culture, new standards, rules and regulations, and experience of the company were mentioned as three closely related aspects affecting ECs and their implementation in the company.

*Professional Culture.* Customers in OSV market were local, they had long relationships with N based on mutual trust. All issues related to ECs were resolved by making phone calls. New customers, however, are much more formal and stricter in their approach. Each issue is thoroughly checked against specifications and standards. Consequently, it takes much longer time to agree on who carries monetary responsibility for the change implementation. This is further complicated by the fact that N must work with *new specifications, rules and regulations* for cruise vessels. Often, something that was not an issue for OSVs appears an issue for the cruise vessel. This increases the number of ECs, which N is not able to predict in advance and must take full responsibility for. Ability to detect such potential issues in OSV market was based on the *experience of the company*, which still needs to be developed for the cruise vessels.

**(2) Supply Chain Network.** N operates in a global supply chain, where either design, engineering or production are often performed by external actors. Here, following aspects are affecting ECs: coordination of ECs across multiple companies, and competence and experience of external actors.

*Coordination of ECs Across Multiple Companies.* In shipbuilding projects design, engineering or production are often performed by separate companies. ECs in this situation result in higher number of iterations between the companies and longer EC implementation time. For example, if an EC propagates from the shipyard to one of the suppliers, receiving input from this supplier can be a bottleneck. The time for supplier to give the necessary information might be even longer if the design and engineering do not have a direct contact with the supplier. For example, in one of the projects several changes affecting the whole design of the vessel (i.e. stability, power supply, etc.) occurred. To update design drawings, N needed updated technical specifications from several suppliers (i.e. engine supplier). However, N was not able to contact them directly since it was external shipyard, not N, who had contracts with these suppliers. Hence, N had to resolve all issues by contacting the shipyard first, who in turn contacted the suppliers. This considerably increased EC processing time and led to project delays.

*Competence and Experience of External Actors.* N yard is able to cope with some minor design and engineering changes without necessarily involving the design and engineering departments. The yard is able to fix the issues and predict possible propagations of such change. External yards are often do not have such experience and the production often must be stopped to resolve occurred problems. For example, when building one of the offshore support vessels in a Chinese shipyard, a lot of problems with cargo system occurred, which could have been solved by the production stuff if the vessel would have been built locally. However, in case of a Chinese shipyard, production had to be stopped, drawings updated by N and translated into Chinese, which took additional several weeks of work.

**(3) Design maturity** affects both the number of ECs, and EC assessment and implementation. Projects with low levels of design maturity (e.g. maturity of the whole product or separate systems and parts) usually generates more changes in the downstream stages of the project. In addition to that, implementation of new technology makes it difficult to predict possible EC propagations to other systems of the vessel. For example, when building platform supply vessel, new exhaust system was introduced. The issue of back pressure on bending pipes was not immediately understood, which led to rework (rearranging pipes) at the production stage. Such propagations are very hard to detect, and they will typically be noticed at a later and more costly project stages; as noted by the interview respondents, cost of implementing EC in shipbuilding projects increases tenfold with each subsequent stage of the project.

**(4) Overlapping design, engineering, procurement and production stages** implies that instead of performing these activities sequentially, each activity starts before the previous is finished. By doing this, products are produced in less time. N follows this approach. However, this approach also implies that there should be design freezes at the design and engineering stages, after which changes are not allowed. However, the shipowner might want to introduce changes at any stage of the project. In this situation ECs affect a bigger number of activities and increases needed coordination efforts. For example, more ECs need to be handled by involving production stage because engineering was not finished before the start of production and incomplete drawings were shared between the project actors.

**(5) Timing of EC Occurrence.** As it was already mentioned, the cost of an EC implementation in shipbuilding projects increases tenfold with each subsequent stage of the project. Early ECs, before procurement and production has started, are resolved by engineering and only include administrative costs of changing the drawings. However, when moving into procurement and production, ECs lead to rework, demolition and scrap of already produced components. This finding is in line with the Rule of Ten, stating that the cost of ECs increases exponentially with each stage of the project, and hence late ECs should be avoided [16]. In addition to that, there are specific cost drivers appearing at different stages of shipbuilding process. The shipbuilding process consists of following stages: part production, block building, block outfitting, block (hull) assembly, dock outfitting and quay outfitting. For example, when moving from block building to block outfitting, following cost drivers will appear, such as reduced accessibility (workers need to operate in narrow spaces), higher risk of damage of already installed parts (some parts need to be covered and protected in case of rework). When moving from block outfitting to assembly, in addition to accessibility and risk of damage, following aspects need to be considered: crowdedness or stacking of trades (several production disciplines working in the same area, which leads to productivity decrease), vertical transportation and long distances to the place of work, work position (not possible to turn sections around). At the quay outfitting, all the spaces are closed, there is no roof in case of bad weather conditions (especially expensive for paint work), fewer available cranes. There additional production specifics of different types of vessels. For example, cruise vessels have 2–3 times more decks, which drastically increases travelling time for the workers.

All the above-mentioned aspects are not easily quantifiable, but they are important to understand and consider when implementing ECs in shipbuilding projects.

## 6 Conclusions and Further Research

This study had provided insights into some aspects affecting ECs and their implementation in shipbuilding projects. First, this study has showed that there are specific aspects of the shipbuilding industry that influence ECs, their management and implementation performance. Specifically, the study showed that entering into a new market segment, low competence and experience of actors in shipbuilding supply chain network, and a low maturity of the design increases the number of ECs at different stages of shipbuilding projects. Supply chain actors' experience and design maturity increase the chance of unpredicted EC propagations. Furthermore, different professional culture of the customers, global distributed supply chain network, competence of supply chain actors, design maturity, overlapping of project stages, and timing of EC occurrence are the aspects that contribute to EC implementation cost and time. These aspects should be taken into consideration by the researchers when working on ECM practices and tools. Future research should perform in-depth analysis of ECs in several shipbuilding (or ETO) projects to determine all the aspects contributing to EC implementation performance. A new approach for EC assessment that goes outside engineering design domain should and takes into consideration such aspects.

It is expected that this paper can support practitioners in making sense of ECs in complex shipbuilding projects. However, the results should be handled with care since, like any other single case study, this paper has its limitations in terms of external validity and generalizability.

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# Practical Guidelines for Production Planning and Control in HVLV Production

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**Abstract.** In this paper we will propose a set of considerations and guidelines we believe are critical to achieve efficient flow in non-repetitive production. The proposed factors are insights gained through application of lean principles to two cases of non-repetitive manufacturers.

**Keywords:** Make-to-order · Planning and control · Coordination for assembly

## 1 Introduction

High-variety, low volume (HVLV) manufacturing aims at providing manufacturing services tailored towards a variety of customised products. The level of product customisation offered by HVLV manufacturers can vary significantly ranging from standard products made to order to pure customisation where the entire product is designed and manufactured according to customer specification [1].

There is no clear consensus in extant literature as to the actual characteristics that constitute a HVLV manufacturer. Many definitions of HVLV production environments are related to supply chain structures and the customer decoupling point [2], however, propose decoupling of the engineering and production dimensions with a separate engineering dimension ranging from Engineer-To-Order, where a new product is designed, to Engineer-To-Stock, where a specific design is already "in stock". Between ETO and ETS engineering modifications are used in varying degrees [3]. In accordance with this, a definition of HVLV as non-repetitive manufacturing [4] is used here without distinguishing different degrees of engineering change or redesign. This to avoid the ambiguous characterisation of an ETO producer depending on the level of engineering content and the confusion surrounding the amount of design standardisation [3].

In this paper we will propose a set of considerations and guidelines we believe are critical to achieve efficient flow in non-repetitive production. The proposed factors are insights gained through application of lean principles to two cases of non-repetitive manufacturers.

Literature on non-repetitive manufacturing tend to focus on creating flow through either Work Load Control (WLC) or a card-based system, such as Conwip [5], Polca [6] and latest Cobacabana [7]. We find however that the challenge in producing products with complex structures, often is in coordinating the different flows of parts in


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order to assemble finished products. We have found little support in existing literature on how to synchronize the flow of unique parts from fabrication to assembly with the possible exemption of Polca [6]. By synchronization we understand the necessary coordination of fabrication lines for customized parts in order to have all parts available at assembly. The presence of synchronization constraints at assembly stations results in intractable analytical models for throughput estimation of fabrication/assembly systems [8]. This paper however proposes some practical guidelines for achieving better synchronization.

## 2 Cases

Case A is a manufacturer of ETO equipment for offshore and maritime industries. The company offers a wide range of tailor-made packages of different equipment for propulsion, manoeuvring and control systems for medium speed configurations. Their main products and spare parts for maintaining earlier installed equipment, are all manufactured at the same plant. The plant produces less than 500 units a year in a large variety of sizes and configurations.

In recent years the company has experienced a shift in demand towards increased physical size and configurations with more and larger machined parts. As a result, the workload of the plant per delivered unit has increased significantly as a result of more machined parts that also require more time for machining due to their size.

Case B produces customized hydraulic cylinders and dampers in a variety of configurations and sizes. The customization ranges from relatively simple modifications of rod and cylinder mountings to complete design of new cylinders according to customer technical specifications. About 50% of the revenue of the factory comes from producing large cylinders of more than 200 mm diameter, but this segment only makes up about 15% of the total number of cylinders. The company has quite recently invested in new machinery for machining large size cylinders and other parts and aims at creating more business in this segment.

Both case companies produce customized products that need to be managed like projects. The degree of customization in a product might vary, but all products contain some parts that are either unique to the customer order due to customization or some parts/components where demand is too low for stock-keeping, i.e. made-to-order.

The typical product structures for both case companies are complex with multiple level BOMs. The parts for several different products/projects are produced simultaneously utilizing the same production resources. All products include both fabrication of parts and assembly of finished products. The fabrication process is a mix of ETO/MTO (project specific) parts and more generic MTS parts. The product structures usually contain subassemblies with similar synchronization constraints as the main assembly. The necessary synchronisations have so far been achieved by routing all parts to stock before (sub-)assembly. This practice is not very lean.

Load distribution between products varies greatly. Many factors influence the choice of which resources to apply for a task, but these choices are often made during the engineering phase. The typical choice of resource is the most technically efficient in terms of processing time. In both companies there are few opportunities to reroute production through other resources with lesser load depending on the current situation although alternative routes are described in some cases.

## 3 Scheduling Challenge

With the fall in oil prices both case companies have experienced serious changes in the demand for their products. Most of their customers used to be in the oil exploration industry so the subsequent decline in activity forced the case companies to look for other markets at a time when many other companies were in a similar situation. Even for highly customised products/producers the typical trends today are:

- Increasing need for shorter delivery times
- Increasing product variety
- Capacity utilisation is still important for cost efficiency

Meeting these requirements implies a balancing act for scheduling: How to create shorter throughput time for all projects, and still maintain satisfactory capacity utilisation from a cost perspective?

## 4 Considerations

### 4.1 Uncertainty and Variations

A common feature of the production in both case companies is that many parts are Made-To-Order. Parts are made for a specific product/customer and there is only limited opportunity for using stocks as buffers. Non-repetitive manufacturing is inherently uncertain as there will always be limited experience in making parts that are sufficiently similar for comparison and guiding towards production time estimates. That some of the products will even be Engineer-To-Order will only add to this uncertainty.

Production buffers against variations are necessary but are limited to either time buffers or slack capacity (underutilisation of machinery) for non-repetitive production. Traditionally this type of industry has solved this by defining slack time either directly as extra time in the manufacturing process or indirectly by adding to process times.

According to [6] the use of slack time is a self-increasing spiral where long lead times imply the need for expediting jobs which in turn delay "normal" jobs and thereby increase the need for additional defined slack time. [9] proposes the use of capacity buffers and points to complex series of dysfunctional interaction that results from focus on the 100% capacity utilization. Adequate slack capacity is also an important condition for lean production.

The start/release of the assembly process should ensure the availability of all parts and the assembly operations thus require high inbound delivery precision. A special characteristic of this type of join operations is that the resulting variation on start-up time for the assembly will depend on the worst outcome of the preceding tasks and the likelihood of a long delay increases with the number of parts that should be assembled [10]. In practice this means that a buffer/slack time is required. The challenge is then to keep control of this buffer without having to resort to standard stock keeping practises. After all, these are non-standard parts assigned to a specific project.

### 4.2 Shifting Bottlenecks and Capacity Utilization

Customization implies that both product structure and routing as well as workload will change from project to project. This creates shifting bottlenecks in fabrication depending on the product mix. These bottlenecks determine the possible throughput of the production system and thus determine the response-time for the project.

Ideally you would want to plan and release workorders to the shop floor that balances workload between the available resources [11]. The result of a balanced workload will be the overall fastest throughput of the production system, but the lack of synchronization between the different value streams may lead to a lot of parts and no finished product.

The sequence of a given mix of project orders has a major impact on the workload distribution on resources and the location of the bottleneck(s). The Cobacana card-based system for workload control [7] claims to achieve a better balance of workloads through managing workloads for the different work-centres when orders are released to the shop floor. Orders with workloads that doesn't fit the current reservations of capacity on the shop floor will sit in a pre-shop pool until the situation changes or the order must be released for due date adherence. Coordination between the fabrication of different parts are however not addressed directly and seems to be dependent on the order release and priority in dispatching jobs between work-centres.

### 4.3 Critical Time Path/Critical Chain of Production Activities

For all products there exists a critical time path indicating the value stream that takes the longest time to finish. All activities on this path must be completed in time or the throughput time of the product will increase. All other activities on the other hand have slack time.

A machine resource is often used to make more than one part for a project. Finding the critical time path thus involve mapping the production as an activity network with the extra restriction that each resource can only process one part at a time.

When several projects are combined in a workflow, the critical paths do not necessarily coincide with the critical chain of activities. The critical chain of production activities will all be located at the present bottleneck resource while the critical time path by definition is related to the throughput time of the project. The sequence and mix of projects will determine which potential bottleneck is active.

Most non-repetitive manufacturers that do both fabrication and assembly, produce modifications on a small number of basic designs. Each product is thereby unique but contain many of the same parts and subassemblies as other projects based on the same basic design. The different basic designs can be thought to generate product families with enough similarities as to routings and estimated workloads. A structured method to define and use product families in designing production control is found in [12]. Using the routings and workload-norm of the product families we can investigate the limitations and resulting bottlenecks for possible production mixes. Changing the product family mix will give rise to shifts in bottleneck resource. Templates based on product families may in other words form the basis for rough-cut capacity planning.

## 5 Proposed Guidelines

We propose takt based planning and control as the planning and control principle for non-repetitive manufacturing. Takt defines how many customized products of a certain type or family the manufacturing system will complete in a fixed time period. Each product family has a defined takt based on prior investigation of how the mix will affect sequencing and resource utilization at the resulting bottlenecks.

### 5.1 All Parts and Subassemblies Must Be Finished Before Final Assembly of a Product

In our interpretation this means finishing the products one-by-one in each assembly cell. There is no 90% finished when it comes to preparing for assembly. Missing one part will stop the assembly process and it will need to be restarted when the part becomes available later.

Final assembly might not be the final activity in the production process, but it's usually the last point where the separate value chains come together (marriage point). Activities that follow the final assembly may be successfully controlled by FIFO chains.

### 5.2 Develop a Takt-Based Plan Using Product Family

We propose that rough-cut capacity plans are made using product families as templates. As pointed out earlier the templates may serve to identify the bottlenecks in producing a certain mix of products. The bottleneck resource defines the maximum output from the production system. Changes in the mix may move the bottleneck to a different resource but the idea is that for a time period the mix of products can be estimated and will also be quite stable. The maximum output for each of the product families will that way be coordinated through the identified bottleneck resource.

The next question is then how to sequence the different production orders. We propose takt time control because takt in addition to levelling activity at the bottleneck also provides opportunities for control and coordination at predictable points in time. For non-bottleneck resources the time leading up to final assembly will include some slack. How much slack depend on the total workload from all products that are produced simultaneously but this excess production capacity may also be utilised for MTS production of generic parts or service parts. Having predictable time limits thus offer other opportunities for fabrication that will not interfere with production of customised products.

### 5.3 Insert Time Buffers Before Join Operations in the Production Process

Before assembly all parts must be available, and this will in our opinion require a buffer before assembly. With takt-based planning and control assembly occurs at regular intervals for each product family and the size of the buffer may reflect the size of normal variations in processing times for that family. A buffer for variations in real processing times can be achieved either through establishing time buffers/WIP, the use of capacity buffers (excess/unplanned production capacity) or a combination of both. With takt time control the size of the WIP buffer translates directly to available time for fixing variations in processing times. Major disruptions will still have to (and should) be handled outside the production lines.

### 5.4 Plan the Sequence of Projects in Production (Operation Plan)

Having excess production capacity (slack) for non-bottleneck resources does not ensure that deliveries can be made to the schedule set by Takt. A plan for latest start of all production activities timed to deliver parts according to takt, will often show conflicts in allocation of capacity between the different products. Often this can be fixed by starting some activities earlier but sometimes the routings prohibit earlier start. However, these sequencing problems may be resolved in various ways including extra/slack capacity, rerouting of parts, etc. The point is that many of these options are available at the planning stage but are more limited when executing the plan.

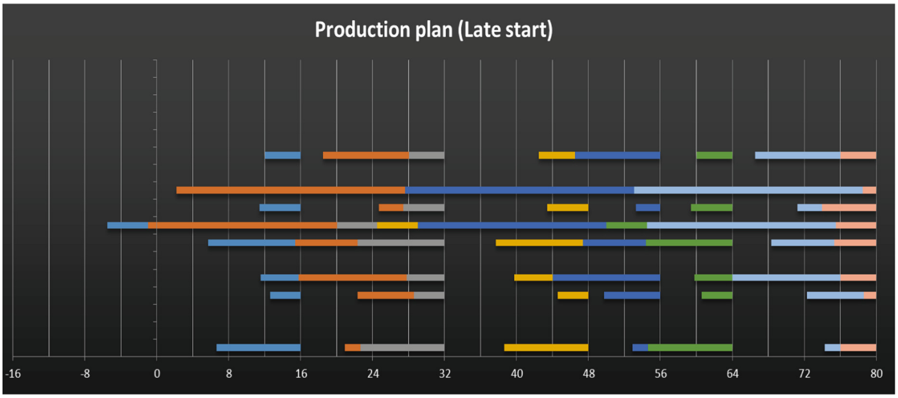


**Fig. 1.** Operation plan for a week (Color figure online)

Some of the concerns are shown in Fig. 1. The figure shows capacity usage by different machine centres (lines in the fig). The plan is for fabrication of all parts of 8 products belonging to two different product families/assembly lines. Each colour bar represents capacity usage for fabrication of a product at each machine centre. Parts should be delivered to assembly line 1 at the end of each day (16 h) and to assembly line 2 each 1,5 day. The plan shows a situation with almost 2 bottleneck resources but the capacity usage at both are within the limit of what can be accommodated. Changes in the production sequence on non-bottleneck machines will however in many cases lead to delayed delivery for assembly.

We propose that an operations plan is made using the real estimates for all products. The objective of this planning activity is to identify these conflict areas and plan how this should be resolved before production is started.

### 5.5 Execute and Evaluate the Operations Plan

Planned times and resource utilization are estimates and deviations will occur. Disruptive events such as machine breakdowns or scrap production we hold to be beyond the scope of the planning system. These types of problems should be managed as exceptions, maybe using the capacity reserve set aside for those purposes. Deviations are thereby limited to naturally occurring variations and buffers should be used to eliminate the accumulation of delaying effects. The size of the buffers needs to be monitored.

We propose that the sequence of projects/customer orders is maintained in production of all parts and subassemblies, unless there has been a disruptive event that renders the plan impossible to implement. Using slack capacity to produce a part for another product with a later due date will not speed up the finishing of that product unless all the other parts for that product also can be accommodated. Changing the sequence of products in parts or subassemblies production thus seldom has positive impact on throughput times and will increase work in progress and confusion about priorities. The objective should be to find a sequence of products that optimizes the use of production capacity in the first place.

## 6 Experience and Further Work

The considerations and guidelines evolved trying to apply lean principles to the production of case A. Their products are complex with a lot of fabricated parts and subassemblies. Several methodologies for lean production control where considered. Inspired by the work of Duggan [12] we arrived at using the assembly subprocess as pacemaker and two distinct product families were identified. The process time of the assembly activities did not vary much within each product family which suggested the use of Takt to coordinate fabrication.

The guidelines we propose is not all that different from standard practice in hierarchical planning with ERP. The major differences are: (1) the investigation of how production mix affects production bottlenecks and (2) the use of Takt to regulate deliveries to the chosen pacemakers.

Initially the guidelines were quite successful by reducing the throughput time of a whole unit by 50%. However, the change in demand brought on by the reduction of oil prices has changed the dynamics of the production system to the extent that our current model for rough-cut planning doesn't work.

Without a working model for rough-cut capacity planning we are not be able to predict how the mix of products may create other bottlenecks than our assigned pacemaker; the assembly process. We are currently working on a new model for rough-cut planning that can accommodate more product families and describe the capacity constraints of different product mixes. We still believe that template BOM/WBS based on product families are adequate estimates for this purpose.

Investigating product families in case B has shown that 70% of the number of cylinders they make are sufficiently similar to organize their production in separate dedicated lines. In other words, the work involved in applying the guidelines has led to better knowledge about the production system that suggested other improvements.

Other areas that need more research are among several; priorities in release of workorders and in execution, a model for operations planning that supports different routings for different parts, joining the routings at assembly and the fact that a machine normally only can process one at a time. We expect that such a model will be a hybrid between a project model and MRP.

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# APS Feasibility in an Engineer to Order Environment

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**Abstract.** This paper discus the feasibility of using advanced planning and scheduling (APS) in an engineer to order manufacturing company. The starting point is a company producing customised variants of standard products involving engineering, machining, sub-assembly, and final assembly operations. There is limited degree of parts commonality as the product variety is high with respect to material and size. APS is normally used in repetitive manufacturing companies but we argue that some ETO companies with a somewhat fixed planning setup could benefit of implementing an APS engine on top of their ERP system. One of the critical elements is, however, whether the company is able to formalise their tacit knowledge in the complicated planning processes to rules and options in an APS environment.

**Keywords:** Engineer to order (ETO) · One-of-a-kind production (OKP) · Advanced Planning and Scheduling (APS) · Enterprise Resource Planning (ERP)

## 1 Introduction

In this paper, we investigate the feasibility of using Advanced Planning and Scheduling (APS) in an engineer to order (ETO) company. APS is mainly used in repetitive manufacturing companies and has become the state-of-the-art within planning and control adding features such as comparing different planning scenarios before plan release.

Manufacturing planning and control systems have gradually developed from simple materials requirements planning towards handling a large variety of core elements in a manufacturing company such as capacity planning, finance, human resources and payrolls [1, 2]. Enterprise Resource Planning (ERP) and Advanced Planning and Scheduling (APS) systems have improved the integration of materials and capacity planning. While MRP systems merely calculated the materials and capacity requirements, APS systems have the ability to create a feasible plan way faster and better than previous systems which involved a number of iterations with manual adjustments [1–3]. APS require good input in terms of data quality and this is more difficult in an ETO company compared to a repetitive manufacturing environment [4]. Further, APS


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systems are very expensive and for many small and midsize companies, it is a question as to whether a high investment in an APS system pays off [3].

Engineer-to-order products are engineered to the specific requirements of the customer order [5]. Each customer order results in a unique set of part numbers, bills of material, and routings for manufacturing. The engineer-to-order strategy is suitable for highly customised, capital intensive, one-of-a-kind products [6]. An engineer-to-order strategy implies that engineering is involved in order fulfilment. The level of engineering adaption to customer requirements can range from new product development to minor modifications to an existing product [7]. Engineering and manufacturing activities are often performed concurrently, and engineering changes can happen in all phases of the order fulfilment process, including manufacturing [8]. The engineer-to-order strategy means a high level of uncertainty in terms of product specifications, demand composition, supply and delivery times, and processing times [9].

The engineering process is an iterative process that aims to find the best solution together with customers and suppliers. Since the design of an ETO product is not realised until after the engineering process have been completed, the information available for planning is limited [10]. The final product structure, routings, and processing requirements are not known before detailed engineering is complete. Manufacturing will basically make a new product for each order, and the uncertainty and variations in processing times can be high.

## 2 Industry Case

This study takes a starting point in a capital intensive Engineer to Order (ETO) case company producing large products with a low to medium engineering complexity. The product structure is deep and includes several sub-assemblies and parts. Manufacturing involves machining, sub-assembly, and final assembly operations. A typical product consists of more than 500 parts, where less than 20 pct. of the parts are engineered to order. There is limited degree of parts commonality as the product variety is high with respect to material and size leading to high inventory levels. The non-customised products stems mainly from one generic unit. Customer orders typically starts with a tender several months ahead. However, it is common that orders are changed in terms of delivery dates and engineering specification adjustments both before and during manufacturing. The design uncertainty is therefore fairly high through the whole order fulfilment process.

Most ETO products are constructed from a mix of parts with different level of customization. There might be cases where the entire product is engineered-to-order. Usually, a large share of the elements has standard design and are made-to-stock or made-to-order. Standard parts and assemblies that are required in low volumes are often made-to-order (or assembled-to-order) while standard parts required in higher volumes are made-to-stock.

To level production and to comply with short lead times, some production orders are initiated before the customer order has been fully specified. Forecasts of expected new orders are used to initialize purchasing to deal with long lead times, as well as production of standard items. High volume spare parts are produced to stock whilst low volume and customised parts are produced as rush orders due to the criticality of deliveries.

The company has developed a configurator to generate customer order specification including manufacturing and purchase order input. This involves selection of process flow and estimation of processing times. This enables the company to use an ERP backbone for planning instead of a project management application which some OKP companies favour. Compared to a repetitive manufacturing company this limits to some degree the quality of the detailed planning process due to the uncertainty of the processing times. The main planning processes are described in Table 1.

**Table 1.** Main planning processes in the case company

| Process | Sales and operations planning | Master production planning | Shop floor control |
|---|---|---|---|
| Time horizon | 6–18 months before delivery | 3–18 months before delivery | 0–3 months before delivery |
| Main objective | Set delivery week for tenders, and balance mix to ensure sufficient capacity | Set sequence in order to compress product through-put times | Balance the flow during manufacturing and handle interruptions |
| Description | Supply planning of internal capacity (feasible mix pr. week) and deliveries from suppliers | Rough-cut capacity planning on critical resources to find feasible product sequence pr. week | Monitoring and control of the flow from fabrication throughout assembly |
| ERP-support | Estimate material and capacity requirements, and to issue long lead-time purchase orders | Calculate material and capacity requirements, and to issue short lead-time purchase orders | Keep track of job status and inventory status |
| Available data | Customer design and delivery preferences, ERP templates for similar parts in terms of BOMs, routings and processing times | Final specifications in terms of BOMs, routings, and more accurate processing times | Inventory status<br>Job status for some workstations (started, completed) |
| Manual decision making | Delivery due date setting. Capacity balancing. Expedite and postpone manufacturing due dates<br>Find alternative resources when overload. Make-or-buy analysis. Supplier selection | Detailed capacity balancing on critical resources. Sequencing of order specific parts Decide which MTS parts and service parts to produce to fill up slack capacity Handle delays in detailed design and purchased parts | Resequencing of machining and assembly orders to reduce number of open orders and delays. Take countermeasures (e.g. overtime, reallocation of operators, re-allocation of parts between projects) to increase capacity or material availability |

Sales and operations planning (S&OP) is performed to estimate delivery dates for bids and aftermarket requests. This is a collaborative process that involves other disciplines such as sales and engineering. Only an overall product specification and design exists at the bidding stage, so the material and capacity requirements will not be accurate. The planning involves a high level of human judgement and is mainly performed on standalone tools for rough-cut planning. A small but profitable share of the sales comes from the aftermarket, and these products often need to be delivered on a shorter notice than ordinary products. A main task for the planner is, therefore, to revise the plan in order to include aftermarket orders and still keep customer deadlines for all products.

With regards to master production planning and shop floor control, the main task for the planner is to find a mix of products per week that ensures sufficient capacity on bottleneck resources and, if needed, to add extra capacity in terms of overtime or outsourcing. There are large variations in work content from product to product, so the likelihood of capacity shortage on some critical work stations or machines is high.

A more accurate material requirement planning is performed after the complete and detailed BOM is handed over from engineering. Work orders are generated by the ERP system and released before start of production. The detailed BOM enables the planner to check the real capacity utilization for each critical resource and to make counter measures if required.

When production has started the progress is monitored by the planner to check that all fabricated and purchased parts are available in time for assembly operations. As the assembly stations receives a broad range of manufactured and purchased parts, the risk of delay is substantial. Identified challenges includes rush orders, engineering change orders, supplier delays, defects on incoming parts, lack of pre-fabricated materials, lack of personnel, set-up problems, lack of correct jigs or variations and uncertainty in processing times for customised parts. Further, shop floor operators may request changed sequences to increase efficiency on machine cells. The main task for the planner is to cope with all variations and create a flow of parts that reduces delays in assembly.

### 2.1 Summary of Planning Challenges

The high degree of customisation, the many engineering changes and the long lead times from suppliers forms a complicated planning environment. On top of this comes the challenges of after sales (rush) orders and a desire to level the production and assembly resources. The challenges are divided in (a) short range planning and scheduling and (b) long range sales and operations planning:

(a) Short range: Most importantly the plan must secure an assembly of products according to customer delivery dates ensuring a balanced capacity load. Different mix configurations generate large variations in work content and shifting bottlenecks. Rescheduling is initiated by customer changes, supplier changes, and shop floor challenges

(b) Long range: Most importantly the plan must include rough cut capacity considerations and supplier availability based on accepted orders and tenders. The final product structure, routings, and processing requirements are not known before detailed engineering is complete. At this stage, product data, processing times and lead times are estimates from a sales configurator which leads to some uncertainty regarding the capacity and supplier constraints. This includes forecasting on materials and capacity needs are somewhat difficult in a OKP environment due to the uncertainty not only on quantities and models but also actual configuration.

## 3 APS Feasibility in an Engineer to Order Company

Advanced planning systems utilize complex mathematical algorithms to forecast demand, to plan and schedule production within specified constraints, and to derive optimal sourcing and product-mix solutions. APS seeks to find feasible, near optimal plans while potential bottlenecks are considered explicitly. Unlike ERP, Materials and capacity issues are considered simultaneously and thereby avoiding ERP planning process with multiple recalculations to obtain the feasible plan both materials- and capacity wise.

APS-systems aim at reducing costs of goods sold and to increase customer satisfaction by initiating production at the best time, using an optimal combination of manufacturing resources. This enables the generation of a far more realistic and reliable production plans than ERP systems [1]. When multiple objectives exist in a manufacturing environment, and most of these are in conflict with each another, an approach is needed for modelling and evaluating the trade-off among the conflicting objectives. Here two options exist, constraint based planning and optimization.

Constrained based planning is based on hard and soft (or goal) constraints. Its distinguished feature is that the objectives can be stated as minimising deviations from pre-specified goals. Hard constraints are not overruled, whereas soft constraints are overruled, if necessary. As no plan optimisation objectives or criteria are considered, this option produces a feasible but not necessarily an optimal plan although a hidden plan objective function minimizing the plan costs is used to drive the planning and trade-off among the soft constraints.

Optimised plans are generated based on plan objectives, penalty factors, and constraints besides the hard and soft constraints. The constraint-based rules are exchanged with decision variables and penalty factors. As in the constraint based plan, hard constraints are not overruled, where soft constraints might be overruled if this reduces the total costs. As an example, overtime work will be preferred in order to avoid late delivery if the penalty for late demand is higher than the penalty for exceeding resource capacity. Industry studies show that optimised plans are rarely used in industry as it is difficult to convert all business decisions into a cost perspective (e.g. late delivery versus overtime work of reduced inventory turns) [4].

As APS is an add-on to ERP, most APS implementations and case studies have been conducted in repetitive manufacturing or process industry (automobile, dairy, oil, steel industry, etc.). We have only identified one study on APS in an ETO environment dealing with possible improvements in a shipyard by adding an APS module to the current ERP system [10]. As little help on this issue is found in literature we have chosen to evaluate the pros and cons according to the challenges identified in the previous section (Table 2).

**Table 2.** Short and long range planning challenges and possible APS support

| Planning challenges | APS support |
|---|---|
| Multiple ERP-run's to adjust the manufacturing plan according to capacity (machines, manpower, and jigs), sequence, materials supply, assembly capacity and customer order lead times | One single APS-run that satisfies all hard constraints and, if possible, soft constrains. The critical issue is the ability to model all the constraints which the planner takes into consideration, not least the estimated process times for new variants |
| Due-day setting of tenders and new orders, based on rough cut capacity considerations and supplier availability. Product data and processing times are estimates from a sales configurator. Forecasting of materials in spite of uncertainties regarding final specifications | Parts of this decision process are well supported by APS but the uncertainties in the engineering phase, as well as the complexity of the sales configurator, makes the value of APS support more doubtful. The most valuable functionality is probably fast what-if scenarios |

The modelling and implementation aspects are discussed in the following section.

## 4 Discussion and Conclusion

The paper has presented an in-depth single case study in an ETO company with the purpose of identifying the feasibility of implementing an APS module on top of their ERP system. APS functionality in terms of short and long term planning has been discussed both theoretically and in practice. However, an important factor for successful implementation of APS is a correct and consistent model [13]. The modelling aspects will, therefore, be briefly discussed in the following.

A supply chain or a manufacturing system can be simple, complicated, or complex [11]. Simple systems have a small number of well-understood components. Complicated systems have many components that interact through predefined coordination. Linear relationships between components that make the behaviour of the overall system predictable, and hence possible to model. Complex systems on the other hand, typically have many components that can autonomously interact through emergent, non-linear rules. This non-linearity makes it impossible to fully predict the overall systems behaviour by knowing its structure and components and hence makes them challenging to model [12]. Inspired by [11–14] the following Table 3 have been constructed:

**Table 3.** Evaluation of APS support in the case company where (↑) indicates high degree of support etc. Inspired by [11–14]

| Factors | Sales and operations planning | Master production planning | Shop floor control |
|---|---|---|---|
| Decisions complicatedness | Medium (↑) | High (↑) | High (↑) |
| Decisions complexity | Medium (-) | Medium (-) | High (↓) |
| Data availability and quality | Low (↓) | Medium (-) | Medium (-) |
| Uncertainty, disruptions, variations | High (↑) | High (↑) | High (↑) |

The planner's value of an APS model is briefly evaluated on 5 factors from Table 3 above:

1. Decision complicatedness. Complicated planning problems can be hard to solve because they include many objectives and elements, but they are addressable with rules and recipes and can be modelled.
2. Decision complexity. Complex planning problems involve many unknown and interrelated factors that must be modelled in terms of rules and processes in a model. A valuable APS model must capture sufficient aspects of the planning problem to provide correct decisions support.
3. Level of aggregation. Aggregation is a process for simplifying a problem by defining condensed data and decision variables [13]. An aggregated model will be less complicated and require less data but provide less detailed answers.
4. Data availability and quality. APS systems rely on a significant amount of detailed and accurate data. Basic data such as item data, bill-of material data, routing data and work centre data, as well as operational data such as inventory status, delivery date requirements and resource utilisation. These data has to be available and have sufficient quality in order to make a feasible plan.
5. Uncertainty and variations. APS systems are well-suited for complicated tasks where the demand and supply are uncertain and fluctuating [14]. However, determining production targets and detailed schedules can be significantly influenced by interruptions such as defects, varying processing times, material changes, engineering changes, sequence-rules that are not followed, maintenance stops, rush orders, prototype work, etc. Such factors reduce the planning correctness, as well as frequent updates of the APS plan can create planning nervousness.

Based on the analysis, the pros and cons of APS in an ETO environment and the 5 factors described above, it has been decided to develop tree demonstrators in terms of constraint-based models of (1) Sales and Operations Planning (due-date settings) and (2) Master Production Scheduling (assembly order sequencing) and (3) Shop Floor Control (machine cell job allocation). The outcome of this work will be used in the final decision making as to whether an APS system is likely to improve the current planning setup. The difficult parts of this work is to enrich the current machine data with alternative routes and process times as well as the tacit knowledge of planners and foremen on e.g. machine and operator capabilities which is currently not formalised in the ERP-system but has a great impact of the useability of the plan. Based on the outcome of the demonstrator a final assessment of the feasibility of implementing APS in the case company will be conducted. In case of a fruitful outcome of the demonstrator, the critical elements of the model development will be used as requirements in the selection phase of the best-fit APS system.

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# The Operator 4.0 and the Internet of Things, Services and People

# Empowering and Engaging Solutions for Operator 4.0 – Acceptance and Foreseen Impacts by Factory Workers

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**Abstract.** Industry 4.0 factories require smart and skilled operators – Operators 4.0. We evaluated three Operator 4.0 solutions that aim to empower and engage workers, so that workers can understand and develop their own competences and they can take an active role in developing the manufacturing environment. 118 shop stewards from different factories assessed user experience, user acceptance and foreseen impacts of the solutions. The results show that there are high expectations towards the virtual factory-based participatory design solution. Opinions were shared about empowering the worker by feedback about worker well-being and work achievements. The solution was seen interesting and useful but there were doubts regarding privacy. Contextual knowledge sharing was felt important but the workers were a bit skeptical as many previous knowledge sharing attempts had been failed. The results give insight to how the solutions should be further developed and how the solutions should be introduced at factory floor.

**Keywords:** Operator 4.0 · User study · User experience · User acceptance · Impact assessment

## 1 Introduction

A central component of Industry 4.0 is its human-centricity, described as development towards the Operator 4.0 concept [1]. Operator 4.0 refers to smart and skilled operators of the future, who will be assisted by automated systems allowing the operators to utilize and develop their creative, innovative and improvisational skills, without compromising production objectives [1]. In future industrial environments, workers are expected to act as strategic decision-makers and flexible problem-solvers [2]. Romero et al. [1] postulated an Operator 4.0 typology with eight different operator types such as Healthy Operator, Collaborative Operator and Social Operator. In later papers, Romero et al. further defined the concepts of Healthy Operator [3] and Social Operator [4]. The visionary papers introduce future concepts but not yet evaluation results.


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Cognitive workload can be relieved by assessing the operator's well-being at work by using wearable technology [3]. With the advances in personal, wearable health technologies, employees can get empowering feedback on their well-being [5]. Virtual reality (VR) technologies are valid tools to support participatory design (PD), because they support common understanding and collaboration among designers and users [6]. To improve team performance, organizations must ensure that knowledge is both shared and applied [7]. New technologies can encourage collaboration among workers, support problem-solving and bring together the right people [4]. The Operator 4.0 paradigm shift cannot succeed simply by introducing new technologies to the factory floor, but work processes need to be reshaped in parallel [8].

The aim of the study described in this paper was to evaluate user experience, user acceptance and foreseen impacts of three Operator 4.0 solutions developed in the Factory2Fit project (www.factory2fit.eu): *Worker Feedback Dashboard, Participatory Design with a Virtual Factory and Contextual Knowledge Sharing*. The solutions can be seen as examples of Operator 4.0 types Healthy Operator, Virtual Operator and Social Operator as defined by Romero et al. [1, 3, 4]. The leading idea of the solutions is that the workers are the best experts of their own work and they should be given effective possibilities to develop their competence, based on their own initiative, and their role should be more active in designing and developing manufacturing processes [8].

In this paper we describe the three Operator 4.0 solutions in Sect. 2. In Sect. 3 we describe the methods, in Sect. 4 the results and in Sect. 5 conclusions.

## 2 The Empowering and Engaging Operator 4.0 Solutions

In the following, we describe the three solutions that we assessed with factory workers.

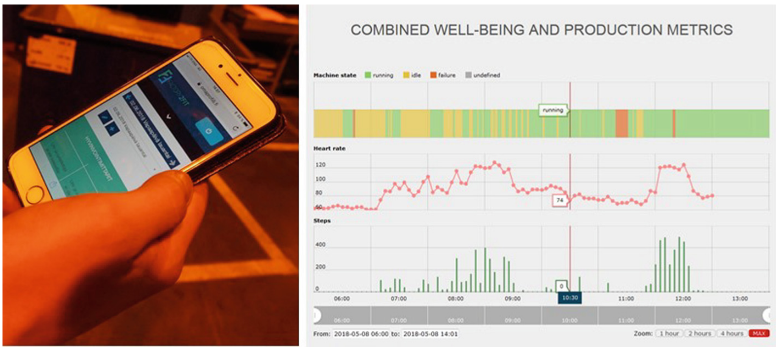


**Fig. 1.** Worker Feedback Dashboard.

**Worker Feedback Dashboard** (Fig. 1) is a web-based solution that provides data-driven, personal feedback to workers about their well-being and work performance [9]. It highlights the accomplishments of the day, creates awareness of the possible relations between selected well-being and production measures and demonstrates progress and development at work. The solution shows both visualized work shift-specific data as well as longer-term trends. The feedback is generated mainly based on automatically collected data: well-being metrics from a personal well-being tracker, such as an activity wristband and work performance metrics from the factory production system.

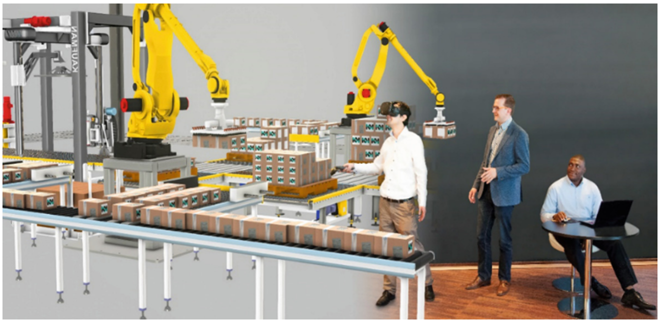

**Fig. 2.** Participatory design with a virtual factory.

**Participatory Design with a Virtual Factory** supports co-design of factory work with all stakeholders, such as workers, supervisors, management and R&D [10]. A 3D simulation and visualization platform (Visual Components 4.1) is used as the virtual factory platform. It allows the creation of virtual factory layouts at different levels of detail from a simple machine to the entire factory floor (Fig. 2). The virtual factory supports gaining a shared understanding of the design and sharing knowledge. During a participatory design session, the virtual factory can be viewed via a projector, or it can be experienced more realistically with a head-mounted display (Fig. 2).

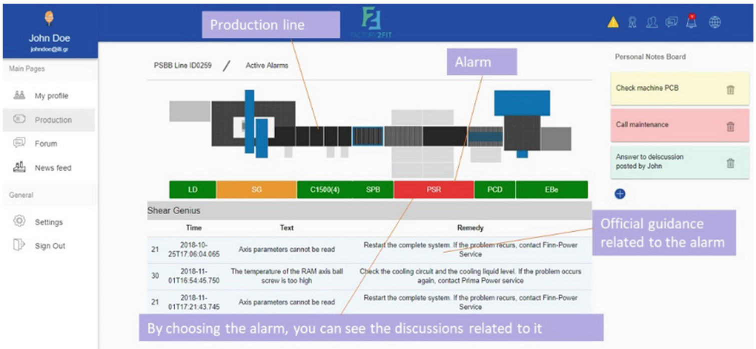


**Fig. 3.** Contextual Knowledge Sharing integrated into the user interface of a production line.

**Contextual Knowledge Sharing** is a platform for work-related discussions, connected to the physical work context such as work machines [10]. The objective of Contextual Knowledge Sharing is to support collaboration, problem solving and knowledge sharing among workers. The solution can be used in one factory or the discussion can be extended to several factories with similar productions. Contextual Knowledge Sharing can be used with a computer or mobile device. It is preferably integrated into other factory information systems (Fig. 3), so that discussions are connected to actual machines and situations on the factory floor.

## 3 Methods

The Industrial Union is the largest trade union in Finland representing workers in the metals, manufacturing and paper industries. Factory2Fit solutions were presented to the representatives of the Industrial Union, who were in charge of organizing their annual meeting. They chose three Operator 4.0 solutions for the evaluation, based on their relevance to the annual meeting participants. Sharing interesting knowledge was important to ensure mutual benefit for both the participants and the Factory2Fit project.

During the Industrial Union's annual meeting, three workshops were organized, one for each Operator 4.0 solution to be assessed. The workshops were repeated nine times, each lasting for 20 min with 10–15 participants. The participant groups remained the same in each workshop but the order of the workshops varied between the groups. In total, 118 shop stewards participated in the workshops. They all filled in a questionnaire that was based on Work Well-being Design and Evaluation Framework [11] and studied user experience, user acceptance and foreseen impacts on work satisfaction and productivity. Each workshop had the following agenda: (1) workshop host presented the solution with slides and video demos; (2) the participants discussed the solution, and (3) the participants filled in the questionnaire.

21% of the participants were female and 79% male. All the participants were working in industry: 31% in large enterprises, 52% in medium-size enterprises and 17% in small companies. 72% of the participants were 40–59 years old, 20% under 40 and 8% were over 60. The participants were all shop stewards, so in that sense they were quite a homogenous group. However, as they came from different sized enterprises, there were differences especially in the degree of digitalization at their workplace.

## 4 Results

Figure 4 illustrates the user experience of the solutions. Participatory design had the best user experience but also the two other concepts had mainly positive user experiences.

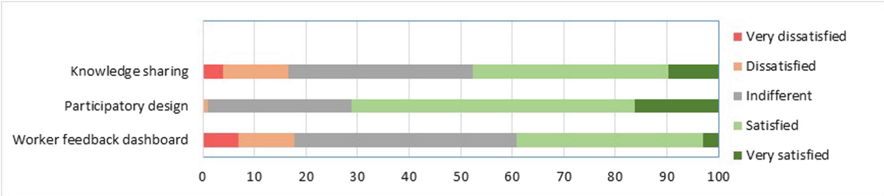


**Fig. 4.** User experience of the solutions.

### 4.1 Worker Feedback Dashboard

The Worker Feedback Dashboard clearly divided the opinions of the respondents (Fig. 5). 41% of the respondents considered the solution suitable for factory work while 21% responded that it would not fit factory work. 37% of the respondents were willing to use the solution themselves while 34% were not interested in using the solution in their work. About half of the respondents neither agreed nor disagreed on whether using the solution would improve productivity or work satisfaction. Positive impacts on productivity were expected by 20% of the participants, and positive impacts on work satisfaction by 23% of the participants.

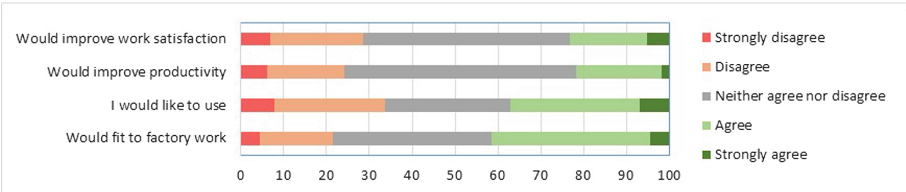


**Fig. 5.** Results of the Worker Feedback Dashboard assessment.

In most of the workshops, the Worker Feedback Dashboard solution raised several questions and vivid discussion. The participants asked questions related to the properties of the solution (e.g., what can be quantified) and the details and usefulness of the measurements. In some groups, the discussion was mainly neutral or positive, while in other groups the discussion focused on the potential risks of the solution. 49 respondents gave free feedback about the solution on the questionnaire. The main concerns were related to data security and privacy, and the participants were skeptical of whether the personal data would stay non-accessible to the employer.

### 4.2 Participatory Design with a Virtual Factory

The Participatory Design with a Virtual Factory was well accepted and positive impacts were foreseen (Fig. 6). 77% of the participants agreed that this kind of solution would fit to factory work. 62% of the participants agreed that they would like to use this kind of solution in their work. Most participants agreed that the solutions would improve productivity (76%) and work satisfaction (66%).

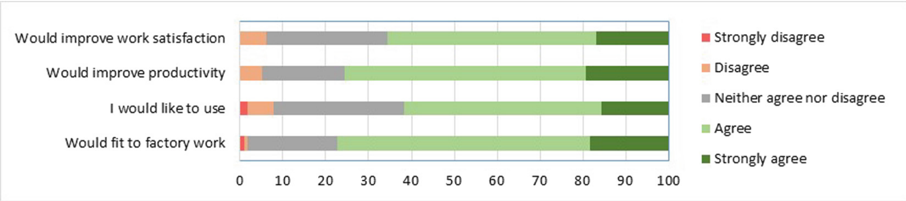


**Fig. 6.** Results of the Participatory Design with Virtual Factory assessment.

The participants provided feedback both on the questionnaire and during the discussions. 53 participants provided comments on the questionnaire. For some participants, the solution was quite new, whereas others had already been using similar solutions at work. The participants agreed that adopting the solution is already topical or will be in the near future. The participants liked the idea that workers are able to participate in the design of their own work but were concerned that employers would not listen to them. The participants commented that the solution could decrease time and costs during layout changes by instantly designing good layouts. With well-designed production lines, productivity will increase. Some participants were concerned that if only productivity and efficiency are improved, there would be no positive impact on work satisfaction.

## 4.3 Contextual Knowledge Sharing

With Contextual Knowledge Sharing, results were distributed (Fig. 7) but so that positive responses outnumbered the negative ones and the moderately positive attitude towards the knowledge sharing platform was the most dominant. As much as 50% of the respondents considered the solution suitable for factory work and, furthermore, the majority of respondents (56%) thought that the solution would improve work productivity. However, less than half of respondents (44%) were willing to use the solution themselves and only 39% assumed the solution would improve work satisfaction.

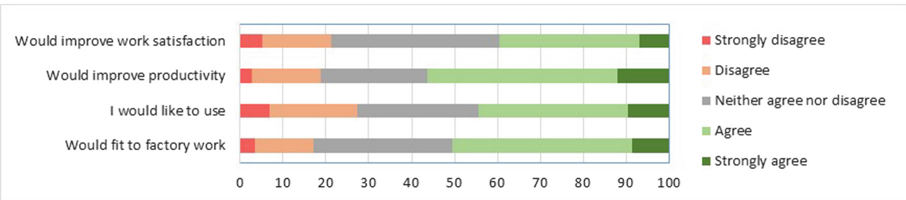


**Fig. 7.** Results of the knowledge sharing solution assessment.

Even if the feedback on the questionnaires was mainly positive, the discussion and the comments tended to focus on foreseen problems and concerns. 57 participants provided comments on the questionnaire and discussion was always raised during the solution presentation. Respondents suggested suitable usage contexts such as maintenance and problem-solving. The solution was not found appropriate when, e.g., a phone is not allowed at a workplace or when work is highly manual. Some participants did not fully understand the contextuality of the solution and claimed that similar solutions exist already. There were concerns that the usage will require too much time or attention at work, causing various types of risks; or that people are not willing or able to share their knowledge, especially in written form.

## 5 Conclusions

The feedback was mainly positive but there were also concerns, especially related to the Worker Feedback Dashboard and Contextual Knowledge Sharing. Participatory Design with a Virtual Factory was clearly the most accepted solution.

The Worker Feedback Dashboard divided opinions. These divided opinions and concerns should be considered when introducing the Worker Feedback Dashboard to the workplace. Ethical aspects and the potential impacts on all stakeholders shall be considered in the design of the solution. For user acceptance, the workers should participate in planning how to utilize the solution, and what kind of work practices should be agreed related to its use. The results indicate that there are potential lead users for the Worker Feedback Dashboard. Introducing the solution via these lead users would facilitate showing the impacts and could then encourage those who were more doubtful to join. Still, using this kind of a solution should be voluntary.

Many participants commented that Participatory Design with a Virtual Factory solution is what they really should have at their workplace, and most participants expected positive impacts both on productivity and work satisfaction. The concerns were mainly related to the culture at the workplace – whether the suggestions of the workers would be considered.

Contextual Knowledge Sharing was quite well accepted but it was evident that there have been several attempts already at the workplaces to introduce tools for knowledge sharing. Attendees seemed a bit fed-up with “again another knowledge-sharing tool”. During the short presentation of the solution, the participants did not fully understand the novelty value of the solution in connecting the discussions to the physical factory floor context. Still, 55% of the participants expected positive impacts on productivity and 39% on work satisfaction. When developing the concept further, the connection to the work context has to be emphasized better. Knowledge sharing should be fully integrated with production systems, extending their content with the user-generated discussion content. For a quick start, knowledge-sharing should be based on actual user communities that already know and trust each other.

The study described in this paper was conducted with a relatively large, homogenous group of participants, as all of them were shop stewards in factories. However, there are some limitations in the results. The solutions were presented to the participants quite briefly, and they could not try out the solutions themselves. The participants filled in the questionnaire after the group discussion, so it is possible that the discussion affected their opinion. However, the discussions may also have supported understanding the proposed solutions better.

Overall, the results are quite promising and encourage introducing Operator 4.0 solutions to factory work. The results of the assessment will be useful in further developing the solutions as well as in designing how to introduce them on the factory floor. Assessing not only immediate implications but also foreseen impacts with the factory workers raised important issues in the discussions and in the comments. These kinds of discussions will be important also in connection to local factory floor design of the solutions and their adoption.

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# Task-Technology Fit in Manufacturing: Examining Human-Machine Symbiosis Through a Configurational Approach

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**Abstract.** With the last few years seeing an increased introduction of technological innovations in factories, one of the most pressing issues is how these technologies can be deployed to optimally support the activities of professionals that are actually utilizing them. Despite heavy investments in novel technologies, there are often negative consequences for the human factor, particularly when there is a lack of alignment between the task that it is used towards and the fit in terms of human training and the needs it is targeted to fulfil. In this research we build on the Task-technology Fit theory and a sample of 182 professionals working in Norway and explore the configurations of elements that drive positive impacts when introducing digital technologies to support factory work. We analyze data through a fuzzy set qualitative comparative analysis (fsQCA) method and demonstrate that there are several different combinations of conditions that can deliver positive impacts.

**Keywords:** Task-technology fit · Human-machine symbiosis · fsQCA

## 1 Introduction

While there have been substantial investments in digital technologies for manufacturing purposes over the last few years [1], a critical issue is that in many cases the technologies used to support tasks of professionals are often not used as intended, or even not adopted at all [2]. Some studies have highlighted that the intended value from investments in novel technologies is not actually realized. A sizeable number of studies suggest that the underlying cause of this is due to a miss-match between what is needed from the human side in relation to work activities and what is provided by the technology [3]. In fact, some researchers have reported that professionals working in the manufacturing industry often have trouble adopting and routinizing newly introduced technologies [4]. This leads to negative impacts on their job performance when they have to utilize such systems [5]. Nevertheless, this problem is not strictly identified in the domain of manufacturing and factory work, and has been a core concern in several other domains including the education, banking and financial sector, and even high-tech companies [6, 7]. It is surprising to see that the human factor has received only


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limited attention to date when taking into account the huge costs invested by companies to develop and adopt such technologies [8].

A growing body of research underscores on the importance of looking into the symbiosis between humans and machine [9, 10]. The main idea is that human cyber-physical systems should serve to improve human abilities to dynamically interact with machines, and improve human physical-, sensing- and cognitive capabilities [2]. The underlying logic of this perspective is that by optimizing human-machine cooperation organizations can realize improvements in performance and efficiency [11]. In doing so there have been a number of different approaches into examining how humans and machines can complement each other capabilities and create value, and what factors influence human intention to adopt and use technologies such as the Technology Adoption Model (TAM) and the Unified Theory of Acceptance and Use of Technology (UTAUT) [12]. Nevertheless, these models don't account for which technologies best fit which task. The theory of task-technology fit (TTF) has been a particularly prominent perspective and well-suited in explaining how specific job-related tasks, aspects of the technology, as well as use practices coalesce to create fit, and subsequently positive impacts [13attention within other fields such as the Information Systems domain, yet when examining the adoption of technologies to support manufacturing and factory work studies are still scarce [14]. There is a growing perspective within the broader field of technology adoption that there may be several different ways by which technological solutions can be used to support professionals work activities [15]. The underlying premise is that individuals in their work are faced with different tasks that they must complete.

The objective of this study is to adopt a TTF theoretical perspective, and examine which are those combinations of tasks, technology, and individual use practices that fit together and lead to positive impacts in the context of manufacturing and factory professionals work. We build on a recent large-scale empirical survey conducted with 182 professionals, and by applying the novel methodological approach fuzzy set qualitative comparative analysis (fsQCA) we reveal several configurations that lead to positive outcomes for job-related activities. In this way we can identify a number of different tasks, the aspects pertinent to technology that best fit task requirements, as well as individual use and adoption practices that facilitate optimal fit.

## 2 Background

To explore how technologies deployed within the manufacturing domain can contribute to positive outcomes of work performance, we develop this research on the task-technology fit theory [13]. Based on TTF theory, digital technologies will be more likely to yield a positive impact when the functionalities they deliver can fit the tasks individuals must undertake. Since its inception, the theory has been extended in several ways, with the latest studies recognizing how individuals use these technologies as well as the design and training practices surrounding adoption and diffusion, have an important role on performance of technology use [16]. Hence, the task-technology fit theory has been applied at various levels of analysis, examining effects on individuals and groups [17], as well as in many different contexts, from specific technologies [18] to effects on industries or particular professions [19]. When looking into the area of manufacturing and factory work, there has been very limited work following this approach. Despite this, recent work has recognized the importance of the human factor highlighting that there needs to be alignment between the jobs humans must perform, the digital technologies introduced to support them, and the training they receive to adopt such systems into their work [20]. To determine how these aspects jointly contribute to drive positive impacts in job performance, we follow a configurational approach in data analysis [21].

Configurational approaches have been growing in interest in the IS and technology management community over the past few years [22, 23]. Such approaches have the advantage that they enable the identification of multiple different paths, or solutions, that lead to an outcome of interest [24]. In practical terms, this means that in the case of positive impacts of digital technology use in the manufacturing and factory work context, it would be possible to detect several successful cases of using technologies to perform specific tasks, along with the individual use characteristics that describe them. Nevertheless, in spite of the promise of such approaches, there is still very limited research in exploring how the different aspects pertinent to task, technology, and individual use coalesce to drive fit, and as a result positive impacts in the factory and manufacturing workplace [25]. The bulk of research building on the task-technology fit theory has emphasized on the two main concepts (i.e. task and technology) [26], while a growing stream of research incorporates in the investigation the role of individuals and how technologies are deployed and routinized in work activities [27]. An increasing number of research is looking into the formal and informal mechanisms of adopting the use of technologies in the workplace, acknowledging the fact that just as important as the technology itself to support a task are the practices through which they are embedded in work [28].

# 3 Method

## 3.1 Data Collection

To examine the configurations of elements regarding tasks, technology, and individual use context that lead to positive impacts in the work environment, a survey instrument was developed. A professional data collection company was commissioned with conducting phone polls to individuals throughout Norway using a database of approximately 10.000 individuals in a variety of different industries, including those of factory and manufacturing workers amongst others. No specific areas of manufacturing were selected, and respondents covered tasks of several different functions. The scales of the questionnaire are described in Sect. 3.2. The callers informed participants about the purpose of the study and asked respondents to answer a number of questions. The data gathering process lasts roughly four months (May 2017–August 2017), and the average time for answering the questions of the survey was 23 min. A total of 182 complete responses were received from the manufacturing industry. From this sample, most responses came from the age-groups 45–59 years (38%) and 30–44 years (37%). In terms of gender distribution, the largest proportion of the sample consisted of male employees (72%) while females accounted for 28% of the sample. When looking at the educational background of respondents, most of them had as a highest academic qualification a degree from high school (42.9%), while 35.67% had until 4 years in higher education (equivalent to bachelor's degree) (Tables 1 and 2).

**Table 1.** Descriptive statistics of sample respondents' profile

| | Sample (N = 182) | Percentage (%) |
|---|---|---|
| **Age** | | |
| Under 30 | 33 | 18% |
| 30–44 years old | 67 | 37% |
| 45–59 years old | 69 | 38% |
| More than 60 years old | 13 | 7% |
| **Highest Educational Level** | | |
| Primary school | 6 | 3.3% |
| High school | 78 | 42.9% |
| Higher education (less than 4 years) | 65 | 35.7% |
| Higher education (more than 4 years) | 33 | 18.1% |

### 3.2 Measurements

Regarding attributes relevant to the task itself, we utilized measures that included questions on the types of tasks in which digital technologies were used, the difficulty ad time-criticality of the task, if the level of non-routineness. Specifically, we measured on a 5-point likert scale the frequency in which respondents used digital technology for core tasks, reporting and documentation tasks, and information/coordination [29]. To determine if they held positions that required leadership skills, we asked respondents to indicate if they had no leadership responsibilities, personnel, managerial, or both. Finally, we asked respondents to indicate how often they were expected to work outside of paid work hours [30].

Concerning technology-related characteristics we followed a similar approach, looking at different aspects related to functionality and user-friendliness, while also incorporating specific types of devices in the questions that are commonly used by manufacturing professionals. We captured the extent to which respondents believed that digital technologies they used in the jobs were functional and reliable, user-friendly, and adaptable [31]. Furthermore, we assessed the extent to which respondents need to use different types of devices to perform their work such as personal computers, mobile devices (e.g. smart phones, tablets and portable equipment), and wearables (smart glasses, smartwatch), or augmented reality technologies [32].

In terms of individual use context, we tried to capture elements that were relevant to how individuals adopt and utilize novel digital technologies, as well as what types of support mechanisms are set up to facilitate such usage. In congruence with past empirical studies we include aspects that can affect how easily and well individuals utilize digital technology [13]. We examine the degree to which individuals have a support network from colleagues when using digital technologies, the extent to which they have been trained to use the latest digital technologies in their organizations (e.g. courses, e-learning, self-education through reading), as well as the level to which they have been involved in the joined planning of introducing new digital technologies [33]. Finally, when it comes to examining the impacts of digital technology use in the manufacturing sector, we operationalize this variable as the level to which the quality of work gets better, work is done fast, and the level to which the work performed relies on the use of digital technologies [34].

## 4 Analysis

To identify the configurations of task, technology, and use practice lead to lead to positive or negative work impact we employ a fuzzy-set Qualitative Comparative Analysis (fsQCA) approach. Applying such an approach is particularly relevant to the case of digital technology usage within the manufacturing context, since depending on the type of task, and characteristics of the individual, different digital technologies and use support mechanisms may be more or less relevant in producing positive impacts [35]. A first step of performing a fsQCA analysis requires that we calibrate dependent and independent variables into fuzzy or crisp sets. To calibrate continuous variables such as the ones we have utilized in the survey into fuzzy sets we followed the method proposed by Ragin [36]. Following this procedure, the degree of set membership is based on three anchor values. These include a full set membership threshold value (fuzzy score = 0.95), a full non-membership value (fuzzy score = 0.05), and the crossover point (fuzzy score = 0.50) [37]. Based on prior empirical research we computed percentiles for each construct so that the upper 25 percentiles serve as the threshold for full membership; the lower 25 percentiles for full non-membership; and the 50 percentiles represent the cross-over point. The results of the analysis are depicted in the table below and discussed in the final section.

**Table 2.** Configurations leading to high work performance

| Configuration | Positive impacts | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| **Task** | | | | | |
| Core task | ● | | ● | ● | |
| Reporting and documentation task | | ● | | ⊗ | |
| Information/Coordination task | | ● | ● | | ● |
| Leadership | | | | | ● |
| Non-routineness | | ⊗ | | ⊗ | |
| **Technology** | | | | | |
| Reliability | | ● | ● | ● | ● |
| User-friendliness | ● | | ● | ● | ● |
| Adaptability/Flexibility | ● | | | ● | |

(*continued*)

**Table 2.** (*continued*)

| Configuration | Positive impacts | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| Personal computer | | ● | | ⊗ | |
| Mobile devices | | | ● | | ● |
| Wearables | ● | | | | |
| Augmented reality | ● | | | ● | |
| **Individual Use Context** | | | | | |
| Colleague support | | | ● | | |
| Training | ● | | | ● | |
| Planning participation | ● | | | ● | ● |
| Consistency | 0.86 | 0.91 | 0.93 | 0.83 | 0.88 |
| Raw coverage | 0.27 | 0.18 | 0.13 | 0.18 | 0.21 |
| Unique coverage | 0.11 | 0.08 | 0.09 | 0.10 | 0.04 |
| Overall solution consistency | 0.86 | | | | |
| Overall solution coverage | 0.42 | | | | |

## 5 Discussion

This study finds that there are different combinations of technologies, features, and mechanisms to routinize depending on the task at hand. Furthermore, the results indicate that tasks that revolve around core tasks, such as those in the workstation can be improved the right combination of technologies and attributes in their design, coupled with the necessary training practices. The black circles denote a presence of a condition while the crossed-out ones an absence of it. For instance, in column 2, the solution reads as follows. When the task of the worker includes activities of reporting and documentation and information coordination and is a routine activity, then high reliability coupled with the use of a personal computer and a collegial support regime are sufficient to drive positive work performance. Likewise, other solutions show different tasks and combinations of them, pinpointing to certain activities within the work environment and how they can optimally be enhanced by means of digital technologies. What is interesting to observe also is that apart from the physical technologies themselves, there are also functional characteristics and design principles that need to be considered. In addition, the strategies applied to deploy and routinize such technologies are identified in solutions. These solutions are by no means exhaustive and can be examined on an even more granular level, nevertheless, they do illustrate a novel approach for uncovering combinations of elements around the use of technology that lead to positive outcomes. Future research can extend on this method and identify how human-machine symbiosis can be optimized.

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# Augmented Reality for Humans-Robots Interaction in Dynamic Slotting "Chaotic Storage" Smart Warehouses

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**Abstract.** Nowadays, smart warehouses mostly use Automated Guided Vehicles (AGVs) controlled through magnetic or painted paths. This approach is suitable for "static slotting" warehouses, and for places where humans do not cross paths with mobile robots. Therefore, fixed-path AGVs are not an optimal solution for dynamic slotting "chaotic storage" warehouses, where picking and delivery paths are often changing. Hence, it is important to create an environment where AGVs have planned their path, and storekeepers can see their paths, and mark restricted areas by virtual means if needed, for these mobile robots and humans to move and stand safely around a smart warehouse. In this paper, we have proposed an Augmented Reality (AR) environment for storekeepers, where they can see an AGV planned path, and they can add virtual obstacles and walls to the mobile robots' cyber-physical navigation view. These virtual obstacles and walls can be used to determine restricted areas for mobile robots, which can be seen for example as safe areas for humans' and/or robots' stationary work. Finally, we introduce the system architecture supporting the proposed AR environment for humans-mobile robots safe and productive interaction.

**Keywords:** Industry 4.0 · Smart warehouses · Operator 4.0 · Augmented Reality · Human-robot interaction · AGVs · Drones · Dynamic slotting · Chaotic storage

## 1 Introduction

According to [1], in a "traditional warehouse", the operations of pickup, delivery, and bookkeeping are accomplished by (human) storekeepers. These manual activities have several drawbacks, particularly when it comes to storing and fetching inventories into and from bin rack storage systems, and keeping paper-based records of the stocks using account books, since both activities are (a) time-consuming, (b) prone to human-error,


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and (c) represent a waste of human talent – from a lean warehousing perspective [2]. Thus, it is imperative to make traditional warehouses *"smart",* meaning: 'automated, unmanned, and paperless – when conducting the operations of pickup, delivery, and bookkeeping' [1]. Furthermore, as the retail revolution in e-commerce, and the rise of personalised products continue [3], the ability to manage a larger number of SKUs with fewer errors, and with faster pickup and delivery times (i.e. intra-logistics), have started to make "static slotting" (i.e. assigning a permanent location in a warehouse for each product [4]) not the best practice in the Industry 4.0 era. This considering the Industry 4.0 vision of "lot-size-one production" [5]. Therefore, "dynamic slotting" is emerging as the new best practice in "Warehousing 4.0" in order to accommodate the variability in products' turnover rates, and future wave of picking requirements for seasonal, mass-customized, and/or personalised products [4]. This "dynamic" approach will contribute to reducing time and transport, by having the location of the prime bins next to the shipping docks with the high moving products of e.g. the week [4]. Moreover, a more advanced and digitally-enabled dynamic slotting approach, known as "chaotic storage", is being practised by Amazon.com, and other online retailers, using any product empty bin with any random product that can fit into it, and having a software keeping track of the product location, and directing an Automated Guided Vehicle (AGV), drone or human to it via an optimised picking route [4]. To be able to control a movement of the AGV in a dynamic environment, two tasks must be solved at once: (i) determining the position of such AGV, and (ii) describing the environment where AGV is moving. Such an approach is well known as Simultaneous Localisation And Mapping (SLAM). It can be defined as a process that helps create a map of an unknown environment (including obstacles) along with its use to calculate the position of the AGV without any need of particular knowledge about its position [6]. SLAM encompasses a number of various methods like e.g. Graph SLAM [7], which utilizes the so-called sparse information matrices based on observation interdependencies. Meantime, further SLAM approaches were developed that differ by used sensors or the purpose of use. For instance, special SLAM for use of RGB cameras is presented in [8], which serves mainly in indoor applications. Another modification of SLAM for indoor tasks utilizes radio beacons and depth sensors (scanners) [9]. To complete this brief overview, in [10] an elderly care system is described, which is integrated together with SLAM.

In this paper, we introduce an Augmented Reality (AR) solution for Humans-Robots (i.e. AGVs and drones) safe and productive Interaction (HRI) in dynamic slotting "chaotic storage" smart warehouses, where these can communicate in a bidirectional way by means of AR mobile/wearable devices at humans, and computer vision at AGVs and drones. The main objective is to be able to visually share between humans, AGVs and drones their picking and delivery routes around the warehouse in order to avoid possible collisions and guarantee their safety.

## 2 AR and Computer Vision for Humans-Robots Interaction (HRI)

The research work and technological development described in this paper focuses on the possibilities of using AR mobile/wearable devices at humans (e.g. the Augmented & Collaborative Operator 4.0 [11]), and computer vision at mobile robots such as AGVs and drones (e.g. Human-Machine Interfaces (HMIs) 4.0 [12]), in the context of dynamic slotting "chaotic storage" smart warehouses. This in order to facilitate humans and mobile robots safe interaction and visual (control) communication. The advantage of using *AR technology* as a shared and augmented visual language for communication between humans and mobile robots, in comparison to traditional and static visual controls (e.g. tracks made of an adhesive magnetic tape affixed or painted on the floor to be followed by AGVs, and respected by humans), is that it can cope with the dynamic nature of the "chaotic storage" smart warehouses, where picking and delivery routes will be often, almost always, changing for humans, AGVs, and drones. Therefore, in a cyber-physical smart warehouse environment, either real objects in the physical world or virtual objects specified by humans and/or mobile robots (e.g. virtual paths and virtual walls or fences), can be used to create safe picking and delivery routes, and restricted areas for the case of humans' and/or robots' stationary work, which mobile robots and humans will be able to distinguish. AR technology can provide additional data about the environment for the SLAM.

In the next sub-sections, we introduce the proposed AR-HRI system architecture design and provide the needed guidelines for its implementation.

### 2.1 Reference AR-HRI System Architecture Design

The AR-HRI system architecture design consists of three separate, but interrelated applications (apps): (i) a Core app installed in a desktop computer, and responsible for creating the "AR smart warehouse view" for the humans (i.e. the storekeepers) and for the mobile robots (i.e. the AGVs and drones); (ii) the AR app installed in a smart mobile phone, or in smart-glasses, allowing the humans, the storekeepers, to view any virtual object added in the smart warehouse cyber-physical space in their perception/view of the real-world; and (iii) the Robot app installed in an AGV or drone, which uses computer vision to also allow the mobile robots to have in this case a cyber-physical view of the smart warehouse as they move around it (see Fig. 1). These apps should support many different network protocols (e.g. Ethernet, Bluetooth, Radio Frequency technology) to be able to work with different robots or sensors. All these apps together, as an AR-HRI system, have the same goal, to provide humans and mobile robots with safe dynamic routes for picking and delivery products at the smart warehouse, avoiding any collision by means of AR visual controls (i.e. virtual paths and virtual walls).

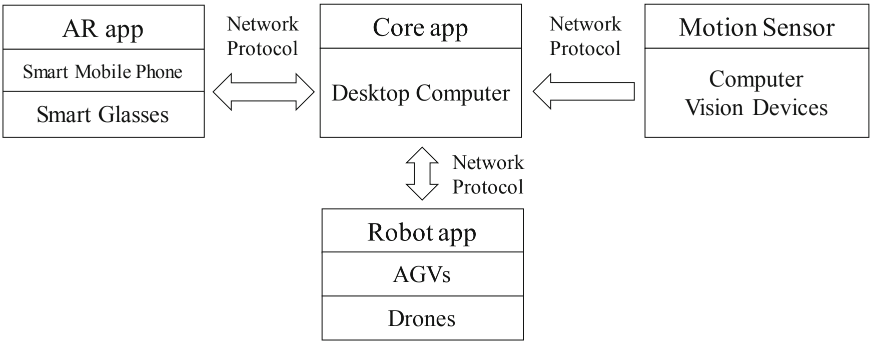


**Fig. 1.** Reference AR-HRI system architecture design

### 2.2 Particular AR-HRI System Architecture: Lab Platform Development

For developing and testing the proposed AR-HRI system architecture, the following software and hardware components where considered for the lab platform development: (i) for the Core app, C# programming language was used for the desktop app dev., since it is a common programming language among desktop and mobile apps development platforms, including Microsoft Kinect [13], and a desktop-computer with the following characteristics: 4-cores Intel i7-4710HQ CPU with base frequency at 2.50 GHz, 16 GB of RAM memory, GeForce GTX970 M GPU, Windows 10 Pro OS; (ii) for the AR app, Unity development platform [14] was chosen due to its multiplatform support, and broad range of software development libraries and packages, which allow the possibly to extend the solution to other AR platforms such as Microsoft HoloLens [15], and a smart mobile phone with the following characteristics: 6-cores Snapdragon 650 w/frequency at 1.80 GHz, 3 GB of RAM memory, Adreno 510 GPU, Android 6.0 OS; and (iii) for the Robot app, except for network communication, C programming language was used due to its popularity among robot programmers, and a Khepera III AGV [16], which runs an embedded Linux OS, and offers all standard C libraries for its programming (see Fig. 2).

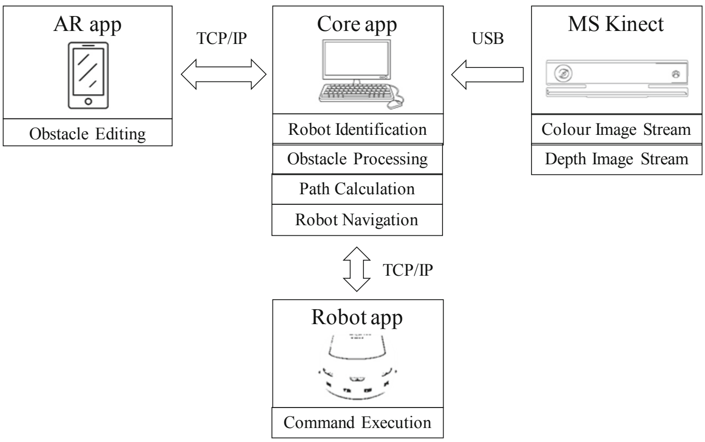


**Fig. 2.** Particular AR-HRI system architecture design: lab platform development

Furthermore, the following lessons learned from the lab platform development are shared hereunder.

**AR App.** The first step to develop an AR app is to detect the scene, and register and differentiate the "virtual objects" in relation to the "physical ones". This itself is a broad topic, and many years of research have been already dedicated to it, so here it comes the advantage of using the Unity development platform [14] since it provides SDKs (Software Development Kits) focusing exactly on these problems. Developers usually divide AR-SDKs into two main categories based on their approach to scene-tracking: (i) marker-tracking tools, which are based on tracking a known pattern placed in the real-world and calculating its transform; and (ii) marker-less-tracking tools, which are designed to work in an unknown environment, usually by a combination of device orientation, and location sensors comparing consecutive images from the camera. Thus, we have investigated and tried multiple AR-SDKs supporting marker-less-tracking for the lab platform development, namely: ARCore, Vuforia, Wikitude, Kudan, and Maxst. All these AR-SDKs were benchmarked based on their compatibility with peripheral devices, performance, quality of tracking, and license type. Maxst [17] was chosen at the end as the best for our AR platform solution since it performs well while using little computing resources. It is also compatible with most Android and iOS devices and offers a free license for non-commercial purposes as long as the application contains the watermark.

**Core App.** All the AR system logic is implemented in the Core app running on a desktop computer. It uses custom protocol built on TCP/IP sockets for efficient two-way connection with both the AR app and the Robot app. The first step is receiving data from the AR app, and additional data from the Microsoft Kinect [13] sensor. These are then combined and processed using various computer vision methods, resulting in the final map of the "cyber-physical smart warehouse environment" containing both virtual and physical objects. Next step is the calculation of the path/route that the mobile robot should take between its current and final position for a product pickup and delivery. Dijkstra's shortest path algorithm [18] was implemented for path planning. This algorithm was chosen because it guarantees to find the shortest path, and is relatively simple to implement. Its drawback is that the algorithm is not the most time-efficient one, but given the size of our pilot smart warehouse space, it only takes a few milliseconds to calculate the AGV path/route. The layout of the Core app can be seen in Fig. 3 and consists of four main parts.

The first three parts (i.e. Microsoft Kinect controls, AR server controls, and robot server controls) are used for communication setup with Microsoft Kinect sensor, AR app, and Robot app. The last part is used for the visualisation of the cyber-physical space. In the bottom-left part of Fig. 3, we offer a top view of the lab platform testing space with virtual obstacles (the blue rectangles); those recognized by the AGV (the yellow circle); the blue line as the AGV path/route direction; and the red number (6) as the AGV identificator. The bottom-right part of Fig. 3 allows visualising the planned path for the AGV (the blue dotted line), the AGV actual direction (the red line), the AGVs position (the orange circle), and the virtual and physical obstacles (the white parts).

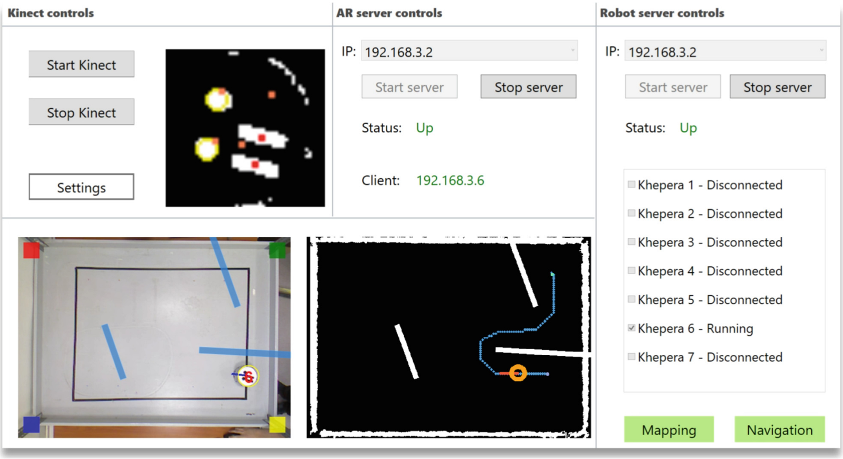


**Fig. 3.** The core app interface (Color figure online)

**Robot App.** This app serves as a client that connects to the Core app immediately after starting. Its only purpose is to set the speeds of the Khepera III AGV [16] motors based on commands incoming from the Core app and providing both infrared and ultrasonic sensor readings in case they are needed. Moreover, the Microsoft Kinect [13] sensor is used to help to solve two problems that appeared in the initial stage of the Robot app development: (i) determining the AGV's position and orientation (see Fig. 3, top-left section), and (ii) detecting physical obstacles in the real world.

## 2.3 Lab Platform Functionalities Testing

Thanks to the AR app developed, the user was able to view through the mobile device camera, the additional virtual walls inserted at the cyber-physical smart warehouse environment, and he/she was also able to add or remove these by simply drawing on the smart mobile phone screen. Furthermore, we have tested different placement, size, and shapes of the virtual obstacles. We have also tested how different obstacles affect the Dijkstra's shortest path planning algorithm [18]. We have proved that the path is achievable with no collisions for as long as the width of the whole calculated path from the start to the destination is at least 10% wider than the actual width of the AGV.

Moreover, the AR app and the Core app are connected through Wi-Fi, and each time the user makes changes, the Core app is notified of the changes made.

Figure 4 shows an example scene. The three blue fences are the virtual walls drawn by the user.

The mobile robot was navigated following a virtual path. To achieve this, the Robot app was continually calculating the direction that the AGV should be moving on in order to keep following the path, then these values along with the mobile robot's current state are used as an input to the fuzzy system [19]. The navigation system is designed so that it outputs two values, one for each AGV wheel. These values are then sent to the mobile robot using the same protocol (i.e. TCP/IP) as for communicating

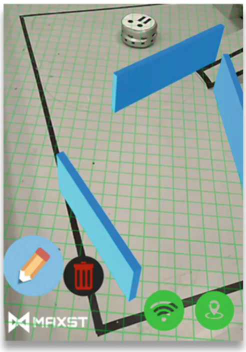


**Fig. 4.** Mobile robot and virtual walls (Color figure online)

with the AR app. Additionally, the Khepera III AGV [16] has a marker placed on top of it. This marker contains several simple shapes arranged in a specified order. Since the layout of the shapes is known (see Fig. 4), we can use it to find the mobile robot in the image and determine its location and orientation. The image is obtained from the Microsoft Kinect colour camera. This task can be also solved using only images from the AR app, but since the smart mobile phone camera is not stationary, it would be significantly more complicated, and the user would be required to keep the mobile robot in the camera view all the time. Hence, the problem of detecting physical objects would be even harder because images in the AR app are captured using only one camera, which means that they lack any information about the depth of the scene. There are techniques for estimating depth from a single image, but these are not accurate enough for our case. The Microsoft Kinect depth sensor has proven to be a good choice thanks to its high precision.

## 3 Conclusions and Future Research

Although not yet widely adopted, AGVs and drones will revolutionise the way products are transported inside a smart warehouse. Nevertheless, not all smart warehouses will become "unmanned", some may still require humans, AGVs and drones collaboration for their optimal performance, so it is in these cases where our AR solution for humans-mobile robots safe and productive interaction aims to contribute. Based on the literature review conducted, we have created a reference system architecture that describes an AR implementation into traditional SLAM techniques. Moreover, we have developed a case study based on the proposed architecture to perform functionalities testing by observations.

Further research will focus on testing other AR wearable/mobile devices such as smart-glasses, testing other shortest path planning algorithms, and testing other robots' localization techniques. Thus, using AR wearable devices such as Microsoft HoloLens headset [15] will bring the advantage of hands-free to storekeepers. Algorithms able to solve path search and planning under "dynamic changes" of warehouse parameters promise considerable improvements to our current solution. Particularly, modifications of the D* algorithm, which is an extension of the Dijkstra's path planning algorithm, will be in the focus of future research [20, 21]. We have used a Microsoft Kinect sensor for localization of the AGVs in lab testing space. In future research, we also plan to focus on more suitable ways of AGVs localization in large warehouses, like Wireless Node Monte Carlo Localization [22], positioning based on RFID technology [23], or localization based on Bluetooth Low Energy [24].

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# Analyzing Human Robot Collaboration with the Help of 3D Cameras

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**Abstract.** Recent developments in robotics allow the design of work systems with enhanced human robot collaboration (HRC) for assembly tasks. Productivity improvements are a common aim for companies that look into the implementation of HRC. To harvest the full productivity potential of these work systems, an analysis of the HRC work processes is essential. However, a dedicated method for the analysis of productivity in HRC is missing. This paper presents an approach using 3D-cameras to observe the employee in HRC. The approach links this information to robot states. The resulting analysis aims at improving the productivity of the work system e.g. by identifying and reducing balancing losses in HRC. The method tracks the movements of the employees in the HRC area and matches the corresponding robot activities.

**Keywords:** Human robot collaboration · Productivity analysis · 3D cameras

## 1 Introduction

Smart manufacturing has a huge impact on the design and operation of manufacturing systems and accordingly the work of employees in manufacturing. Romero et al. [1] identify 8 types of technology induced employee augmentation. One aspect of this typology is collaborative automation or "the collaborative operator". Recent developments in robotics allow the design of human robot collaboration work systems with a very deep integration of robot activities in manual operations. As described by Romero et al. [1], HRC can transfer tedious, non-ergonomic and vulnerable tasks to the robot and achieve productivity and quality improvements as well as an increased operator satisfaction. Of the manifold reasons for the implementation of HRC, improvements in productivity are most important for many companies [2]. To ensure a high productivity in HRC work systems, an adequate analysis of work processes is essential.

Many approaches exist to analyze the productivity of manual work (work sampling, time studies) as well as of machines (overall equipment efficiency) [3, 4]. A dedicated approach to analyze HRC work systems that supports continuous improvement actions is missing.

This paper presents an approach to analyze HRC work systems with the help of 3D-cameras and a robot interface. The camera tracks the position and the movement of the employees and a software matches corresponding robot data to create a digital twin of


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the HRC work system. The recorded data is analyzed with the help of state type diagrams as proposed by Schweitzer [5].

## 2 Collaborative Robots and Human Robot Collaboration

When referring to collaborative robots or cobots, many authors describe robots that are capable of working within the same environment as human employees without external safety barriers such as fences [6]. In order to do this, these robots usually provide enhanced safety features like rounded edges, reduced weight, limited power and force and protective skins that can detect collisions or the proximity of the employee. In addition to these safety requirements, Romero et al. [1], Maurtua et al. [6] and Wang et al. [7] refer to enhanced interaction mechanisms as necessary feature for HRC.

Many authors describe HRC regarding the temporal and spatial relation of collaborating humans and robots. Human robot collaboration is assumed to have at least partially no spatial and no temporal separation of human and robot. This includes simultaneous and supportive work of human and robot on the same workpiece at the same time [2, 7, 8]. In addition to these forms of collaboration, employees and robots may also work independent when completing tasks with spatial separation or with temporal separation.

Deploying HRC in a way that increases productivity is a complex design task [2]. While the initial design and task allocation is addressed by some authors (for instance in [9]), a methodology that supports analysis of work in the operation of HRC for continuous improvement is missing.

## 3 Productivity and Work Analysis

### 3.1 Productivity and Conventional Work Analysis

In the context of HRC, both the productivity of the employee (labor productivity) and of the robot (machine productivity) are important. Due to the deep integration of human and robot activities, breakdowns or waiting times of either the robot or the employee can lead to losses in the overall productivity of the work system.

While measurement of machine productivity can be automated in many cases, the vast majority of existing methods for assessing labor productivity uses observers to analyze the work processes (see [3]). In order to draw conclusions, states of robot and operator have to be captured simultaneously. This usually exceeds the cognitive capabilities of an observer, also because the robot state is not obvious (especially when deploying external equipment) and robot control information is not available for the observer.

### 3.2 Analysis of Work Processes with 3D Cameras

Motion capturing systems track human positions and movements and make this data available for further processing. These systems can be used to analyze work processes without the need of an observer. Both electro-mechanical systems that use special suits to determine human motions and optical systems as 3D cameras can be used to track human movements. 3D cameras often emit an infrared light, which is reflected by the human body or special markers and captured by a stereoscopic sensor set. Optical systems require special software to detect human bodies. While electro-mechanical systems usually provide a superior data quality, the additional equipment is often expensive, has to be carefully attached to the employee and may impede the work process. Optical systems often suffer from a lower data accuracy, especially in environments that partly conceal the observed employee [10]. We opted for 3D-cameras, because their accuracy is good enough for the purpose of productivity analysis and because they are easy to use.

Various approaches have been developed to analyze work processes in regards to productivity with the help of optical systems. Escoria et al. [11] developed a method to detect characteristic work processes on construction sites on the basis of specific body positions. Ying et al. [12] propose an approach that uses convolutional neural networks in order to detect different activities of workers in a scaffolding process with the help of regular cameras. Benter [10] uses the Microsoft Kinect sensor and the corresponding software set to determine stopping points of the whole body or single body joints. Benter uses these stopping points to distinguish different movements during manual processes, which enables him to automatize a detailed productivity analysis of manual assembly processes.

While the existing approaches provide methods for the analysis of manual work processes, they do not integrate machine or robot data in the analysis.

## 4 Analysis of Human Robot Collaboration Work Systems

### 4.1 Methodology

To analyze the work processes of HRC work systems, our approach aims at mapping states of employees and robots in the work system on a synchronized timeline with the help of state type diagrams. The methodology aims to reveal situations that will reduce the work systems productivity and result from the collaboration of employee and robot such as:

- balancing losses that result from an unbalanced task duration of robot and employee,
- breakdowns of the robot or related peripheral systems,
- disturbances in manual processes,
- speed losses and minor stops that result from the close proximity of employee and robot.

Balancing losses occur if either the robot or the employee needs to wait for the counterpart. Consequently, balancing losses either decrease the robot or employee productivity.

Breakdowns of the robot or a related system will force the employee to repair the disturbed system or to wait for an expert to resolve the issue. Breakdowns therefore cause productivity losses for employees and robots.

Disturbances in manual work processes will force the employee to resolve the disturbances while the robot has to wait for the employee in order to proceed. Thus these situations will cause productivity losses for employee and robots.

Due to safety reasons, collaborative robots will stop if they get in contact with the employee or will work with decreased speed in their close proximity. This is inevitable if robot and employee are about to collaborate. However, these situations may also occur if robot and employee work independently in close proximity. Those situations should be avoided by a better workplace design.

### 4.2 Exemplary Work System

In order to illustrate the idea of the analysis, an exemplary HRC work system for research purposes was developed at Garz and Fricke GmbH in Hamburg. The work system consists of a manual work station and a robot work station for collaborative processes and of two handling points where employees take materials for processing or place already processed materials. In this case a Universal Robots UR 10 robot is used. Figure 1 shows the set-up.

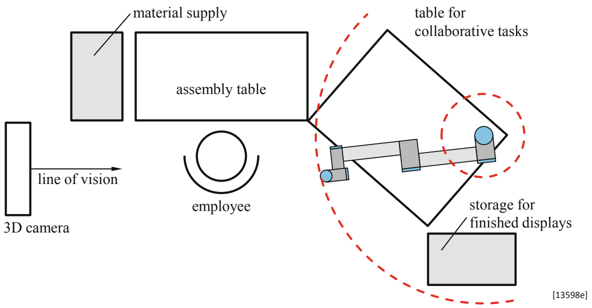


**Fig. 1.** Set-up of the HRC work system

In this exemplary work system, touch display components are glued to plastic frames. This involves the preparation and manual inspection of the frame, the cleaning of the components with ISO-propanol, activation of the frames surface with a plasma activator, application of the glue and the joining and adjustment of the components. The preparation and manual inspection is performed by the employee as this involves the handling of small parts. Due to the higher repetitive accuracy, cleaning, surface activation and the application of glue is performed by the robot. Joining and adjustment of the components is done by employee and robot in a collaborative step. The exemplary set up therefore contains independent, synchronized and collaborative work steps.

## 4.3 Relevant States

Schweitzer [5] suggests an analysis approach for concatenated production lines consisting of states and state diagrams. These approach uses the states regular activity (tact), disturbance, waiting, blocking and set up. These states are also suited for the assessment of HRC, but need some additions. The activity needs to be tracked with greater detail, since robots can perform a wider range of activities. Therefore not only the activity, but also the kind of activity e.g. cleaning, surface activation or glue application has to be detected. In addition to machine warnings or disturbance types, also safety information must be recorded.

The robot states can be applied to the employee with limitations in the states of set up and disturbance. For the robot as well as for the employee it is important to distinguish between different regular activities, since both can perform a variety of tasks. It is also necessary to identify collaborative activities. Employees can also encounter disturbances. Usually these disturbances are not directly related to the employee, but are related to missing material, information and tools, that is required for the task processing. This is the same with set up activities, since employees may be involved in the set up of the robot or of the work station.

**Table 1.** Robot, employee and collaborative states of the exemplary work system

| Robot states | Collaborative states | Employee states |
|---|---|---|
| Activity | Activity | Activity |
| – Clean display | – Transfer frame | – Prepare frame |
| – Clean frame | – Join components | – Join components |
| – Activate frame | – Transfer display | – Transfer frame |
| – Apply glue | | |
| – Prepare display | | |
| Waiting | | Waiting |
| Disturbance | | Disturbance |
| Safety state | | |
| – Reduced speed | | |
| – Safety stop | | |

## 4.4 Data Recording and Analysis

We use an optical tracking system based on the Intel RealSense D400 sensor family and the Nuitrack SDK [13] to capture the employee position and motion. A robot TCP socket interface is used to capture robot data. The following section describes the underlying data structure, the state detection approach and the resulting analysis HRC work systems.

**Data Structure**

The robot interface provides basic raw data such as the position of the tool in the robot coordinate system, robot control variables for external devices, robot state messages and safety messages. This data is transformed into robot states in a later step. Based on the infrared depth map of the Intel real sense 3D-camera, the Nuitrack SDK provides information about the position and orientation of 18 human joints of a tracked body. In order to detect different employee states, we intend to define work stations that are linked with activities. A workstation data set consists of the position of the work station and the associated activities. In addition to the work station other areas may be defined in order to detect other states as waiting or disturbances.

**State Detection**

To analyze the work process of the HRC work system, it is necessary to detect the states discussed in the prior section. The state detection is carried out by a self-developed software that stores the detected robot, employee and collaborative states in a spreadsheet. To detect a robot state, the user defines a single parameter or a combination of parameters provided by the robot interface for a certain state. The activity state “apply glue” for instance can be detected if the robot tool position is set in the area of the glue dispenser and the robot control variable that activates the glue dispenser is set to “high”.

The employee activity is mainly derived from the employee position, since the employee states are connected to work stations and additional areas. For example the state “prepare frame” in Table 1 is associated with the assembly table work station. It is detected if the employee is present at the assembly table and is moving arms and hands.

So far the detection of robot and employee states has not been tested in the exemplary work system. However, the employee state detection was tested in the learning factory of the institute. The robot state detection was tested with the help of an offline simulation software for the UR 10 robot.

**Analysis**

In order to identify the losses described in Sect. 4.1 and to find ways to prevent these losses, an analysis of the captured state data is necessary. The state type diagram (Fig. 2) displays the states of the employee and of the robot over time adapting a diagram introduced by Schweitzer [2] for production lines to HRC work systems.

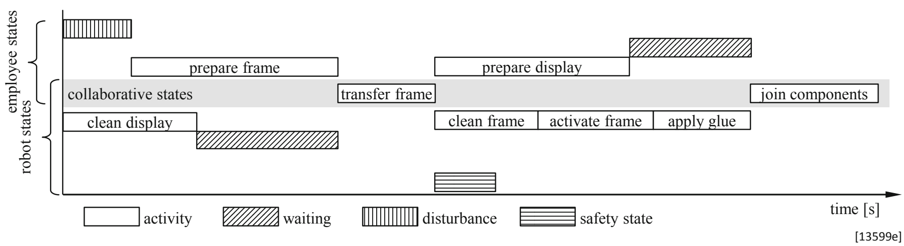


**Fig. 2.** Exemplary state type diagram for HRC processes

Collaborative states are placed in the center, employee states in the upper, and robot states in the lower half of the diagram. Activity states of employee and robot are placed close to the center in order to better illustrate the workflow. Waiting, disturbances, and safety states are positioned more to the outside of the diagram. In the example of Fig. 2, the diagram reveals balancing losses after cleaning the display (robot) and after preparing the display (employee) and shows the underlying circumstances of these balancing losses. Employee and robot states can also be displayed in pie charts to show the distribution of all states, so that the user can easily identify the percentage of value adding states and of collaborative activities (Fig. 3).

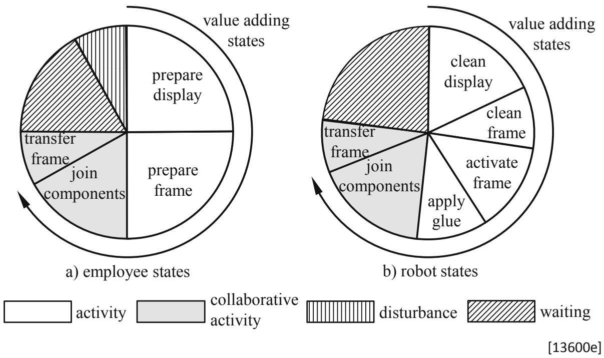


**Fig. 3.** Exemplary state distribution of employee and robot states

## 5 Summary and Outlook

This article presents an approach to analyze the productivity of HRC work systems. The method uses a 3D-camera to track the employee and several types of robot data. The data is used to detect the states of robots and employees and to map them in state type diagrams. This enables the user to identify productivity losses due to an insufficient balancing of employee and robot tasks, disturbances of the robot or the employee processes and mutual disturbances of employee and robot. The proposed method supports continuous improvement of productivity in a HRC environment, e.g. the reallocation of tasks between employee and robot in case of balancing losses.

However, it is not designed for the use of planning a completely new HRC work system. This requires a more detailed analysis and the integration of other aspects as safety, implementation costs, flexibility of the automation, etc. While a detailed test and evaluation of the presented methodology for the entire work system is still pending, the functionality of single components was tested with positive results. A detailed evaluation in HRC work systems is therefore an important next step.

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# Investments of the Automotive Sector and the Industry 4.0. Brazilian Case

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**Abstract.** This text deals with the nature of the investment of companies of the Brazilian automotive sector to suit the Industry 4.0. The data were collected through a survey applied to executives of this segment, through the observational method and bibliographic research. The results show that the participants are aware of the need for investments for the proposed adequacy and productivity gains, but that this volume of investment is still not enough for a robust modification. The importation of technology is not portrayed as fundamental, where the level of investment required in addition to the lack of training of the labor force, are impeding factors for the evolution of the Industry 4.0. It was observed that due to the economic crisis that has taken place in Brazil, the automotive industry has focused on the survival in the market under current conditions rather than strategies for investment in Industry 4.0 technology.

**Keywords:** Investments · Connectivity · Industry 4.0 · Technology · Automotive

## 1 Introduction

The technological advance provides an important range of knowledge and relational competence in the production chain, in addition to pointing to one of the main pillars of the evolution of production processes and economic growth. The continuous process of technological improvement has provided qualitative "leaps" for the industries in general. In contrast to the productive models resulting from the first Industrial Revolution, which took the steam engine as the driving force of the production system and the circulation of goods and services, the manufacture and use of Information Technology were in the following century concomitantly as second and third industrial revolution as a result of the complexity of the productive system [1].

In this sense, the twenty-first century suggests a new mode of production by establishing the need for connectivity. What is at issue when it comes to connectivity is precisely the production infrastructure that joins together the Technology of Operation (TO) and Information Technology (IT), using tools capable of ordering a mass of data, ideas and associated things, so that the human element occupies a central but not


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centralizing position in this process, since machines and computers cannot have ideas of autonomous form [2].

It is interesting in this case to explore how the contribution of new technologies is associated with the automotive industry in the context of the Brazilian market in relation to investments. The assumption is that technological innovation on the national scene becomes a competitive element that does not completely unlink the human workforce and that the realization of investments is fundamental in the search for competitiveness and superior performance. Given the needs and investment conditions of the automotive industry in Brazil, the issue is: how organizations in the automotive segment prioritize investments in the industry 4.0. The objective of this study was to analyze the nature of the investment of companies in the automotive sector to fit the Industry 4.0.

## 2 Literature Review

Industry 4.0 is an integral concept of the Fourth Industrial Revolution. The idea is that it manages the integration of Cyber-Physical System (CPS), joining the real with the virtual and connecting digital, physical and biological systems, raising personalized mass production [3]. It is based on nine pillars: big data, autonomous robots, simulation, vertical and horizontal integration systems, internet of things, cyber-physical systems, cloud, additive manufacturing or 3D printing and augmented reality [4], among those cited the most representative is the horizontal and vertical integration of the systems that portrays the industrial base in relation to the administration and the interdependence between the companies [5].

Four elements (types of intelligence) are highlighted for the transition to Industry 4.0, they are: Smart Manufacturing that seeks to transform the most intelligent and advanced machine through new technologies; Smart Products and Services, which deals with the connectivity of digital products and services, by opting for the communication and data collection between companies and clients; Smart Working, which uses technologies to improve work efficiency; and the Smart Supply Chain, represented by external integration in the value chain. However, for these fundamentals to be a part of Industry 4.0, they need to be supported by the internet of things and more advanced technologies, generating connectivity and more efficient business systems [6].

Intelligent factories, designed as the core of Industry 4.0, operate in an integrated network. Four characteristics are highlighted: the vertical integration of intelligent production systems; horizontal integration through networks and the global value chain; engineering across the value chain and acceleration through exponential technologies [7]. Connectivity can hardly be considered something new, the ease in achieving this connectivity is that it presents itself as innovative, impacting on general manufacturing operations, corroborating with other studies [6] on 04 elements of intelligence, highlighting the importance of new technological tools as a source of connectivity in enterprise systems.

Recognized as the next phase of manufacturing, Industry 4.0 applies digitization in its processes and is leveraged by disruptive technologies such as increased data volume by computational capacity and connectivity; the possibility of data analysis by market intelligence sectors; new models of interaction between man and machine; improved transfer of digital commands to the physical environment [8]. The use of these technologies and the application of artificial intelligence techniques, allow a greater understanding of the shop floor, facilitating the planning of the predictive maintenance with decrease of failures and increase the efficiency in productive processes [9]. Continuous monitoring of the condition of production assets provides reliable data for performing predictive maintenance planning in anticipation of problems and avoiding losses.

It should be emphasized that the fourth industrial revolution goes far beyond the innovative technologies employed, since they contribute to the differentiation of companies in business management, knowledge management and training of workers able to participate in productive processes [3].

In Brazil, as well as in emerging markets, developments in industrial processes can be represented by the transition to Industry 4.0, requiring the investments that promote the adaptation of infrastructure and manpower capacity [10].

## 3 Methods

This research was exploratory, of a qualitative and quantitative nature, performed through interviews with executives from the industrial area, belonging to the automotive segment.

The primary data were collected through a survey sent to the managers and directors of the manufacturing area of assemblers and auto parts. Twenty-five questionnaires with 11 questions were addressed, emphasizing the knowledge about Industry 4.0, the priority regarding investments made in connectivity and the adaptation to new technologies.

The elaboration of the questions occurred based on the professional experience of the authors in the studied segment, based on observations in loco. For the respondents the questions were arranged in a random way and for the presentation of the results, grouped in 04 different figures. Figure 1 portrayed the interviewees' opinion regarding the knowledge about the theme, the positioning and the need of the segment to enter the Industry 4.0. Figure 2 the idea was to understand the nature of investments. Figure 3 addressed priority and relative gains. Figure 4, which dealt with the elements that may be necessary to the transition, being the same listed based on the resources used by automakers and auto parts.

Of the sample submitted, 21 questionnaires returned, of which 48% are large assemblers and 52% are medium-sized auto parts. Secondary data were collected through documentary analysis [9, 11, 12] and bibliographic references. The observational method was used to calculate and analyze the results, considering the professional experience and participation of the authors in the segment.

## 4 Result and Discussion

The results are presented by means of the figures below.

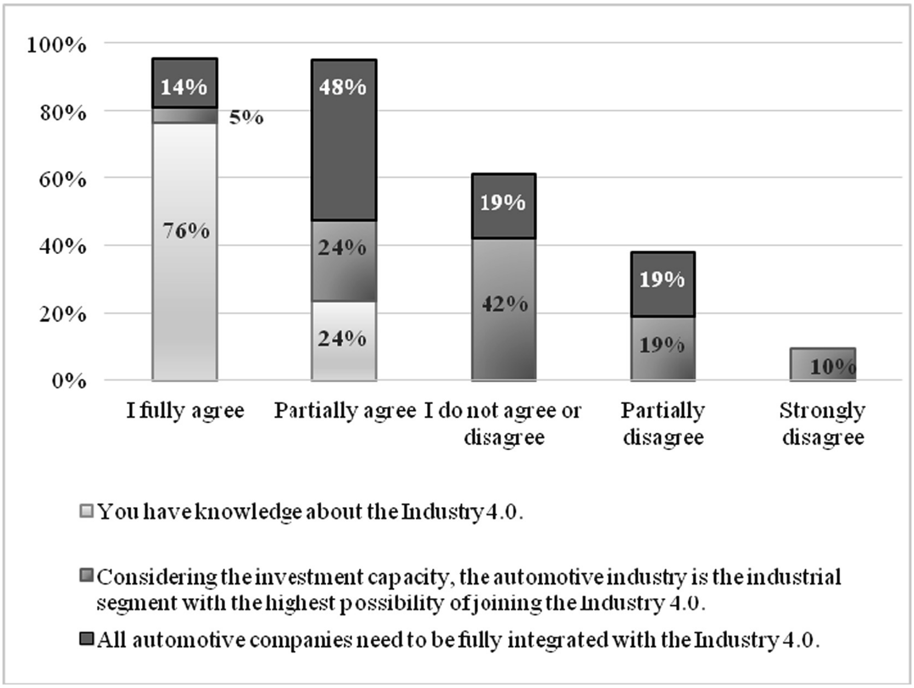


**Fig. 1.** Knowledge of topic (Source: prepared by the authors)

Figure 1 indicates that 100% claim to know about the issue, but they do not reiterate the automotive segment as the main driver of the Industry 4.0. Regarding integration 62% believe that all companies need to be integrated. It is noticed in the correlation of the answers and based on the observational method, that although the participants of the research claim knowledge on the subject, this understanding may be superficial considering the complexity of the subject and the impossibility of measuring the interpretation given by each interviewed. Secondary data [11] reveal the low knowledge industry users generally have about digital technologies and their benefits, stressing the need for greater dissemination on the subject.

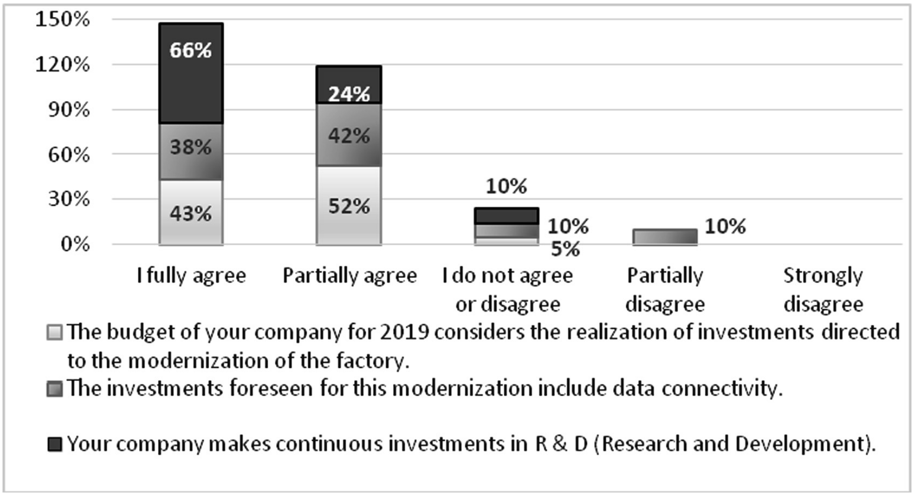


**Fig. 2.** Nature of investments (Source: prepared by the authors)

As shown in Fig. 2, companies invest in research and development and in the modernization of factories. Regarding connectivity, although the answers point in the same direction, a disagreement is observed, which may indicate that the investment volume for this issue occurs to a lesser extent, when compared to the others mentioned.

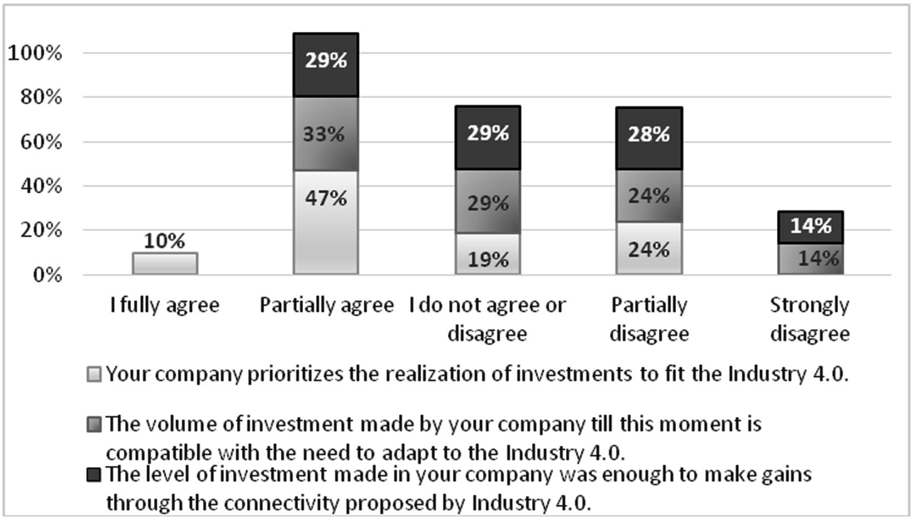


**Fig. 3.** Priority of investments and gains related to connectivity (Source: prepared by the authors)

Figure 3 shows that companies partially prioritize investments and that the volume invested is neither compatible with the necessary nor enough to obtain gains from connectivity.

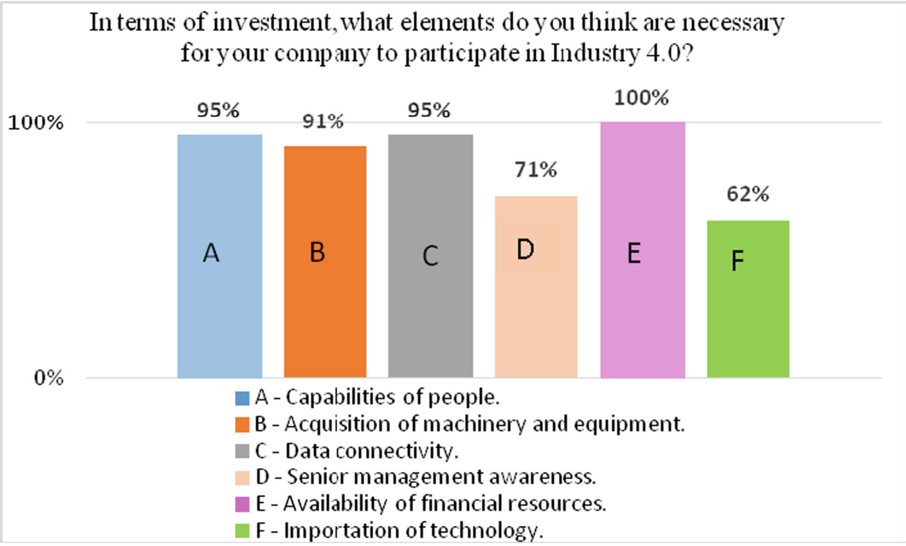


**Fig. 4.** Elements necessary to transition (Source: prepared by the authors)

The elements portrayed in Fig. 4 were considered relevant for participation in Industry 4.0, with the importation of technology and awareness of top management less mentioned. It can be inferred, from these results, that the executives of these companies perceive the necessity of the realization of investment. The importation of technology has not been portrayed as fundamental, which based on responses and on the observational method can lead to the fact that the synergy between resources and training of manpower can result in the development of national technology.

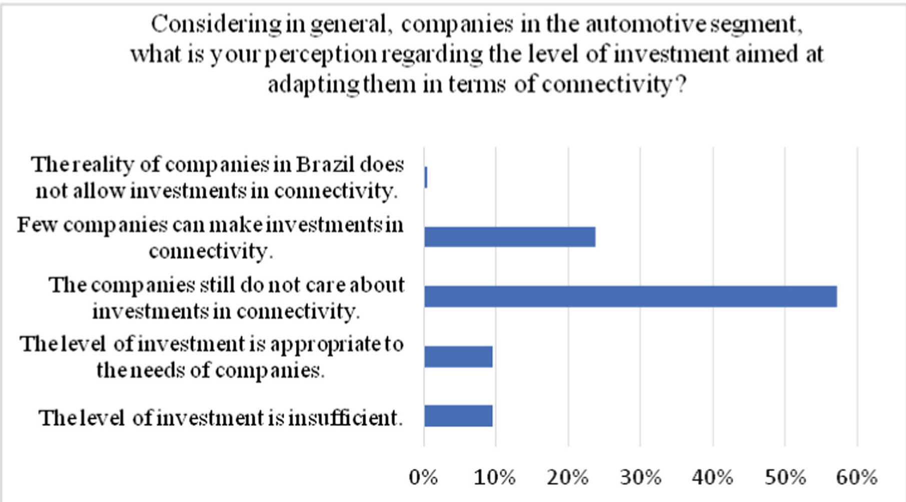


**Fig. 5.** Perception regarding the level of investment for connectivity (Source: prepared by the authors)

Considering what has already been portrayed and based on observations, the indication of the companies' lack of concern for investments in connectivity can be explained by the Brazilian economic crisis [12], which leads them to first seek survival in the market and then prioritize the investment in connectivity (Fig. 5).

## 5 Conclusion

The objective of this study was to analyze the nature of the investment of companies of the automotive sector to fit the Industry 4.0. Based on the results of the survey applied to executives of the area, through the observational method and bibliographic research, it can be verified that the respondents know about the subject, understand that the integration of the companies is necessary, but they do not recognize this segment as main reference for the evolution of the Industry 4.0 in Brazil.

It was found that the budget of the companies surveyed contemplate investment for modernization, research and development and, to a lesser extent, connectivity. Although they prioritize investment, though in a partial way, the volume invested when compared to the needs is insufficient, including to obtain productivity gains from connectivity. This fact can be explained by the Brazilian economic crisis [12], which leads the automotive industry to favor survival in the market in current terms, instead of strategies to make more investments.

Thus, it can be said that the level of investment demanded, added with the lack of training of the labor force, are factors that impede the evolution of the Industry 4.0 in Brazil. However, studies [9] point out that the transition to Industry 4.0 is a necessary reality, which brings productivity gains and opens opportunities for national development and greater international competitiveness.

The present research does not allow definitive conclusions, due to the limitations inherent in the sample size. Despite being careful in presenting, analyzing and interpreting the data to ensure the results obtained, they can not be generalized to the universe of segments and companies, but they open up possibilities for future studies that may deepen the question of investments destined to the transition of Brazilian industry for the Industry 4.0.

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# Process Innovation in Learning Factories: Towards a Reference Model

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**Abstract.** The fourth industrial revolution, also known as Industry 4.0, implies significant new technological opportunities for today's manufacturing industry. However, manufacturing companies still lack knowledge and skills on how to fully utilize these innovative technologies. This is in particular the case as regards development of process innovation. In order to advance this knowledge, the concept of learning factories is useful to support the manufacturer's learning and movement towards innovation. In short, a learning factory, that supports process innovation, can be described as a learning process for industry participants, which utilizes a learning factory to create rapid and innovative process solutions in industry based on the paradigm of Industry 4.0. Research on this topic is however still relatively scarce and scattered, meaning that no common conceptual frame of reference exists to support the research field of process innovation. Consequently, the theory building on innovation in the context of i4.0 is still fragmented and in its infancy, in spite of the rapidly increasing interest in this empirical phenomenon. To advance this domain of research, the current study unites and synthesizes existing research on process innovation in learning factories. Based on the findings of the literature review, the initial work of a reference model for process innovation in learning factories is presented.

**Keywords:** Learning factory · Process innovation · Industry 4.0 · Literature review · Reference model

## 1 Introduction

Industrial revolutions refer to paradigm shifts in industrial production, often caused by technology leaps. Thus far, three paradigm shifts have occurred and thereby also three industrial revolutions. Currently, the manufacturing industry is moving towards a fourth paradigm shift, which is generally recognized as the fourth industrial revolution or Industry 4.0 (i4.0) [1]. The overarching vision of i4.0 is to have intelligent end-to-end processes enabled by autonomous decision-making and cyber-physical systems throughout the supply chain [2, 3]. The implementation of i4.0 is expected to be enabled by a combination of Internet technologies, and "smart" machine and product technologies [1]. Despite agreement on the potential for using i4.0 technologies to make technological advancements in the production [4] and improve the competitiveness of the company [5], the implementation of innovative and valuable i4.0


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solutions in industry is highly complicated, and requires a dedicated focus on developing new skills and competences [4, 6]. Creating process innovation by the use of i4.0 technologies is complex and abstract for companies [4] among other things due to lack of understanding of the potential caused by radical changes as a result of a shift in paradigm [7]. Furthermore, the speed of the technological development is increasing, which means that companies need to both learn about and implement new technologies faster than ever before to stay competitive. Therefore, existing learning methods related to i4.0 technologies may be too time consuming while they, at the same time, may restrict the participants' creativity and thereby the potential for achieving innovative solutions. In order to rapidly develop new knowledge on i4.0 technologies and construct innovative solutions on the basis of these technologies, companies may benefit from being more experimental in their learning approaches. At the same time, companies need to enter into new collaborations with e.g. supply chain partners to fully exploit the potential of i4.0. Consequently, new and faster learning methods which support the development of i4.0 manufacturing systems are required [1]. Several examples exist from both academia and industry where learning factories are used to train i4.0 solutions and thus development of i4.0 manufacturing systems [8, 9]. However, we argue that the concept of learning factories has a broader usefulness for conceptualizing the development of generic innovation methodologies for i4.0 manufacturing systems. Since research on this topic is scarce and fragmented, a common frame of reference is needed in order to create a common conceptual understanding of the research field. Reference models seek to create common understandings of e.g. a research field [10]. Therefore, the objective of this research is to present the initial work of a reference model, which can provide a common understanding of the use of learning factories to support process innovation in relation to i4.0. This is achieved by conducting a literature review, which seeks to answer the following research question: *How do learning factories support process innovation in i4.0?*

The paper is structured as follows: The applied research methodology is presented in Sect. 2. Afterwards, the findings of the literature review are presented in Sect. 3 and significant conclusions for establishing a reference model are emphasized. Lastly, findings and conclusion on the research are presented in Sect. 4.

## 2 Methodology

A structured literature review was made which addresses the research question: *How do learning factories support process innovation in i4.0?*

The initial applied search string was: "learning factory" OR "learning factories". Additionally, an initial search on innovation in learning factories was made. The chosen database was Web of Science, which ensures the academic standards of chosen publications. The search provided 192 hits. Upon first round of revision of the material, it became clear that most of the retrieved research focused on learning factories in education environments and that only limited research was related to industry participation. This led to initiation of a second round of literature search, which focused on capturing research on the topic, which could potentially have applied an adjacent terminology to learning factories. Combinations of several terms related to the research objective were tested. The terms were found in papers related to the research topic and through inputs from experienced researchers in the fields of robotics and automation, manufacturing systems, and operations development. It was chosen to broaden the scope of the literature topics to be included in this research. Leavitt's Diamond model from the 1960's was used as inspiration for structuring both the literature search and the subsequent analysis. The model was originally used for describing and analyzing organizations based on four parameters: Structure, technology, people, and task [11]. Through the four parameters, process innovation in learning factories was investigated in relation to the technologies in center of the innovation (technology), the people who learn by using the learning factory (people), the tasks these people do in relation to the innovative technology (task), and the applied learning process (structure) to answer the research question. Three search strings for each of the four parameters were constructed to search for literature. Only papers published after 2008, written in English language, and with a subject related to i4.0 innovation in learning factories in the manufacturing industry were included. This means that e.g. research on learning factories in education environments was excluded. Based on these criteria, the three most cited articles for each search string were selected for analysis, thus 36 articles have been selected in total.

## 3 Literature Review

This section presents the analysis of the papers retrieved through the literature search. Each analysis is rounded off with a summary of those findings which are of particular relevance to process innovation learning factories.

### 3.1 Structure

Technological process innovation is important for manufacturers' competitiveness in the market [5, 12]. Consequently, learning approaches which boost innovation in manufacturing are crucial [13]. Learning factories are applicable of providing the format and methodologies for this, since learning factories improve the learning productivity [7]. Several learning factories have been installed at universities and research institutions for research, education and/or industrial training [8, 14, 15]. However, the learning processes in learning factories and their objectives differ. Wagner et al. [8] for example studied learning factories focusing on changeable and reconfigurable manufacturing systems and concluded that only few learning factories have changeability characteristics and thus may be used to develop innovative solutions in regard to manufacturing system changeability and reconfigurability. Schallock et al. [15] found that more learning factories are being oriented towards i4.0 topics. The learning factory at Ruhr-Universität Bochum focuses on resource efficiency, management and organization, and process optimization to improve the workers' ability to accommodate changes in the production [14]. This corresponds to the findings of Abele et al. [13] who discovered that learning factories are often used to develop industry participants' ability to manage complex and unfamiliar situations. An example of a learning process related to i4.0 is described by Schallock et al. [15]. The training in the learning factory consists of two parts: One for the high-level managers and one for the line managers. The high-level managers are first coached and prepared for leading the change process of implementing i4.0. Afterwards, the line managers have two trainings. The first is a basic training, which introduces general principles needed for the second part. The second training focuses on i4.0 technologies and the implementation of these in production processes. After completing the training in the learning factory, the organization receives guidance and coaching on-site in the following six months. Another example is the learning process at the learning factory at Ruhr-Universität Bochum, which is centered around business games and simulations of real production processes [14]. Tisch and Metternich [16] present seven success factors for methodical modelling of learning processes and make suggestions for how each of the seven factors can be addressed through learning factories to build successful learning factories.

The literature furthermore indicates that different types of collaboration have a positive influence on learning. According to Macher and Mowery [17] manufacturers in the semiconductor industry that use diverse teams for problem-solving and co-locations, which strengthens the relations between employees in manufacturing and development, learn faster. Additionally, Un and Asakawa [5] found that a R&D collaboration between a manufacturing company and a university positively affects process innovation at the manufacturing site, which also supports the findings of Abele et al. [7] who found that complexity and costs of translating research results into operations can be costly for especially smaller companies.

The main goal of learning factories differs based on their application. For research purposes the main goals are often technological and/or organizational innovation, whereas for education and training of industry purposes, the main goal is to effectively develop competences [13]. Though, according to Abele et al. [7] learning factories would benefit from having a closer relation to innovation.

Based on this, it can be concluded that the use of learning factories differs depending on whether the purpose is related to industry or research. Currently, the use of learning factories to support innovation is related to the research domain, which however indicates that learning factories may be used to create process innovation in industry. Furthermore, there are indications that collaborations between industry and universities have a positive impact on process innovation.

### 3.2 Technology

New, innovative technologies are introduced with ever-increasing frequency, which gives manufacturing companies new possibilities for improving production processes. However, as mentioned before this also sets requirements for rapid knowledge acquisition and solution design for future manufacturing systems [18]. Learning factories support this process by focusing on new technologies and methods in their learning goals. Some learning factories use a holistic view by exploring topics such as i4.0 technologies and methods [19, 20], digital solutions [19], cyber physical production systems [20] and Internet of Things technologies [21, 22] whereas other learning factories focus on specific technologies and methods. Examples of these are industrial robots [18], logistics systems [23, 24], digital twins [25], and agility in operations [26]. The main focus in current use of learning factories is related to specific technologies and methods and only little attention is given to develop conceptual understandings of i4.0 in spite of it being a new manufacturing paradigm which may therefore require development of an overall understanding of i4.0 manufacturing systems.

### 3.3 People

Competence development is a recognized target of learning factories [27], which for instance should prepare industry participants for successful implementation of innovative i4.0 technologies [28]. The employees in focus are e.g. shop-floor workers [29], engineers from areas of expertise related to production [30], and employees from small and medium sized enterprises since they need information and innovative solutions which fit their corporate size and needs [31, 32]. According to Tisch et al. [33] most existing learning factories' industrial target is engineers. However, possible target groups may also be i4.0-specific roles, which have not yet been created [34]. Participants are primarily trained in homogeneous groups [33], though to reflect real workplace situations, Tisch et al. [33] propose to design learning processes which also focus on heterogeneous target groups. According to the findings of Macher and Mowery [17] presented in Sect. 3.1, using heterogeneous groups may also imply faster learning.

Participation in learning factory learning processes does not necessarily imply improved competences for the participants [27]. Therefore, in an attempt to avoid this problem, Enke et al. [35] suggest to compare the companies' actual state to the wished target state and based on this, design competence-oriented learning processes.

Based on this, it can be concluded that current research focuses on developing shop-floor employees' competences so that they are capable of implementing and operating i4.0 solutions and only limited attention is given to the development of management.

### 3.4 Task

Through learning factories, employees from industry should get hands-on experience with innovative i4.0 technologies. However, to achieve this, suitable learning methods and tasks must be applied [36, 37]. Therefore, Schuh et al. [37] studied factors relevant for creating a learning process, which increases the efficiency for participants to learn innovative i4.0 characteristics. Several learning processes put emphasis on training employees in the implementation of innovative technologies (see e.g. [38–41]) through practical, hands-on application, which is often combined with theoretical lectures. For instance, in the learning process described by Prinz et al. [42], the participants start with a theoretical introduction to i4.0 and assistance systems. This is followed by several hands-on simulations starting with a complex production with no assistance system and ending with a fully integrated assistance system to show the participants the differences. The learning process ends with a best-practice tour [42]. Several other learning factory concepts have also used simulation tasks (see e.g. [4, 43]) where the main objective is to transfer knowledge on innovative technologies from research institutions to industry. Consequently, it can be concluded that there is a tendency to use predefined simulation tasks for participants to learn about i4.0 and not using tasks which support innovation.

## 4 Findings and Conclusion

As this research shows, research on process innovation in learning factories is scarce. Consequently, to support future research in this area, a common frame of reference needs to be established. The findings of the literature review are used to construct a discussion on using learning factories to support the creation of process innovation, and thereby introduce the initial work of a reference model in this section.

The vision of an i4.0 factory consists of integrated seamless processes, which are able to efficiently control the increased complexity resulting from accommodating customers' unique requirements. Modularity, flexibility, complexity management, data exchange, and i4.0 technologies are examples of tools and methods, which support the development of the factory of the future. However, i4.0 is not limited to the implementation of isolated innovative methods and technologies, but is a new paradigm that requires manufacturers to see i4.0 from the perspective of the whole manufacturing system and its supply chain. Consequently, to avoid sub-optimizing individual production processes, the company's management needs to acquire a conceptual understanding of the i4.0 paradigm to use as guiding principle for individual i4.0 development projects. i4.0 learning factories could be used to develop this conceptual understanding. However, from this research it is evident that the current research focus in learning factories is to transfer knowledge on innovative i4.0 technologies to implement these in the production and not to develop a conceptual understanding of the i4.0 paradigm and support process innovation. Current focus is on employees who implement and operate the technologies and as a result of this a managerial perspective is lacking. Therefore, compared to existing learning factories, learning processes need to also support the generation of the conceptual understanding of i4.0 by using a management perspective. Additionally, the findings indicate that simulation is a frequently used method in learning factories which means that focus is on making knowledge transfer from research institutions to industry participants on i4.0 technologies and methods. However, if learning factories should support process innovation, this would require tasks and learning processes which encourage the participants to experiment and be creative.

A learning factory for process innovation distinguishes itself from existing learning factories because of its main focus being to create innovation in industry. Consequently, with an offset in the findings of this research we can describe the characteristics of a process innovation learning factory which stand out from existing use of learning factories. A process innovation learning factory can, therefore, be described as a learning factory which supports process innovation in industry through tasks that may be experimental and encourage creativity compared to existing learning factory approaches. Furthermore, to succeed, these learning factories should support the long-term and visionary development of i4.0 manufacturing systems, and thus focus on development of a conceptual understanding of i4.0 besides focus on individual i4.0 technologies and methods which are already used in learning factories today.

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# Applicability of Agile Methods for Dynamic Requirements in Smart PSS Development

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**Abstract.** Smart Product-Service Systems, i.e. solutions consisting of tangible and intangible components interacting with their environment through information and communication technology, are subject to various dynamic influences along the life cycle. Stakeholders to the solution may change, as well as their needs and technological capabilities. This makes the requirements for the solution volatile, uncertain, complex and ambiguous. The system scope and associated requirements are constantly changing. In this paper, it is discussed how agile methods can help to deal with these influences in the development phase. A literature review and an industrial case study are used for analysing the problem of dynamic requirements, and agile methods are identified that can be applied for Smart Product-Service Systems.

**Keywords:** Product-Service Systems · Smart Products · Smart Services · Agile development · VUCA

## 1 Introduction and Problem

For manufacturing companies, it becomes more and more relevant to provide additional services to their products and to enlarge the target market through innovative business models. This results in a transition from product- to service-oriented industries, in which the development process is increasingly based on participatory and co-creative design principles and thus makes an integrated products and services development process more relevant [1]. The implementation of Industry 4.0 can be seen as a catalyst and accelerator of this change. The gathering and evaluation of data support processes like design, operation or maintenance and can lead to optimized industrial value chains in the medium and long term [2]. Manufacturing companies can create a unique selling point in an addressed market niche by offering an attractive bundle of Smart Products and Smart Services, using the potential of new technologies for sensors, actuators and data processing.


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The combination of Smart Products and Smart Services to an integrated solution can be seen as a "Smart Product-Service Systems" (Smart PSS). During the life cycle of such a system, stakeholders, scope and configuration will change. This means that also the dependencies and interactions between the product and the service elements may vary, and consequently this affects the overall solution design [3]. Therefore, the engineering of Smart PSS is evolving from a temporal development process for individual solutions towards permanent orchestration of distributed product, service and information technology elements adapted to a dynamic environment [4]. This requires that these systems are aligned to the environment of stakeholders, technology and constraints throughout the life cycle, which implies that also the requirements towards the Smart PSS are dynamic.

It is therefore relevant to question the methods used for designing and developing such systems. Conventional approaches aim to generate static requirements documents, which limit the reactivity to unforeseen changes in needs. Tools and methods are required that support the gathering and analysis of dynamic requirements throughout the development phase and (prototypical) operation. In the software domain, similar challenges have led to the introduction of agile methods, which rely on continuous feedback loops to catch instantly new requirements [5]. Thus, our main research question is: *Are methods of agile software development transferable to Smart PSS in order to support agile system development there?* The aim of the paper is to design a procedure model for agile system development of Smart PSS based on an analysis of the applicability of agile methods from software development. More specifically, this paper looks into the suitability of SCRUM and Design Thinking.

The paper is structured as follows: The next section explains the research approach and methodology, followed by an overview of the state-of-the art in the fields of dynamic development environments and agile development methods. Section 4 presents a procedure model for the agile development of Smart PSS, which is applied in a case study for Smart PSS development in automotive plant engineering in Sect. 5. The following Sect. 6 illustrates the application results for the identified tools and methods in the use case. Finally, in Sect. 7 we discuss next steps and future work.

## 2 Methodology

The main objective of our work is two-fold, thus we have used a mixed method approach for our research approach: a literature review in combination with action based research, in this instance a case study. A literature review in the field of agile design methods and design of smart PSS was planned, conducted and reported. This analysis showed that there is a research gap in the need for specific application areas of agile methods for Smart PSS. In order to dig deeper into the problems and to shed some light on under which circumstances agile methods can be used in an industrial environment and how they can form the basis for agile development processes, empirical research was carried out in an automotive plant-engineering case study according to Sein, Henfridsson et al. [6].

# 3 State-of-the-Art

This section summarizes the results of the literature review and describes the current challenges in Smart PSS development originating from an environment characterized by volatility, uncertainty, complexity and ambiguity. Furthermore, agile development methods are introduced as an approach to deal with these influences.

## 3.1 Smart PSS Development in a Dynamic Environment

Smart PSS are complex systems that have to be aligned to an environment of stakeholders, technology and constraints. This environment is dynamic and changes have an impact on the requirements for the solution. Its characteristics influencing Smart PSS development can be described with the elements of volatility, uncertainty, complexity and ambiguity (VUCA). *Volatility* denotes strong fluctuations of a state over a relatively short period, making it hardly predictable. *Uncertainty* means that causal relationships of the system under consideration are known, but not their probability of occurrence to forecast future developments. *Complexity* describes the unpredictability of system behavior due to the abundance of elements and connections. *Ambiguity* refers to the obscurity of causal relationships, when an event cannot be clearly assigned to a potential effect, leading to false assumptions [7, 8].

Developing Smart PSS poses particular difficulties under these conditions. Influences from the volatile system environment have a direct impact through technological interfaces, e.g. the real time processing of Big Data. As future operation scenarios are often vague and can only be described by probabilities, there is uncertainty about the requirements for the Smart PSS. Furthermore, they are complex systems with a large number of different elements and connections, making it impossible to predict precisely the behavior of the system. As Smart PSS are by nature one-of-a-kind solutions, there is no pattern to derive requirements, leading to ambiguous specifications.

In order to cope with a VUCA environment in Smart PSS development, an approach has to be able to handle these conditions. It has to be agile enough to react to volatile changes and unlock additional information sources to reduce uncertainty. Furthermore, processes should be restructured to match system complexity and involve experimentation with prototypes to reduce ambiguity. Such methods and tools have been introduced in computer science as agile software development [7].

## 3.2 Agile Development Methods

Agile development methods address the challenges of VUCA-influenced development environments with an iterative and incremental way of working [9]. They start as quickly as possible with value-creating development tasks in order to achieve a so-called Minimal Viable Product (MVP), which is repeatedly subjected to customer feedback, leading to a participatory design approach. Compared to plan-driven product developments there is no need to draw up specifications, but new requirements are continuously added. An agile approach is consequently suitable for Smart PSS developments, in which the complete specification of requirements at the beginning of the project is impossible. Based on reviews of agile development approaches in industry [10–13], two methods with a high relevance for physical product development are examined more closely – Scrum and Design Thinking.

**Scrum** is the most widespread agile approach [10], with a focus on small, highly efficient teams. As shown in Fig. 1, product development is orchestrated in the form of events that are held at fixed intervals and with fixed durations. An iteration in the development is called "Sprint" and is timed between 1 and 4 weeks, depending on the project. The Development Team plans the development activities and scope of the Sprint with the Product Owner and discusses the progress in a Daily Scrum meeting up to a maximum of 15 min. Each iteration ends with the Sprint Review, where the implemented functions are presented by the Development Team and accepted by the Product Owner. A reflection on the methodical work is carried out in the team within the Sprint Retrospective [14].

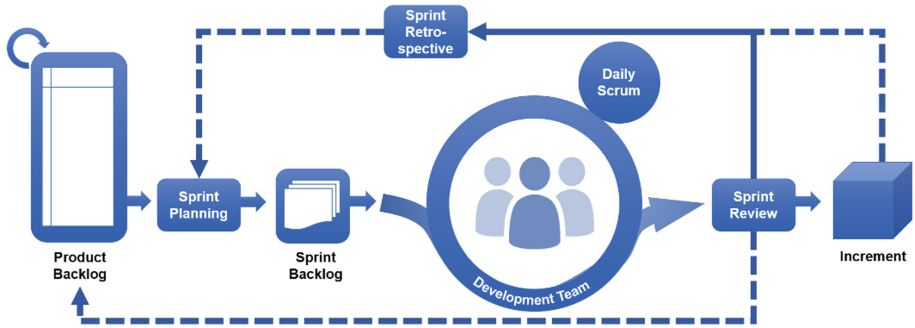


**Fig. 1.** Scrum framework, following [14]

**Design Thinking** is an agile method to promote innovation focused on the intuitive thinking processes of interdisciplinary developers by approaching the problem from several perspectives [15]. The Design Thinking process combines empathy for the problem context with creative problem solving and rational analysis of proposed solutions, as illustrated below (Fig. 2).

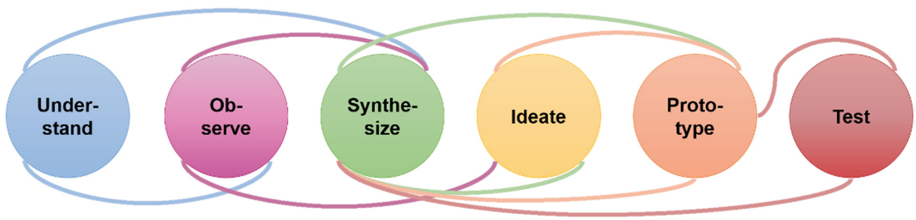


**Fig. 2.** Design Thinking process, based on [15]

In the first phase, the development team builds understanding for the problem. In the second phase, the developers acquire the user perspective by recording their needs in direct interactive exchange as well as indirectly through observations. The synthesis defines the team-wide view of the problem from the findings. Based on this common view, ideas are then generated and finally implemented in prototypes. From then on, the prototypes offer the possibility to test the functions and thus to recognize false assumptions at an early stage. Based on the test results, the development team generates a new, deeper understanding of the problem and starts the design thinking cycle again. By repeating this process, the problem and ultimately the solution space are narrowed down [15].

## 4 Procedure Model for Agile Smart PSS Development

According to [11], the application of Scrum is suitable in the early steps of product development in automotive plant engineering due to the availability of detailed descriptions how to perform the method. Scrum is also the method most widely used in an industrial context, so that benchmarking would be possible [10]. A high user acceptance is also probable. A disadvantage of the exclusive application of Scrum is the absence of a methodical development of an initial product vision [14].

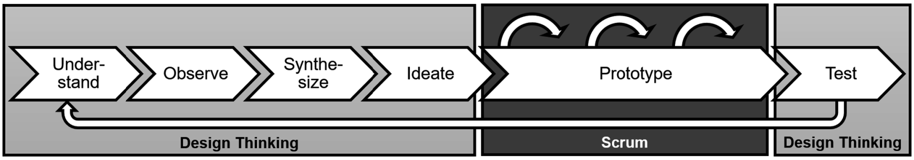


**Fig. 3.** Phases of the procedure model for agile Smart PSS development

In contrast, the use of Design Thinking methods in the early steps of product development make it possible to develop an initial product vision [15]. In plant-engineering, consistent usage of Design Thinking in the development phase could have an effect on the modernization of the service portfolio and organizational structures. The integration of the Scrum method into the Design Thinking process is thus proposed as a concept for the realization of the procedure model for agile development of Smart PSS and is illustrated in Fig. 3 above.

## 5 Case Study

The thyssenkrupp System Engineering subsidiary of thyssenkrupp AG manufactures systems for automotive body and engine assembly, as well as the associated test stations. The change to electric drive and shorter product cycles make the automotive plant-engineering environment extremely volatile, while the preference for different power and energy storage technologies remains uncertain. While the complexity of automotive production lines is increasing, their bespoke design causes ambiguous requirements.

Therefore, a training system was developed to examine whether future employees could be familiarized with their work processes already in the design phase. The standard training method so far has been to introduce employees to the basic welding process in the welding school in order to train aluminum welding, and then receive practical training in production on the real work piece. This procedure repeatedly led to high training effort and consumption of the training components during the learning phases. In order to get better learning results at lower costs with fewer resources, a virtual training environment has been implemented as a part of the Scrum phase (prototyping). This integrated virtual training environment as an integrated part of the prototyping phase can be seen as a Smart PSS.

The virtual training project was set up to check whether the use of Virtual Reality (VR) technology and the CAD models of the assemblies would make it possible to familiarize the trainees with complex work processes. A concept was developed to simulate the station and work processes using VR. The objective of the project was to review firstly the concept for internal purposes. After this, the system can be offered to external customers (Fig. 4).

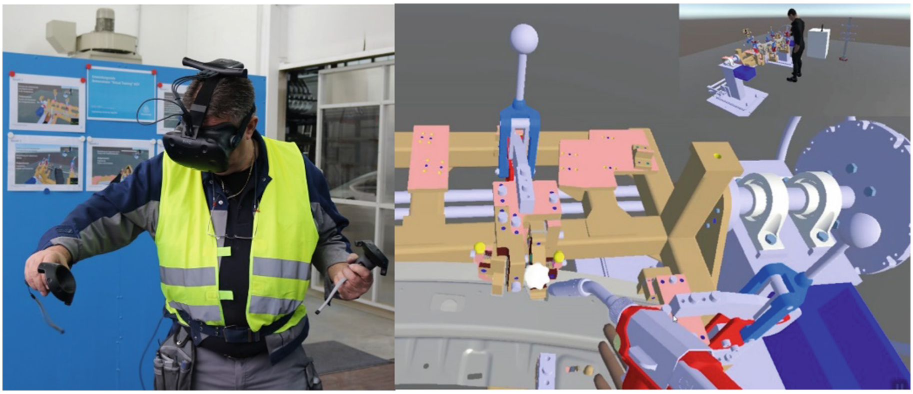

**Fig. 4.** Virtual reality application and virtual workstation

During the introduction of agile development, the team and the project manager were introduced to the basics of the Scrum framework. The differences between the roles of a classical project manager and the Product Owner were explicitly addressed. The Scrum methodology was applied in the development phase. Two sprints of three weeks each were run through. Additional techniques such as testing and the virtual task board were integrated in the course of development.

The sprint length of 3 weeks at thyssenkrupp System Engineering is commonly used across all industries. In contrast to the cross-industry practice of daily scrums, in the case study scrum meetings were held every two days. This deviation was due to the sector-specific organizational structure of a weak matrix organization and the resulting design of the Scrum process. In the context of the final retrospective, the work with the Scrum methodology was evaluated. At thyssenkrupp System Engineering, 15 of the Scrum users answered an online questionnaire, which is partly based on the questions of the study Status Quo Agile 2017 [10].

## 6 Results

At thyssenkrupp System Engineering, 15 of the employees with Scrum experience answered an anonymous online questionnaire, derived from the questions of the Status Quo Agile 2017 study [10]. The resulting feedback was compared with the statements of the cross-industry study in order to enable conclusions about the applicability especially for automotive Smart PSS. The overall performance of Scrum was assessed positively, with 80% of the users rating the performance as good or very good. This is close to the cross-industry ratings with 86% positive feedback. The thyssenkrupp System Engineering Scrum users rated the development method in each criterion (transparency, innovation potential and speed) better than the participants in the comparative study did. It could be proven that cross-industry studies and the application in the case study show similar tendencies. The survey shows that the Scrum development method is accepted by thyssenkrupp System Engineering developers. Through the exemplary application and the feedback of the Scrum users, the applicability of Scrum in the case study development project could be demonstrated. The applicability of Scrum in the early product development of an internal Smart PSS R&D project could be shown.

## 7 Conclusions and Future Work

The pre-selection and evaluation of the agile methods was carried out based on industry-independent literature. The theoretical applicability of Scrum and Design Thinking was derived, which was used to build a procedure model for agile product development in automotive Smart PSS. The investigation of the applicability of agile methods for the development of Smart PSS in automotive plant engineering was conducted as a pioneering activity. The resulting procedure model supports agile system development by applying two agile methods, Scrum and Design Thinking. The Scrum part of the model could be implemented exemplarily in a case study. The evaluation of the Scrum method exceeded those of a cross-industry comparative study. In the test phase of the procedure model, a high result quality could be confirmed and the need as well as the readiness for user integration into the development process was validated. The procedure model developed represents an approach for the industry-specific application of agile methods for Smart PSS. In future research, the process model will be validated including the ideation phase with the application of Design Thinking activities. Based on the results from the case study and literature review, better results can be expected for the early development phase. In addition, it is necessary to examine the applicability in the medium and long-term, as well as the transferability to other Smart PSS developments with a high ratio of physical components.

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# Smart Service Engineering: Promising Approaches for a Digitalized Economy

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**Abstract.** In our digitalized economy, many traditional service engineering models lack flexibility, efficiency and adaptability. As today's market differs significantly from the market of the late 20th century, service engineering models must meet different requirements today than they had to meet in the past. The present paper starts off by providing an overview of the requirements that modern service engineering models need to fulfill in order to succeed in today's economic environment. Afterwards, three promising models that meet several of these requirements will be introduced.

**Keywords:** Smart services · Service engineering · Requirements

## 1 Introduction

Over the past decades, service engineering models have proven to be valuable aids for the design and implementation of new services. They guide companies through the different steps that they need to take when developing new service offerings, starting from the initial generation of ideas and concluding with the service's market entry and subsequent adjustments or improvements. A great variety of service engineering models has been developed in the past, and many of them have displayed practical benefits in different contexts and industries. However, today's service industry differs significantly from the service industry of the late 20th century when the first service engineering models were developed. One of the major factors inducing these changes has been the ongoing digitalization. While it has opened the door for numerous possibilities, it has also created multiple challenges. Among other things, the digitalization has led to an exponential rate of change in the way services are created and delivered [1, 2], and it has lowered the barriers of market entry and thus paved the way for stronger competition and an increased supply [3]. Consequently, companies must now differentiate themselves from competitors by continuously delivering innovative solutions that speak to individual customer needs.

Existing service engineering models often lack pace and are too inflexible to succeed in the face of today's ever-changing market situation. Many older models also require excessive temporal and material resources, which makes them highly inefficient. Service engineering models that want to succeed in today's market situation must be highly flexible and efficient, economic in their use of resources and align the entire


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development process with the needs of the customers [4, 5]. There are some promising approaches toward service engineering from recent years that may be able to succeed in the digitalized economy of the 21st century. The present paper introduces three promising service engineering models and examines how well each of them suits today's market situation. For this purpose, the requirements that service engineering models need to fulfill today will be summarized in the following section. Afterwards, three selected models, each of which meets several of these requirements, will be described and compared to one another.

## 2 Present-Day Requirements to Service Engineering Models

As hinted at in the introduction, today's digitalized economy poses specific challenges to companies who seek to develop new service offerings. Consequently, service engineering models must meet different requirements today than they had to meet in the past. Instead of prescribing a detailed, but inflexible approach to the development of services, they must now provide a highly flexible, adaptable and efficient course of action, allowing companies to quickly develop prototypes and to rework feedback or changing customer or market requirements at any step of the development process. A comparison of recommendations from recent literature and trends in service engineering reveals three best practices for the development of new services. A further specification of these best practices results in seven requirements for modern service engineering models.

The first best practice, user centricity, pursues a **co-creative** approach in which the user is continuously integrated and their individuality considered in the design process. In a second step, a first prototype developed based on customer ideas can be introduced into a **feedback** loop until it meets user expectations [6–8]. The second best practice is using service ecosystems to enable companies to **collaborate** and thus profit from shared resources. Today's **digital** infrastructure facilitates and enhances this exchange [4, 9, 10]. The third best practice follows a resource-efficient agile mindset [11, 12] combining **adaptability**, i.e. the design process being customized to meet any changing requirements while value is constantly being measured, with a **lean** mindset and **cross-functional** development. Therefore, this approach allows for reduced waste and resources and a shorter time to market by developing minimum viable products [13, 14]. For further information, please refer to the paper "Service Engineering Models: History and Present-Day Requirements" by Senderek and Kuntz.

## 3 Promising New Service Engineering Models

While many service engineering models do not meet the requirements summarized above, some recent models display multiple characteristics of innovative, modern service engineering. The following section presents three recent models and points out to what extent they meet these requirements. Each model emphasizes at least one of the three categories of best practices and can therefore be considered a promising approach to developing services in today's economic environment.

### 3.1 Smart Service Engineering

The first model to be presented here is Smart Service Engineering (SSE), an approach for the development of data-driven services developed by FIR at RWTH Aachen University. The model relies on speed and an early positive market impact for its success, and therefore focuses on an agile customer centric approach. It consists of three consecutive loops. The loops are not designed for a linear process, but for a flexible movement between different tasks and multiple iterations of the same loop as needed. While there is a perceived starting and finishing point, they don't need to be the first or last task to be performed. Instead, the tasks can be completed as the circumstances of each project call for.

The main goal of the first SSE loop is to develop a strategy for the company to follow throughout the service engineering process. First, the company needs to analyze its ecosystem, which includes a differentiation of competitors, an identification of key customer segments and a consideration of both the company's current and desired market position. The second task is the development of user stories, which represent typical application scenarios and provide insight into the customer's goals and actions. Following, the company can begin to formulate value hypotheses for its new smart service, which is the third task belonging to the first phase.

The second phase of SSE is the creation of a prototype. This loop allows the company to quickly test its ideas following the principles of a minimum viable product (MVP). The first task here is to define the service's core functions that are required for user testing. The second task is to develop the core functions before they can be tested with the user, which is the third task of the loop. Following these tasks, the company can ascertain the strengths and weaknesses of the new service regarding user satisfaction and rework that feedback into a new prototyping iteration.

The main goal of the third loop of the SSE model is to enter the market. The first task is to devise market entry strategies. Building upon the previously identified customer segments, the company can determine suitable sales channels and communication strategies. The second task to be performed here is to build up all resources required to deliver on a wide scale. The third task is to develop the business case for the new service, focusing on developing the cost structure and revenue streams to support the business model as well as consolidating the value proposition [15].

### 3.2 Multilevel Service Design

The second service engineering model to be discussed here is Multilevel Service Design (MSD), which stresses user centricity and the integration of multiple digital interfaces in the service design process. MSD is clearly designed for the digital age as it makes direct references to digital channels at certain design activities. MSD follows an iterative process consisting of four consecutive steps. This iterative character of MSD relates toward the individual tasks, as the model is designed to be executed in a linear fashion with a clear finish line in the form of the final task and outcome.

MSD begins the first step by a thorough examination of the customer experience. To this end, data is collected on three levels: the Value Constellation Experience (VCE), the Service Experience and the Service Encounter Experience (SEE). The ultimate goal of this step is for the company to achieve an in-depth understanding of the customer's desired experience on each level.

The second step is the design of the service concept. It begins by understanding the VCE, the collective co-created experience from all interactions between the customer and the service provider. Afterwards, the service concept is designed through the Customer Value Constellation (CVC), a construct that expands upon the VCE by putting the customer's given activity in the center and mapping all the services they rely on to fulfill said activity with their interrelations to one another. The CVC allows the company to analyze its surrounding service offerings and reflect on how it can reposition its service concept within this shared space to improve its position.

In the third step, the service system is designed. The first task here is to understand the customer's service experience, including his preferred interfaces and communication paths. Afterwards, the service system is designed with the help of the Service System Architecture (SSA) and the Service System Navigation (SSN). The company can thus easily view where it is active and add or remove elements of its service system to improve the service experience. In the design process, alternative service interfaces should be included without simply replicating service offerings on each interface. The SSN then adopts the SSA and describes how the customer may navigate through the service system, which allows the company to optimize the connections between the interfaces.

The final step is the design of the service encounter. Again, MSD begins with a comprehension task that aims at understanding the SEE. For each service encounter, the company analyzes how the customer interacts at each service interface to fulfill a specific service task. At this point, the critical experience factors, which can range from usability to interface aesthetics, need to be determined. Using this knowledge, the company designs the service encounter using the Service Experience Blueprint (SEB), a variation of the Service Blueprint by Shostack that captures each participant's actions in the service encounter, identifies service interface links and allows the company to enhance the SEE by exploring design alternatives [16].

### 3.3 Design Thinking for Industrial Services

The third model to be introduced here is Design Thinking for Industrial Services (DETHIS). Apart from a service development model, DETHIS also includes a digital toolbox with practical Design Thinking methods that empowers SMEs to apply DETHIS without external help. DETHIS adopted the Design Thinking process by the HPI D-School [17] and added a phase at the beginning and at the end of the existing phase sequence. Hence, it consists of eight phases, each serving a singular purpose and including prescribed methods to complete it. Despite the seemingly linear outline, the model follows an iterative process which can be started or finished at any given phase. Still, the process should be completed in the given order as this enables the Design Thinking mindset to be implemented successfully.

The first phase of DETHIS is the design challenge, during which the company defines what it wishes to accomplish. The design challenge forces them to obtain a more open and customer-centric perspective, which guarantees the company's chances of success as it initiates the subsequent Design Thinking process with the correct mindset. The second phase's goal is to understand the parameters of the problem at hand and to build empathy toward all stakeholders involved. This understanding is validated in the third phase, in which the company must observe and analyze the stakeholders closely.

In the fourth phase, the customer's point of view is defined. By incorporating all critical aspects of the customer's character into the persona, the company guarantees that it has a strong grasp of how the customer thinks and acts. In phase five, the company uses the previously established point of view to generate multiple ideas that address the customer's needs. The ideas are then clustered and weighed before the most promising one is selected for prototyping. In phase six, the prototype of the selected idea is created before it is tested with the customer in phase seven. All feedback is then reworked as need be. The last phase of DETHIS is an implementation phase, in which the broader implementation of the developed idea is planned out and integrated into the company. Given the iterative nature of the Design Thinking process, the steps described above may be repeated multiple times depending on customer feedback [18, 19].

### 3.4 Comparison

The service engineering models described above can be examined with regards to the seven requirements for innovative service design presented in Sect. 2. This comparison lays open the individual strengths and weaknesses of each model. A qualitative evaluation for each requirement reveals the degree to which each model reflects a given requirement compared to the other three models. The results can be illustrated with the help of Harvey Balls (see Fig. 1). The evaluation discussed below is thus of relative and indicative nature and aims at contrasting the three reference models only.

The first model introduced above is Smart Service Engineering. In terms of user centricity, SSE utilizes user stories to form value hypotheses. While this promotes a user centric mindset, it is limited to the functional needs of the user and does not delve deeper into the bigger picture. On the other hand, the prototyping cycle at the heart of this model allows for the speedy testing of development hypotheses and ensures the offering is constantly aligned with the user. This prototyping cycle makes SSE the most agile of the three models, as it directly adopts MVP best practices. Prioritizing the development of the MVP is also in line with lean principles. Additionally, the iterative cycles allow the model to maintain a consistent pace of development and easily adapt to changing parameters. However, SSE falls short when it comes to utilizing service ecosystems. The full potential of partnerships or new forms of resource combinations are not explored. SSE stresses the importance of cross-functional project teams, promoting the dissemination of knowledge and agile development practices. Moreover, the model was derived from case studies and collaboration with industry partners, who tested the model and validated its agile approach. Thus, SSE can be said to display a high practical relevance [15].

The second model introduced above is MSD, which particularly shines in its user centricity. The model simultaneously identifies other actors within the user's value constellation that can be partnered with to improve the offering. At the same time, this analysis provides the model with the insights into the types of interfaces that best suit the user, allowing it to adapt its forms of service delivery. MSD is cross-functional in its use

| | Requirement | SSE | MSD | DETHIS |
|---|---|---|---|---|
| User Centricity | **Cocreative**<br>- Continuous user integration into design process<br>- Users encouraged, empowered to innovate and add value<br>- Offering is individualized for different users<br>- Design of personal subjective customer experiences | ◑ | ● | ● |
| | **Validated**<br>- Hypotheses constantly tested and aligned with user<br>- Constructs fixed feedback channels | ◕ | ● | ● |
| Service Ecosystems | **Collaborative**<br>- Utilizes internal and external resources<br>- Offering is designed as service platform<br>- Value is created in combination with other actors<br>- Shares knowledge and removes company boundaries | ◑ | ◕ | ◑ |
| | **Digital**<br>- Integrates complementary data for deriving user insights<br>- Exercises multichannel service delivery<br>- Applies modular architecture in offering's design | ◔ | ◕ | ◔ |
| Agile | **Adaptable**<br>- Pivots to meet changing requirements<br>- Progresses in iterative consistent development cycles<br>- Value continuously measurable during development | ◕ | ◔ | ◑ |
| | **Lean**<br>- Output oriented, adopting rapid MVP prototyping cycles<br>- Prioritizes working prototype over thorough documentation<br>- Prioritizes resources for creating measurable customer value | ● | ◔ | ◕ |
| | **Cross-Functional**<br>- Employs multidisciplinary self-organizing project teams<br>- Upholds constant communication between all functions | ● | ◕ | ● |

**Fig. 1.** Comparison of the three selected models

of interdisciplinary methods such as the Service Experience Blueprint for the development process. However, the use of cross-functional teams is not explicitly mentioned. The main disadvantage of the MSD model lies in its limited adaptability. By basing the model on fixed interdependent methods of service design, it leaves little room for companies to improvise or adjust the design process. Its practical implementation in different industry contexts does, however, speak for its utility in practice [16].

DETHIS builds on a Design Thinking approach and therefore excels in its user centricity. The entire process is based on understanding the user's inherent needs and emotional drives, which puts DETHIS in a strong position to create resonant personal user experiences. Furthermore, it adopts an early and iterative prototyping and testing approach in order to validate its hypotheses and create measurable customer value. The Design Thinking technique promotes creativity and collaboration among multiple disciplines, thus, benefiting from cross-functional knowledge and expertise. DETHIS, however, does not include any references or methods for utilizing service ecosystems. Indeed, it suggests conducting a stakeholder analysis in the early stages of understanding the user, yet this is not capitalized on later by other methods [18].

## 4 Outlook

While many old service engineering models are no longer suitable for today's economic environment, there are some recent approaches to service engineering that might be suitable solutions for the challenges of the digital age. These newer models focus on user centricity, make use of service ecosystems and incorporate an agile mindset. All three models presented above meet several of the requirements for modern service engineering models, and some of them have been successfully tested in practice. They can therefore be considered promising approaches toward developing new service offerings in the complex and digitalized economy of the 21st century.

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# Strategies for Implementing Collaborative Robot Applications for the Operator 4.0

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**Abstract.** To accomplish a flexible and highly productive production system, collaborative robot applications, such as co-bots, can be one solution. Hence, last year: 2018, less than 4% of the industrial robot investments had "collaborative roots". In order to increase this number, clear strategies for the implementation of co-bots are vital. This paper will present the results from the study of 40 SMEs, and six OEMs, regarding where and when to implement co-bots in production. Furthermore, which KPIs to consider when implementing these collaborative robot applications. The Lotus Blossom technique has been used to create the first steps towards strategies for implementing collaborative robot applications for the Operator 4.0. Seven areas of application have been pre-selected, and one area has been left free of choice for the companies. The results show that the areas with greater strategic interest are 'pick-n'-place' tasks and 'load-unload' tasks.

**Keywords:** Co-Bots · Collaborative robots · Collaborative applications · Human-robot interaction · SMEs · Industry 4.0 · Operator 4.0 · Production systems

## 1 Introduction

*Automation technology* was originally developed with the aim and hope of increasing the precision and economy of production operations while, at the same time, reducing the operators' workload and training requirements [1]. With the new (r)evolution of *collaborative robots (co-bots),* new possibilities and tasks situated 'side-by-side' or 'face-to-face' with the operators have increased [2]. *Adaptive co-bots* [3] combined with 'smart cognitive support' for the operator [4] can be one solution in order to increase human-robot interaction. The *adaptive co-bots* are 'dynamically adapting' to the human's pace, stress-level, and experience. This results in increased flexibility [5], decreased ergonomic related issues [6], and increased quality (i.e. 100% Complete & Accurate Assembly Tasks). So, the flexibility and changeability of assembly processes require a close linkage between the worker and the automated assembly system [7]. The operator needs to be skilled and performing 'cooperative work' with robots, and other machines and cyber-physical systems, e.g. *The (Collaborative) Operator 4.0*


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[8, 9]. Hence, according to the IFR[1], *industrial robots* have been increasing their presence at the shop-floors with over 10% per year over the last years, but less than 4% of the total investments have been in *collaborative robots.* SMEs want to implement 'co-bots', but the lack of clear strategies makes it hard to understand where and when to implement a human-robot collaboration solution, and how to show a Return of Investment (ROI) for the top management. This paper will present a study made with 46 Swedish companies, both SMEs and OEMs, on how to create strategies for collaborative robot applications by using a creative technique known as "Lotus Blossom".

## 2 Designing Collaborative Human-Robot Workplaces

When designing a *collaborative human-robot workplace,* a series of design guidelines must be considered in order to obtain acceptable, successful design solutions. These can be divided into the following five *design criterions* [10]: (i) operational efficiency, (ii) safety [11], (iii) ergonomics, (iv) development of the work content and work organization, and (v) acceptance or trust in automation [12]. A *collaborative human-robot workspace* is defined as a shared space within the operating space where the robot system, including the workpiece, and a human can perform tasks concurrently during a production operation [13–15]. The robot system, or co-bot, within this system is defined as a robot designed for *direct interaction* with a human within the defined collaborative workspace [13]. Hence, different research works show that a direct interaction between humans and co-bots is hard to accomplish and that a division of several levels of interaction is easier to implement [2, 10, 16]. The two lowest levels of *human-robot interaction* are: (i) *co-existence* – where the human and the co-bot are located close to each other, but separated without overlapping each other's workspace, and therefore tasks, and (ii) *synchronization* – where the human and the co-bot share the workspace, but there is no direct contact between them in a step-by-step process of human and co-bot sequential tasks. These two (low) levels of interaction are the ones more commonly used today in industrial applications. Whereas the two higher levels of *human-robot interaction* are: (iii) *cooperation* – where the human and the co-bot share the same workspace with direct contact, if necessary, and also share the work task in a sequential process, and (iv) collaboration – where the human and the co-bot share the same workspace with direct contact, and share the work task in a simultaneous process. These two (high) levels of interaction are more commonly used in R&D lab environments [7].

In order to achieve a *human-centered approach* [17] towards *automation* [18], 'task allocation' strategies are fundamental. The task to be accomplished sets the tone for the system's design and use when discussing human-robot interactions [19]. The assembly tasks need to be well defined in order to fully understand where and when the interaction between humans and co-bots will take place, how to design collaborative human-robot workspaces [20], and how to create future strategies and scenarios. Consensus between managers and operators [21] is also essential in order to ramp-up the implementation of collaborative robot applications. Highly skilled operators that

[1] International Federation of Robotics (IFR) – https://ifr.org/.

can interact with the co-bots, and other systems, is also indispensable, e.g. *The Operator 4.0* [8]. Depending on what type of human-robot interaction combinations [19] the workforce choose, different issues need to be considered and addressed.

Moreover, in order to fully realize the benefits of *collaborative robot applications,* a combination of other enabling Industry 4.0 technologies [22] and organizational practices is needed. For example, the Internet of Industrial Things (IIoT) [23], human cyber-physical systems [8] and softbots [24] combined with skilled operators and novel work structures can make the co-bots applications even more flexible, adoptable, and interactive.

In order to create a 'Robotics & Automation (R&A)' strategy for companies that still are in the Industry 3.0 era, a simple start is recommended. *Co-bots* were the first choice for the SMEs within the conducted study. The most common reason was that they have already worked with robots before, and they saw the benefits of investing in them.

## 3 Methodology

To create a *collaborative human-robot workplace* it is important to understand where (i.e. in which area within the manufacturing system) and when to implement the collaborative robot application (i.e. the co-bot). The companies tend to choose too complex tasks to automate and too high levels of interaction. To generate concrete cases for automation, the *Lotus Blossom technique* was used for the case companies. The *Lotus Blossom technique* is especially useful for generating strategic scenarios [25] and it was tested at the case companies to see if it could be utilized as a first step towards defining their R&A strategies. The technique is used to increase creative thinking [26] and to understand and decrease the boundaries of knowledge sharing [27]. The technique begins with a central core idea or central theme, in this case, the core idea/word is 'collaborative robot applications', which is surrounded by an ever-expanding set of related ideas, like the petals of a 'Lotus Blossom' (see Fig. 1).

Figure 1 shows a stepwise example. First, we have a core idea: *Collaborative Robot Applications.* Then, we choose different KPIs that can be used to measure the selected application impact: *Joining Task – Quality Improvement.* Finally, we rank the different KPI parameters to be measured: *Quality Parameters – e.g. First Time Through (FTT).*

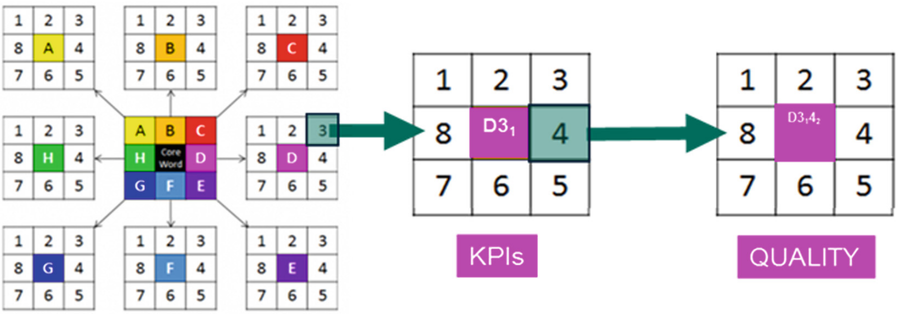


**Fig. 1.** Lotus Blossom technique steps

In this paper three sets of related ideas or rounds have been conducted:

- *Step 1 – Identify and Rank Collaborative Robot Applications:* Which tasks do the case companies want to automate? Seven collaborative robot applications have been identified as the most common to start with, and are presented in Sect. 3.1.
- *Step 2 – Identify Different Areas for the Collaborative Robot Applications:* Which area of the manufacturing system do companies want to automate? Sometimes the same type of task can be applied in many different areas, for example, a 'pick-n'-place' task can be applied in both final assembly and manufacturing operations.
- *Step 3 – Identify KPIs for the Collaborative Robot Applications:* Which parameters can be measured to prove the improvements offered by the automation solution of the selected tasks?

### 3.1 Identifying Collaborative Robot Applications – Through a Literature Review and Interviews with Robot Integrators (Step 1.1)

To identify the first seven areas, i.e. Tasks for Automation, to be used in the *Lotus Blossom,* a small literature review and interviews with the five largest robot integrators in Sweden were conducted. The seven areas or tasks are described in Table 1.

**Table 1.** Common applications for collaborative robots

| Area/Task | Description |
|---|---|
| Pre-assembly | Pre-assembly robots/co-bots use their part handling, high-speed picking, and assembly capabilities to assemble parts and components into sub-assemblies, freeing up the operators to do other more value-added tasks at the assembly line |
| Inspection | Inspection robots/co-bots use their computer vision capability to evaluate the conditions of a part or a product in a very short-time and with higher accuracy when compared with humans' vision |
| Kitting | Kitting robots/co-bots combine their coordinated computer vision with their picking-n'-placing capabilities to identify individual parts or products and assemble them in specific kits (assortments) |
| Joining | Joining robots/co-bots hold a welding torch or a glue gun and use their precision capabilities to deposit material at a constant rate and in a fixed path |
| Final Assembly | Final Assembly robots/co-bots use their part handling, high-speed picking, and assembly capabilities to assemble final assemblies into a final product |
| Packing | Packing (n' Palletizing) robots/co-bots use their handling capabilities for shrink-wrapping, box assembly and loading, and box collating or placing onto a pallet for shipping |
| Pick-n'-Place | Pick-n'-Place robots/co-bots use their part handling and high-speed picking capabilities to place a part in a different location. Manual pick-n'-place is one of the most repetitive tasks performed by human workers today |

An additional area/task called: "own choice", was added during the workshop in order to increase the motivation and creativity of the participants, and it is illustrated as 'F' in Fig. 2.

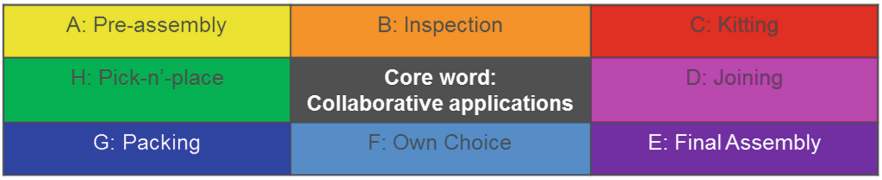


**Fig. 2.** The first seven +1 areas with the core word: collaborative robot applications

### 3.2 Ranking Collaborative Robot Applications (Step 1.2)

Seven workshops were conducted during 2018–2019 with a total of 46 companies, 40 SMEs and six OEMs. The SMEs were mainly small companies that had between 10 to 50 employees and were mostly sub-contractors (70%) or had their own special niche (30%) (see Table 2).

**Table 2.** Workshops within collaborative robot applications

| Workshop | | No. of participants | | |
|---|---|---|---|---|
| 2018 | 2019 | OEM | SMEs | Persons |
| 1 | | 1 | 6 | 27 |
| 2 | | 0 | 5 | 14 |
| | 3 | 2 | 7 | 18 |
| | 4 | 0 | 5 | 12 |
| | 5 | 0 | 8 | 22 |
| | 6 | 2 | 5 | 16 |
| | 7 | 1 | 4 | 25 |

At each workshop, the companies ranked the seven +1 areas, illustrated in Table 3, in two different ways:

1. Importance for the companies, and
2. Time horizon for implementation.

**Table 3.** Ranking of collaborative robot applications areas

| Ranking | Level of importance | Time horizon for implementation |
|---|---|---|
| 1 | Very important | <2 years |
| 2 | Important | 3–5 years |
| 3 | Medium important | 6–10 years |
| 4 | Less important | >10 years |
| 5 | Not part of our company's tasks | Never |

Table 4 shows the average ranking of each area in each workshop and the overall average of the workshops at the bottom line.

**Table 4.** Results from the 1st step of the Lotus Blossom technique

| Workshop | | Level of importance (Average) | | | | | | | | Time horizon for implementation (Average) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2018 | 2019 | A | B | C | D | E | F | G | H | A | B | C | D | E | F | G | H |
| X | | 4 | 2 | 4 | 5 | 3 | 3 | 2 | 2 | 4 | 3 | 4 | 5 | 3 | 3 | 2 | 2 |
| X | | 4 | 2 | 3 | 2 | 3 | 5 | 1 | 1 | 4 | 2 | 3 | 2 | 3 | 5 | 3 | 2 |
| | X | 2 | 2 | 2 | 4 | 3 | 4 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 4 | 3 | 3 |
| | X | 3 | 3 | 3 | 4 | 4 | 3 | 2 | 2 | 3 | 2 | 3 | 3 | 3 | 4 | 3 | 2 |
| | X | 2 | 2 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 3 | 3 | 4 | 3 | 3 | 4 | 3 |
| | X | 2 | 2 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 2 | 3 | 2 |
| | X | 3 | 3 | 3 | 2 | 4 | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 4 | 4 | 3 | 3 |
| **2** | **5** | **3** | **2** | **3** | **4** | **3** | **3** | **2** | **2** | **3** | **3** | **3** | **3** | **3** | **4** | **3** | **2** |

### 3.3 Identifying Different Areas for Collaborative Robot Applications (Step 2)

A trend was that when there were OEM companies participating in the workshops, 'Pre-Assembly' and 'Final Assembly' tasks were ranked higher. While the SMEs tended to rank 'Pick-n'-Place' and 'Load-Unload' tasks higher (see Table 4).

The areas/tasks that were ranked as the highest of the seven +1 were the collaborative robot applications: H(2:2) and B(2:3), i.e. Inspection and Pick-n'-Place tasks (including Load-Unload tasks) (see Table 4). The SMEs often had machining tasks as their primary tasks as they were producing components as sub-contractors for the OEMs. This is one reason for the high ranking of 'Load-Unload' tasks. Another explication could be that these tasks have a lower level of human-robot interaction, often 'co-existence' or 'synchronized', and therefore, made it easier to start with.

Most of the companies that have not implemented collaborative robot applications yet, had a time horizon of 3 to 5 years before they thought that they will have an implemented application. The reasons for this were management and financial issues. A common misconception was that robots still are too expensive to buy (see Table 3).

The lowest ranked areas/tasks were D(4:3) and F(3:4), i.e. Joining and Own Choice (see Table 4). The 'joining', e.g. gluing, welding, etc. was better off for traditional industrial robots according to most of the companies. One important factor was the safety around the manufacturing cell.

After the first round, the case companies had one up to eight different scenarios that they wanted to investigate further in terms of collaborative robot applications, and 10% had already invested in a co-bot and had started to implement it. These implementations were 'Load-Unload' tasks into CNC-, Drilling-, and Milling- operations.

### 3.4 Identifying KPIs for Collaborative Robot Applications (Step 3)

The most common KPIs for the case companies were: (i) to increase ergonomics, (ii) to have a more even cycle time, (iii) to increase quality, and (iv) to increase resource- and volume- flexibility.

## 4 Conclusions

To implement collaborative robot applications successfully, a clear *R&A strategy* is important. The results from the workshops show that the case companies do not have the expertise in where and what to implement. *Collaborative robots* tend to be the first enabling technology within Industry 4.0 that SMEs chose to implement. There is also a tendency towards implementing Additive Manufacturing as a second step, mostly to print fixtures or grippers for the co-bots. Combining *Collaborative Robots* with other enabling technologies such as IIoT, Artificial Intelligence, or Augmented Reality will make collaborative robot applications even more effective and efficient when it comes to quality assurance and time-efficiency in programming.

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# Situation Awareness for Effective Production Control

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**Abstract.** Situation awareness is a growing need for manufacturing operators with the digital transformation of manufacturing environments where operators are expected to take larger responsibilities and tasks on the production flow. To make effective production control decisions, workers need to be aware of the situation that consists of multiple factors such as the production status, and internal and external demand requirements. Adapting existing models for situation awareness, this paper presents four case examples of manufacturing companies that implement digital technologies for situation awareness.

**Keywords:** Situation awareness · Production control · Manufacturing industry

## 1 Introduction

Most of the modern manufacturing companies operate in complex and dynamic organizations composed of equipment, people, information and information systems, which are influenced by a multitude of internal and external factors. In such complex environments, the decision makers often lack the holistic view of the situational factors, which leads to suboptimal local decisions and actions [1]. Earlier work [2] has attempted to apply the situational awareness framework of Endsley and Garland [3] in order to describe and understand operators need for data and information in their decision-making on the shop floor. Situation awareness (SA) is "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future" [4]. This relates back to classic decision-making theory to the more recent frameworks for describing workspace awareness [5]. In workspace awareness, there is the recognition that awareness in personalized technology, such as the personal computer, and the need for "groupware" in order to collaborate virtually.

In the highly automated and digitalized factories of the future, operators will have fewer physical tasks, but more decision making and problem-solving tasks. Today's information systems mainly address the higher-level decision makers such as planners' needs, while there is a certain gap for decision support on the shop floor. In line with Industry 4.0 thinking, the idea was that technology can enhance and extend the human abilities in production control – and in the most advanced form the tightly integrated


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cyber-physical system of production machine and operator. However, the impetus in Industry 4.0 has been heavy on the technologies and has less focus on the softer side of enhancement. Nevertheless, true SA only exists in the mind of the human operator. Data does no good unless it is successfully transmitted, absorbed and assimilated in a timely manner by the human to form SA [6]. This shortcoming has previously been described at length within the computer-supported collaborative work field [7]. While the idea was that media-rich shared spaces would foster comprehension and projection; it often fails to do either.

With the introduction of more personalized technology on the shop floor, going from collective-by-design solutions such as whiteboards and various KANBAN solutions to individual-by-design solutions such as smart glasses or smart watches – this mirrors the development in the office. The need for industrial groupware – to support coordination and collaboration when hardware by design is non-inclusive and lacks the option for physical collaboration between users. While SA in manufacturing is an emerging topic receiving interest from academia in recent studies, there is a research gap in investigating the practical applications of technologies providing SA to operators. In this study, we have attempted to explore how SA of operators is supported in manufacturing companies, through four cases of technology for operative production control.

## 2 Situation Awareness (SA) in Manufacturing

SA has been coined into the literature by aviation researchers fails [8], studying the cognitive tasks of aviation practitioners, and then have been spread to numerous application areas and work environments, including manufacturing. A central SA concept in the manufacturing context is the level of automation (LOA) that aims to provide various levels of support to the operators [9], depending on their task. Identifying and using various types of support is needed to avoid the potential out-of-the-loop performance problem (OOP) which refers to the slow intervention of operators when automation fails [8]. Following types of support are identified for SA of operators.

### 2.1 Perception Support

Perception-support is at the core of Endsley's model, the basic ability to perceive and be aware of processes in your environment. At the basics, perception support can be measurement equipment (e.g. thermometers, calipers) that allows the operator to observe physical quantities more precisely – or observe quantities not visible to the human eye (e.g. radiation). With connected digital sensors, perception support also includes *teletranslation*, i.e. that one can observe quantities not directly in the local environ or inaccessible due to hazards (inside operating machinery). However, basic focus on the data accessibility from multiple sources lead to information intensive unmanageable complexity for the operator with the increasing complexity of production environments [10]. For an efficient perception support, cognitive standpoint should be taken to integrate the required information with operator's cognitive tasks [11].

## 2.2 Comprehension Support

At the next level, putting physical observations or quantities into context requires the ability to comprehend the values. This requires knowledge of the manufacturing context on the operator. The context model of the operators in manufacturing consists of several elements; the context model of the operators built according to the operational (e.g. process, task), organizational (e.g. the team that operator belongs to) and user-centric (e.g. competency profile of the operator) dimensions of context [12]. Or a more extended context model, including the environmental (e.g. outdoor conditions) and system (e.g. devices) dimensions [13]. For some processes, it is also necessary with comprehension support due to complex causality or similar. For example, handling unexpected events in production control in a timely and appropriate manner require that operators comprehend the cause, impact, and context of the event [1]. Such support is traditionally available through control-room systems where a mathematical model or simulation is conducted on the sensor data before *results* are presented to the operator. One can see a similar use of statistical process control charts [14], which is a manual tool for putting measurements into a monitoring and control context.

## 2.3 Projection Support

At the highest level of Endsley's SA model, the ability to not only reason over the current state, but also over the project measurements and observations into a future state given the current comprehension [3]. This requires predictive power in the causality relations that underlie the comprehension support. Predictive Situation Awareness in manufacturing can benefit from artificial intelligence (AI) methods that can enable reasoning methods to estimate current situations as well as to predict future situations [15]. Nevertheless, most AI methods are tested for limited use case scenarios. In real world applications, where the situation is far more complex, the prediction accuracy is still a critical issue to be solved for the implementation success of such methods.

## 2.4 Coordination Support

In all processes where there are interdependencies between tasks or products, where multiple workers must work together to achieve overall quality or flow – there is a challenge in coordinating the production. Cooperative work involves many interdependencies, effective management of these interdependencies - i.e. coordination – is pivotal [16]. The traditional way of managing coordination in manufacturing is standardization of work and procedures. Takt time is one way of also standardizing the flow of work in manufacturing. However, in production mixes where takt is infeasible – other forms of coordination are necessary. Many of which, requires perception, comprehension and projection of the situation of colleagues onto your own situation. Therefore, improving awareness by increasing the visibility of information's through technology is important means for support coordination.

### 2.5 Collaboration Support

Collaboration may be defined as "departments' willingness to work together, whereby they share resources and understand and have consensus on common vision and goals." [17]. It is now possible to realize collaborative work and SA from technological point of view, however there are still big gaps from human factors point of view [18]. Collaboration requires more than cooperative work; it is necessary to do master the mutual adjustment and trade-offs of cooperative work – but for true collaboration it requires even more streamlined production and closer collaboration between members of the value chain in order to achieve efficiency and smooth flow through the dependencies between each process steps [19].

## 3 Case Examples

In this paper, case study research methodology has been applied to study, exemplify, and validate the research constructs drawn in Sect. 2. Case companies have been selected from ongoing or completed industry-driven research projects focusing on digitally enhancing the manufacturing operators' tasks. The three of the cases are collected from production companies in Norway, all of which at the corporate level have turnovers in excess of $100 MUSD and operate in a primary export-oriented global market. All three have processes involving metal-work and machining operations. The last case is collected from European companies involved in an EU project. The authors have worked with the companies over years – both in development, implementation and evaluation of technological as well as organizational solutions for operator productivity and efficient production. This collaboration has enabled accessibility to rich data from companies. The primary empirical data source has been workplace observations and semi-structured interviews with the operators. Enterprise data and documentation (e.g. production data from ERP system) have also been collected and analyzed.

### 3.1 Case I: Tablets Connected to the Control System on Each Machine

The case company has implemented a manufacturing analytical solution called Vimana on the tablets located at the CNC-control system for six of their machines at the department of cutting heads. In this department, each operator runs two machines simultaneously. The analytical software provides visibility and deep insight into the machinery performance, for all of the six machines. The operators obtain a good indication of machine status by taking a quick glance at the tablets. Information on key figures, such as machine stops, production time, and amount of production over the last few hours, with relevant, actionable data are provided. This increases situational awareness of the operators, enabling better planning, problem solving, and execution so that assets are optimized, work is simplified, and a data-driven culture is adopted. Using these tablets, the operators have built a stronger team feeling internally in the cutting head department. They work together towards common production goals and assist each other if downtime on the various machines occur. Furthermore, the operators move orders between machines in case of downtime or absenteeism of colleagues.

However, worth noting, changes in the production site require a good implementation process and great leadership. This is especially true in a change process where new digital tools can be used as a mean for surveillance, which is a well-known problem when implementing digital technology for collecting and sharing data. During the introduction of the tablets, some operators expressed their concerns, fearing that this digital solution would contribute to increased surveillance and not lighten their workday as intended. It could be argued that this happened as a result from weak leadership and a poorly managed implementation process. The management did not sufficiently inform the operators before implementation. Now, one year later, most operators are far more positive. They have realized that the tablets are implemented in order to support them in their workday by providing important and useful information, and as a result, the tablets have contributed to significant productivity gains for the department.

### 3.2 Case II: Computers on Each Working Station with Software-Solution for Production Planning

The case company developed their own production planning tool and made it readily available to all operators in production. The idea behind the software was for it to act as a replacement for mainframe systems, where one could control production orders and sales orders. The company wanted to place computers in the production, so that the operators themselves could plan their own working day and be able to optimize the production orders and attain visual control over the queue on their machine. The system is used to obtain all kind of information regarding different orders. The operators can find information on each order, such as 3D models, drawings, specifications, production priority, delivery deadline, raw materials and inventory, picking list, production statistics, reasons for previous wrecks, the load on the various machines, production deviations, and the value chain for each order. The operators can keep track of where each order is located, and whether the order is in working progress in the relevant step in the value chain. They can find order history, such as deviation history and production details, related to specific orders. This kind of information is often very valuable and facilitates work. The system displays the order list by priority. When priority order changes, for example as a result of an urgent delivery, the information is updated.

The system also shows the planned workload on each machine in the coming weeks, so that the operator can facilitate optimal planning of his own working week. If a machine has a lot of queue, it is possible for the operators to coordinate between themselves and move orders to other machines with less workload. The planning phase is largely entrusted to the operator and the operator actively uses the information from the system into the planning phase to make everything ready for the production phase. The system is based on transparency. All information is available to everyone in the company, and this is highly valued among the employees. The operators appreciate the fact that that the software is made in-house considering that both operators, planners and designers can continuously propose new features and enhancements to make the system more customizable to display the information they need in their workday. However, as the system can continuously be developed, there is a danger of a user interface which becomes less user-friendly and messy as a result of information overload.

### 3.3 Case III: Production Control Events Delivered to Smart Watch

The case company has a factory wide machine monitoring solution, that monitors OEE and similar metrics for all CNC machines and machine control. This is a partly custom solution, tightly integrated with the maintenance scheduling system, allowing operators to view the operational status of all machines live. This is also used for calculating and showing key performance indicators in various dashboards. Parts of the production is based on multiple machines per operator, hence certain parts are machined with the machines running un-attended. However, operators are on hand (covering a pool of machines) to address any unforeseen events or stops in the programs. When covering multiple machines, the ability to perceive and project future states becomes a challenge requiring good short-term memory skills and mental capacity to be able to balance and coordinate their own workload. Unforeseen events cause loss of productivity with machines remaining idle until the fault is corrected. To support the workers in addition to more traditional "traffic lights" indicating machine status, visible from a distance, the company extended their production control system with a smart-watch interface that allows certain messages to be pushed to individual operators. This includes projection cues such as "15 min remaining in program" to the more perception aiding messages such as "Machine [X] stopped due to [Y]". This reduces time-to-discovery of unforeseen stops, and ideally also aids the operator's ability to plan and self-coordinate.

### 3.4 Case IV: Knowledge in Time, an Industrial Augmented Reality Solution for the Operator on the Shopfloor

The Knowledge in Time (KIT) service aims to provide cognitive support tailored to the needs of each individual operator. The KIT service has been deployed at three end-users covering a range of different industries, namely aeronautics, robot manufacturing and furniture manufacturing. Each of the end-users has differing production rates and product/process complexities, which have their own challenges:

*Furniture Manufacturing:* The primary use of the system is for training purpose of the operators. However, the system is also used by the experienced operator by bringing to their attention intricacies of the assembly operation based on their past performance and evidence of retention concerning process. The secondary use of the system is to verify the quality of the training and decide on potential workplace optimization.

*Robot Manufacturing:* The system provides step-by-step instruction support, whilst monitoring the operator's activities to assess the quality of their work and capturing evidence of the work. The secondary use of the captured data is to support quality auditing of the production process.

*Aeronautics:* The system supports the operators by indicating the most common process mistakes incurred in the recent past. The system in this case monitors the operator's actions and indicates the error probability in the task, thereby bringing to the attention of the operator. The secondary use of the system is to improve the process optimization.

The operators have appreciated the use of augmented reality with machine learning to increase their cognitive capabilities tailored to the particular context of work being carried out. However, the secondary use of the system to support long-term cycle provides the means to augment and improve existing company knowledge.

**Table 1.** Summary of case examples

| Support | Perception | Comprehension | Projection | Coordination | Collaboration |
|---|---|---|---|---|---|
| Case I (Tablet) | Machine status and performance such as system failures | Impact on the rest of the order, time available to perform the order | Showing when to change tools to avoid production failure | Helping operators work together towards common goals and assist each other | None |
| Case II (Computer) | Status of orders and resources, changes in orders and plans | Possible to coordinate between orders on the machine | Root-cause analysis of variation in input/output | Possible to coordinate between orders on different machines | None |
| Case III (Smart watch) | Provides remote perception for certain key events | None | Provides temporal cues for the operator | Only self-coordination | None |
| Case IV (KIT) | Better understanding of the work context, through sensed environment | The reasoning modules allow KIT to decide when the operator is in need of cognitive support | Insight into upcoming steps in the process | With contextual information, SA in a team of operators is improved even if just one is using the device | Collaborative workplace optimization |

## 4 Discussion and Conclusion

This paper has investigated the topic of SA in the manufacturing context. The case examples for SA support from real manufacturing companies are summarized in Table 1. Referring to the research gap stated in Sect. 1, we see that the emphasis is on immediate support for situational awareness-building aspects in real life production environments. The coordination and collaboration needs are less supported in the technology used in our case companies. The more interesting discussion is on the introduction of individualized technology in the workplace. Several of the technology cases, has taken up smart watches and individual tablets. The extreme of this trend is the introduction of head-mounted computers (e.g. HoloLens). All of these convey information and foster an individual interaction. This is an interesting conflict with the principle of visual control ("mieruka" in Toyota parlance), wherein the concept of transparency and visibility strengthens the control aspect. This is very similar to experiences in software for office workers, where the technology is by design mostly individual. In contrast to collaborative-by-design technology such as physical status indicators on a shop floor; individualized technology needs software to aid coordination and collaboration. Future research will focus on wider adoption of the digital technologies to enhance the SA of manufacturing operators in consideration with the human factors, as well as will address the individual and collaborative SA concepts.

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# Intelligent Diagnostics and Maintenance Solutions for Smart Manufacturing

# A Study on the Diagnostics Method for Plant Equipment Failure

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**Abstract.** Recently, in the era of the Fourth Industrial Revolution, the rapid development of ICT (Information and Communication Technology) and IoT (Internet of Things) technology have been actively applied to collect and utilize the status data of plant equipment during their operation period. With these technologies it is very important to keep the availability and reliability of the equipment during its usage period without any interruption or failure. In this vein, the CBM (Condition Based Maintenance) or PHM (Prognostics and Health Management) policy which carries out maintenance activities based on the condition of the equipment has been increasingly applied to the plant industry. Although it has a high potential to derive the important value from operation data of plant equipment through data analytics, research on data analytics in the plant industry is still known as an early stage. In this study, we briefly introduce a method to diagnose the fault state of the equipment by detecting patterns related to the failure modes of equipment based on gathered sensor data. To develop the method, we apply the well-known clustering/classification algorithms and text mining and information retrieval method. In a case study, we apply the proposed method and show its possibility throughout preliminary experiments.

**Keywords:** Failure diagnosis · Plant equipment · Maintenance · CBM

## 1 Introduction

Generally, a plant is the complex system consisting of a number of highly reliable equipment. It has been in operation for decades, usually through years of design and construction. Recently, the rapid development of ICT (Information and Communication Technology) and IoT (Internet of Things) technology have been actively applied to collect and utilize status data of major plant equipment during their lifecycle. With these technologies it is very important to keep the availability and reliability of the equipment during its usage period without any interruption or failure. During the plant operation, any small accident could lead to a lot of human and material damage at the industrial and power plants such


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as nuclear power plants, petroleum refineries, chemical plants, etc. For example, in the case of an energy plant handling hazardous chemicals with high risk, a leak accident can cause catastrophic damage to workers in industrial facilities as well as to civilians outside the industrial facility. Therefore, it is necessary to develop the diagnostics method for plant equipment failure in order to prevent such an accident in advance.

In this vein, the CBM (Condition Based Maintenance) or PHM (Prognostics and Health Management) policy which carries out maintenance activities based on the condition of the equipment has been increasingly applied to the plant industry. Although it has a high potential to derive the important value from operation data of plant equipment during its operation period through data analytics, research on data analytics in plant industry is still known as an early stage.

In this study, we briefly introduce a method to diagnose what kinds of faults will appear in the future by detecting fault patterns related to plant equipment based on gathered sensor data under the CBM policy. We apply the TF-IDF (Term Frequency-Inverse Document Frequency) technique frequently used in text mining and information retrieval to detect anomalous patterns related to equipment failure types. The TF-IDF value is a value indicating how important a word is in a specific document, and many search engines use it for evaluating the importance of words existing in a document. In this study, we used the TF-IDF technique to extract patterns of faults that were related to the fault type among the patterns that occurred before the specific fault. In addition, we applied the SVM (Support Vector Machine) to establish the fault diagnosis model. To evaluate the proposed method, we have carried out a case study for the centrifugal pump and found out the possibility of the proposed method throughout preliminary experiments.

This study is organized as follows: Sect. 2 reviews the relevant previous works. Section 3 briefly introduces the overview of the proposed method. Section 4 summaries the preliminary test result of the case study. Finally, Sect. 5 concludes the paper with a short summary.

## 2 Previous Works

In general, maintenance activities are divided into ‘breakdown maintenance’ and ‘preventive maintenance’. Under the breakdown maintenance policy, maintenance activities are performed after recognizing the failure. On the other hand, the preventive maintenance performs maintenance activities based on the time or equipment condition before the failure occurs. The preventive maintenance is again classified into TBM (Time Based Maintenance) and CBM (Condition Based Maintenance). The TBM is a method of regularly checking and preserving the target equipment with a fixed period of time. The CBM is to carry out maintenance activities based on the condition of the equipment. This study focuses on the CBM policy. In the CBM, one main challenging issue is the failure diagnostics.

So far there have been several research works related to CBM studies and fault diagnosis methods. For example, Bunks *et al.* [1] proposed a state-based conservation method using the HMM (Hidden Markov Model) and conducted case studies using data collected from the Westland helicopter gearbox. Djurdjanovic *et al.* [3] presented the concept of a watchdog agent to perform CBM on mechanical equipment using sensors and wireless internet technologies that collect various data. Dong *et al.* [4] diagnosed the state of the equipment based on the data collected from various sensors with the HSMM (Hidden Semi-Markov Model) technique, which is different from the HMM with fixed state transition probability, that changes the state transition probability with time. Wang *et al.* [9] used a partly-linearized neural network to extract features using a continuous wavelet transform technique for centrifugal pumps for diagnosing equipment failure. Furthermore, Li *et al.* [6] proposed a method for predicting the deterioration of a gas turbine engine using a combination of linear regression and quadratic regression. Fei *et al.* [5] proposed a methodology to diagnose the failure of power transformation based on the information of gas collected from equipment using SVMG (Support Vector Machine with Genetic Algorithm) method which determines parameters of SVM using genetic algorithm did. Zhao *et al.* [10] proposed a generic intelligent fault detection and diagnosis strategy that simulates the actual diagnostic thinking of chiller experts. The diagnosis is performed by a three-layer DBN. Muralidharan *et al.* [8] studied the method of extracting features from centrifugal pump by using continuous wavelet transform technique from vibration data and diagnosing equipment failure by SVM. In addition, Moon and Kim [7] proposed a system that could efficiently diagnose mechanical failures such as mass imbalance and axis alignment failure frequently occurred in wind power generation system by using artificial neural network and wavelet transform. Cai *et al.* [2] applied an expanded BN model to the failure prediction process of a complex system under uncertainty, and built the corresponding model from a data mining algorithm based on the divide-and-conquer principle.

In this study, we first propose a method to diagnose the state of equipment using TF-IDF technique, which is mainly used in information retrieval and text mining. In many studies, wavelet transform was used to extract anomalous patterns from univariate (mainly vibration) data. However, in this study, features are defined for multivariate (vibration, temperature, etc.) data. The abnormal pattern is extracted using the TF-IDF technique and clustering methods. These points are different from the previous studies.

## 3 Approach

In this section, we briefly introduce the approach to diagnose the failure type of the equipment based on sensor data collected from plant equipment. Figure 1 shows the overview of the method proposed in this study.

As shown in Fig. 1, the proposed method is largely divided into two parts. One is the learning process to diagnose the condition of the equipment and the other is the process of predicting the state of the equipment using the learned model.

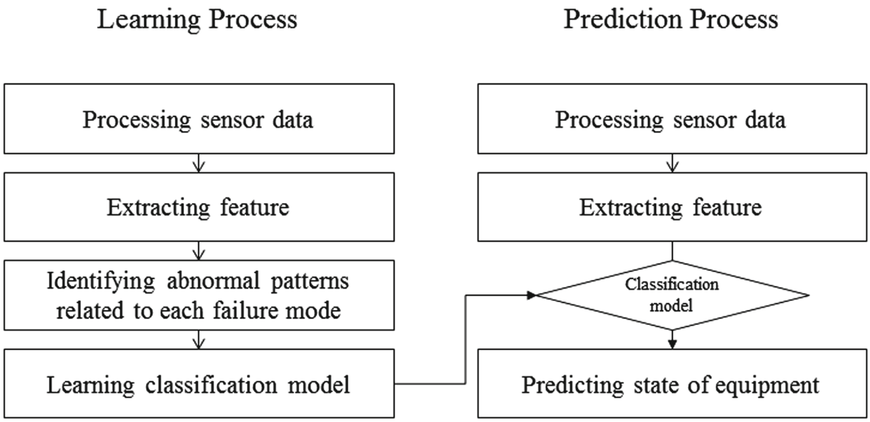


**Fig. 1.** Overview of the proposed approach

Before assuming a concrete explanation of the method, the assumptions of this study are as follows. First, the state of the equipment consists of normal and fault types. Second, there must be at least two states of equipment. Third, there is at least one pattern in the state of each equipment.

The overall procedure for learning is as follows. The first step is to remove the missing values and perform the normalization process to refine the collected sensor data. In the second step we divide the data interval and extract the data summation value of gathered sensor data in each interval to construct the feature vector. In this study, the feature is defined as a data summation value (e.g., average, standard deviation, maximum value, minimum value) in a specific interval, and a feature vector is defined as a set of data summation values in a specific interval.

In the third step, we find the patterns associated with failure types. The pattern means the clustered feature vectors and the abnormal pattern means the pattern related to a certain failure type. The normal pattern means the other patterns except the abnormal patterns. To find the patterns among feature vectors, the $k$-means clustering method is applied. Then, to identify the pattern associated with the failure type, the PF-IFF (Pattern Frequency – Inverse Failure mode Frequency) value based on the TF-IDF technique between the pattern and the equipment failure type is calculated with the following formulae.

$$PF(p, f) = 0.5 + \frac{0.5 \times f(p, f)}{max\{f(c, f) : c \in f\}} \tag{1}$$

$$IFF(p, f) = log(1 + \frac{|F|}{|(f \in F : p \in f)|}) \tag{2}$$

$$PF\_IFF(p, f, F) = PF(p, f) \times IFF(p, F) \tag{3}$$

Here $PF$ denotes the degree of occurrence of a particular pattern $p$ in a particular failure mode $f$, and $IFF$ denotes the degree of occurrence of a particular pattern $p$ in the failure mode set $F$ in common. Thus the $PF\_IFF$ value is a score indicating how important a pattern is in a particular failure mode when there are multiple failure modes.

Next, the patterns with a high $PF\_IFF$ value in a particular failure type are determined as the failure patterns associated with that failure type. In the final step, the relationships between the $PF\_IFF$ values of the patterns from feature vectors and their matching failure types are studied using the SVM technique. After the learning model is built, the state of the equipment is diagnosed by inputting a feature vector composed of data newly gathered into the classification model learned in the learning process.

## 4 Case Study

In this study, a case study was conducted based on the data collected from centrifugal pump of a Korean company to verify the effectiveness of the proposed method. The centrifugal pump is an energy conversion device that transfers mechanical energy to the working fluid. The data to be covered in the case study are the centrifugal pump state data collected from June 2013 to July 2015 at intervals of 10 min, and the data attributes include the vibration, temperature, speed, and axial movement of each of 15 pump positions. The types of failures to be considered in this study are 'leakage', 'misalignment', and 'bearing damage'. In this study, the data analytics language $R$ was used to implement the proposed method.

The case study was conducted by dividing the training data and the experimental data at a ratio of 4:1. The classification model that can diagnose the state of the equipment with learning data has been built. Based on it, we evaluated the performance of the classification model by predicting the state of equipment with experimental data.

The performance criterion for the proposed method was set as AUC (Area Under the Curve) in the ROC (Receiver Operating Characteristic) Curve. The closer the AUC is to 1, the better the performance.

**Table 1.** Preliminary test result

| Method | Normal | Bearing damage | Leakage | Misaligment |
|---|---|---|---|---|
| PF_IFF used | 0.957 | 0.977 | 0.930 | 0.765 |
| PF_IFF not used | 0.722 | 0.593 | 0.739 | 0.689 |

Table 1 compares the AUC values of two kinds of models: One is our approach that uses $PF\_IFF$. The other is the method that does not use $PF\_IFF$. Preliminary experimental results showed that the diagnostic performance of each condition of the equipment is 0.957 for Normal, 0.977 for Bearing Damage, 0.930 for Leakage and 0.765 for Misalignment. Thus, the $PF\_IFF$ method proposed in this study showed the better performance in all cases in diagnosing the equipment condition than the unused method.

## 5 Conclusion

In this study, we have briefly introduced a method for diagnosing failure types based on data collected from sensors in plant equipment. The $PF\_IFF$ technique using TF-IDF used in keyword extraction of the text mining and the information retrieval field was used to extract anomalous patterns for each type of equipment and SVM was used to diagnose the failure pattern. The TF-IDF value is a value indicating how important a word is in a specific document. The case study was conducted based on the data about vibration, temperature, and axial movement collected from the centrifugal pump. AUC was used as a performance evaluation criterion of the model, and the performance of the diagnosis model of the equipment using the proposed $PF\_IFF$ was evaluated. Preliminary test results showed that the diagnostics performance of the equipment with our approach is reasonable.

There are two limitations of this study. First, although the proposed method predicts what kind of failure will occur when an anomaly pattern is found in the equipment, but it cannot estimate when the actual failure will occur. The second is that certain patterns that appear could be diagnosed unexpectedly as normal if they occur in all types of failures in the equipment, despite the fact that there is an abnormality in the condition of the equipment in a particular section. These must be future research issues.

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# Detailed Performance Diagnosis Based on Production Timestamps: A Case Study

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**Abstract.** This paper demonstrates a detailed performance diagnosis of a production process. With limited investment power for new technologies, managers want to diagnose the reason for system underperformance, i.e. diagnosing performance gaps. This paper found detailed performance measures for specific production orders by using event log data, i.e. a set of timestamps that denote the occurrence of an atomic event in production. Sequential time registrations for each production order give detailed insights in how the production process is behaving. The reported case study gave managers a web application that lets them zoom in and out of different characteristics to get an understanding how their production process results in a certain performance. Based on the background and case, a framework and way forward are proposed on how to perform detailed diagnosis to explain performance gaps in production.

**Keywords:** Data-driven production management · Event logs · Problem diagnosis · Performance measurement

## 1 Introduction

While computing power and data science are developing at high speeds, production companies often rely on self-constructed spreadsheet solutions for data-driven decision taking for planning and control [1]. This is not wrong and has been proven useful over the last 20 years to measure along the performance of resources, output and flexibility [2].

Companies rely on less advanced data sources as they are not matured into digital factories. Using sensors and buying expensive systems to support them is neither feasible nor the core business of most companies. This does not mean that there is nothing to be won from the data stored in existing systems; with little capital investment data analysis tools are available to give performance insights along the production process, at a more detailed level than established single number key-performance indicators (KPI) used in traditional production control methods. This enables the possibility to diagnose problems occurring in production at a more detailed level.

In this paper we present a web application for detailed performance diagnosis in production based on event logs, i.e. a set of timestamps that denote the occurrence of atomic events. The background describes the current challenges with translating performance measurements into relevant diagnoses first. Second, a background on the use of event logs is sketched, coming from the domain of process mining. Then we


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describe a method and case where event logs were used for diagnosis, discuss the results and a framework for data-driven performance diagnosis, before concluding the paper.

## 2 Background

### 2.1 From Performance Measure to Diagnosis

Performance measurement systems (PMS) in production measure along the lines of resources (cost containment and efficiency), output (customer service) and flexibility (ability to respond to a changing environment) [2]. Having a performance measure, however, does not ensure that corrective action will result in the desired outcome. It is therefore unclear whether users of PMS outperform those that do not [3]. So while it seems imperative that “if you don’t measure progress toward an objective, you cannot manage and improve it” [4], organizations can perform with or without measuring it, as long as they learn how to perform [5]. Learning how to perform or how to solve problems, however, requires diagnosis.

Wagner [6] frames diagnosis as “the analysis of a present condition or present state of the system” [6], differentiating between causal diagnosis in which one tries to determine a cause to an issue, and situation understanding, in which no deviations from a desired state are researched. A single aggregated performance measure does not give a causal analysis or a situational understanding and more information would be required to explain why performance is as it is.

There is a large theoretical and practical domain for diagnosis or problem analysis, e.g. root-cause analysis, fishbone diagrams, and 5-whys. Wagner [6] summarizes how diagnosis should be undertaken:

1. Have an indication that there is a performance gap, i.e. the performance is different from the desired situation.
2. Description of the system under investigation.
3. Listing potential causes.
4. Planning the search, i.e. how to identify problem sources.
5. Analysis and model building; identifying what is wrong by eliminating all the causes and explanations that are not supported by evidence.

This leads to today’s challenges in translating a performance measure to a diagnosis. Many manufacturers want to achieve a combination of on-time performance, low work-in-progress (WIP) and related low throughput times, low inventory, and high output [2]. The basis for improving these performance measures could start with the theory-of-constraints approach [7] or a lean approach. To see the development of these performance measures over time, one could use the throughput diagrams from load-oriented manufacturing control [8]. To be able to diagnose a performance gap, however, the buildup of a KPI must be understood. Unlike other theories, this paper considers the possibilities of modern data-analytics to analyze multiple factors that influence the KPI, arguing against aggregated KPIs.

### 2.2 The Use of Event Logs and Data-Driven Diagnosis

When production data is collected, it often comes with a timestamp, i.e. a time and date associated with an atomic event that indicates an activity or action has occurred. Moreover, it is often possible to attribute events to an instance of a certain process, e.g., the handling of a specific Production Order (PO). One data-driven method to apply on such timestamped data that can be grouped according to process instances, which are also denoted as event logs, is process mining. Based on event logs, process mining method can discover a model of how processes are actually executed [9]. Such discovered models are then used to analyze deviations from the planned process both to investigate compliance (quality, regulations) and performance (bottlenecks, re-work) related questions [10].

In a production context, some applications of process mining have been reported. For example, in [11] workload in a production process is analyzed using process mining methods, in [12] production shutdowns are analyzed, and in [13] process mining is used to predict the cost of a manufacturing process. In addition to process mining, there is a large domain of other data analysis methods reaching from data-collection technologies, data processing and various methods for data visualization.

## 3 Methodology and Case Description

This paper builds a new method for diagnosing the performance of production. The method is built from a pragmatic perspective using a real-life dataset and existing theory as described in the background, advancing the use of data analytics for performance diagnosis, but at the same time considering the limitations of a real case.

The case company is a metal parts producer in the Netherlands. Production orders (POs) are prepared to customer specification. A PO leads to the production of a batch of the same part. The factory floor is organized in machining centers for each operation. Each machining center has multiple machines with different specifications, e.g. the bending center has multiple machines with different capabilities.

Capacity is calculated by the maximum revenue the factory can generate. POs are scheduled backwards from the order due date with five days buffer, one day per planned operation and seven days for preparing the order for production. This gives a two-week lead-time for a PO that needs to be processed in two machine centers.

The cutting operation is the first operation performed on each PO and is controlled for by optimizing the nesting of sheet metal. The other operations are organized based on earliest due date, machine availability and machine changeover time. This process is controlled by the supervisors of the different machining centers and is not formalized.

The case company has one enterprise resource planning system (ERP). For each PO, the system registers start and end times for all its operations which results in an event log. In addition, each logged event contains information on the end-customer, planned production dates, and the kind of operation performed. The registration of start and end times is a manual process by scanning the order slip barcode. For each PO production operation, a machine is assigned. This assigned machine satisfies the minimal capabilities to perform the required operation. During execution, POs can be operated on a machine with a better specification, but this is not registered in the ERP system. Wrong time registration and variations in machine use can skew the data.

Using the start and stop timestamps of all the operations of the POs, a detailed record of all POs flowing through the factory can be constructed from the moment an order is finished at first machining center until finishing its last operation, i.e. each PO is a process instance of possible processes in the factory.

The data analysis was performed with the R statistical software package. This resulted in a web-application that builds up performance measures and graphs from the available event log. Table 1 summarizes the different performance measures that can be calculated, and the possibility to select specific PO timestamps in the event log based on selection criteria by filtering the data. Figure 1 demonstrates how for all selected POs throughput time and waiting time between cutting and other operations is visualized in a graph, such that variation and outliers become immediately apparent.

**Table 1.** Performance measures per focus area, based on selection possibilities

| Performance measures | Selection possibilities for these performance measures by filtering data |
|---|---|
| **Total process:**<br>Average throughput time (days)<br>Standard deviation throughput-time (days)<br>Average value added (hours)<br>Average waiting days for outbound transport<br>Average days late<br>On time percentage<br># of POs delivered early<br># of POs delivered late | Selection of specific POs<br># of operations performed<br>Specific customer<br>On time delivery (yes/no)<br>Min/max throughput time<br>Order type (customer and stock orders)<br>Time range (all orders started within a time range) |
| **Between cutting and other machine centers:**<br># of POs waiting for next operation<br>Average waiting time until next operation<br>Standard deviation in waiting time until next operation | Selection of specific POs<br>Machining center following after cutting |
| **WIP:**<br># of POs in production over time | – |

For example, one can select the time range 1 January 2017–21 February 2017, for a specific customer and for POs that had between 3 to 6 operations. For this selection of POs in the event log, all performance measures and graphs are calculated instantly.

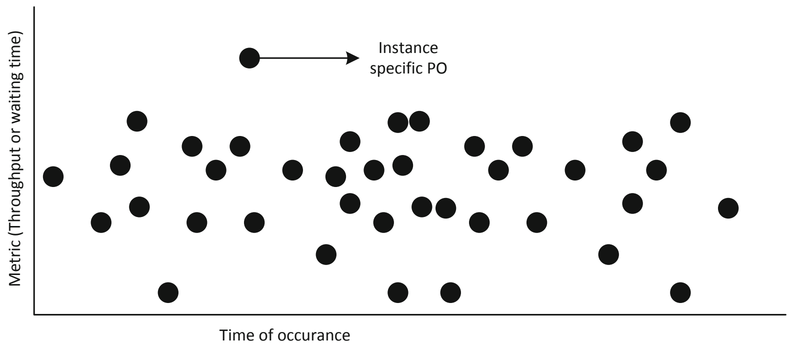


**Fig. 1.** Visualizing the individual POs to show variation and outliers for the filtered data

# 4 Diagnosis Results

Based on perceived performance gaps, diagnoses were performed by using the web-application. Before addressing the perceived performance gaps, trends over the last two years are discussed. From the first half year in 2017 to the last year in 2018, the throughput time on average increased by 1.5 days and the delivery performance dropped by 20% points. At every moment in time between 50 and 225 POs were on the shop floor as there is no limit on the amount of orders that can be released into production.

For each perceived performance gap, the performed diagnosis is described:

1. A general perception of no flow in the factory, POs queuing at various points, especially after the first operation for each PO, metal cutting.

Using the web application, it was tested whether orders had a throughput-time equal to the planned throughput time. The planned throughput times were exceeded significantly mainly due to an average waiting time of over 3 days with a standard deviation of more than 6 days between cutting and the subsequent machining operation.

This indicates that there is no connection between the planning of the first operation and the subsequent operations, overloading some machining centers after cutting the metal.

2. The different machining centers focus on optimizing the utilization of their bottleneck machines and less on delivery dates, leading to bad delivery performance.

The analysis found a great spread in delivery performance and throughput times. This leads to potential explanations: Many POs run on bottleneck machines, while other POs flow through without delaying queues. A second explanation is that optimizing the usage of machining leads to unnecessary delays for certain POs.

3. Perceived low delivery performance.

This could be confirmed and visualized by plotting the earliness or lateness of each order in a two-year period, seeing the variation in delivery performance, also seeing that many orders were delivered early. In addition, some customers were favored over others, having a much higher delivery performance (difference of 20% points to the average), while this is not official policy. Orders that were delivered on time, on average took 2.9 days less to produce than orders that were not on time.

The diagnosis confirmed several challenges:

- The planned days to perform an operation are underestimated and throughput times have increased significantly in the last two years. The planning method based on revenue capacity does not account for bottleneck operations. As the number of orders keep on growing, this will become more visible.
- The order release for the first operation is not linked to the availability of machines in subsequent operations, leading to long and variable waiting times after cutting.
- There are most likely bottleneck machines that are not planned for.
- Delivery performance has drastically decreased in the time-period of the provided dataset.

## 5 Discussion

The diagnosis in the last section lead to potential explanations of several performance gaps under investigation. It also gives the possibility to formulate hypotheses and start testing improvements in practice, as it gave a detailed image of a production environment up to the machine center level. In this also lies a risk: The data does not contain all information and other methods might be necessary to diagnose the performance gap. For the case described in the last paragraph, this applies for bottleneck machines and a recommendation would be to start registering timestamps for the use of specific machines instead of machining centers.

Figure 2 illustrates a framework that integrates decision-making from production control with data available from past performance. From production, timestamp data is recorded that is used to calculate performance measures. For each performance measure a threshold must be set, such that a performance gap can be detected. Once a performance gap is detected, the diagnosis process starts. The case in this paper used performance measure calculations based on timestamp data. The diagnosis should lead to potential causes to explain the performance gap. The case study did not go further than this activity.

Based on the potential causes, hypotheses can be formulated to describe the effect between the potential cause and the performance gap. Testing the hypothesis with the available data can be a difficult exercise. Instead we propose to introduce improvements that reduce the effect of the potential cause on the performance and monitor the effect of the outcome.

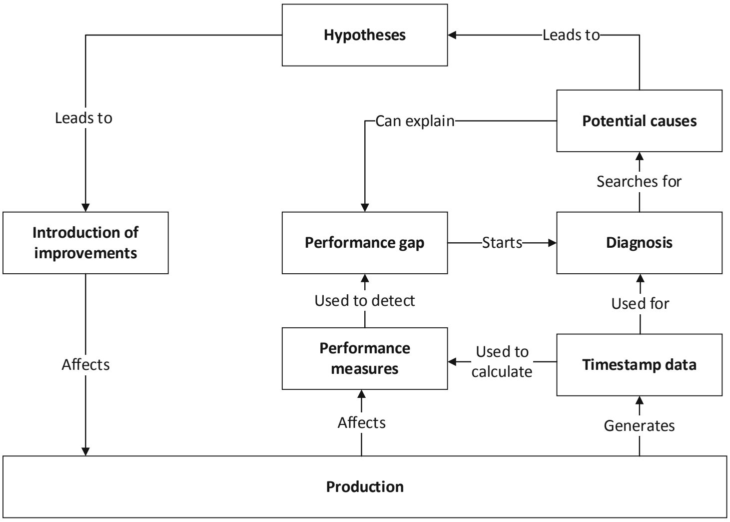


**Fig. 2.** Framework for detailed performance diagnosis using an event log

## 6 Conclusion and Future Work

In this paper, we discussed a realistic way forward for detailed performance diagnosis using an event log. For our case we demonstrated that traditional performance measures for production management can be specified for a specific case selection, depending on the quality and granularity of events recorded in an event log.

The use of timestamped data for each process instance lead to a process perspective where we could calculate performance measures for a specific dataset that complies with certain conditions. We related this method to problem diagnosis to come up with a method for detailed performance diagnosis in production.

Compared to traditional methods, the filtering of an available event log on characteristics such as time-period, number of operations performed, customer and delivery performance, gives managers a method to quickly identify causes for certain performance gaps.

This research can be extended in multiple ways:

1. An integration of process mining techniques and performance measurement to facilitate better performance gap diagnosis within production. This specifically holds for visualizing production processes in process models and enriching them with performance measures.
2. Using atomic event production data in existing methods for visualizing workload control (see [8]).
3. The use of different types of data in production and data-analysis techniques to facilitate the diagnosis of performance gaps.
4. The use of new technologies to facilitate better data and easier, faster or more thorough diagnosis. One way to overcome data quality issues is automatic data

registration, e.g., based on activity recognition using sensorised environments and wearables in a smart manufacturing environment.

Even though factories are not fully digitalized, valuable information can often be extracted from existing systems to diagnose the performance gaps that factories are experiencing. General available software can be used to gain new insights, avoiding a technology push to facilitate the hype around IoT, machine learning and artificial intelligence. Data-driven production management should not be a solution, but an increasing powerful set of tools to facilitate diagnosis and problem solving. Connecting these toolsets to performance measurement within supply chains and general problem-solving techniques is as equally important as further developing technologies under the digitalization or Industry 4.0 paradigms.

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# Modeling the Maintenance Time Considering the Experience of the Technicians

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**Abstract.** Typically, maintaining a machine requires two different distinct tasks: to select which components to focus their attention; and the subsequent task is to check, repair or replace the selected components. For both tasks, the experience of technicians plays a critical role. An experienced technician is likely to select fewer components and requires less time for the subsequent task compared to an inexperienced technician. As a result, the maintenance time will be varied depending on the experience of the technicians. Extant research for maintenance has predominantly used exponential distribution family for modeling primarily because of its analytical tractability but at the cost of fidelity and inability to capture important characteristics such as technicians' experience. With the growing adoption of networked sensors based on Internet of Things (IoT), big data, and real-time machinery diagnostics using artificial intelligence it is imperative to develop models with better fidelity for maintenance operations. Therefore, in this paper, we explore a model based on using the negative-hyper geometric distribution for maintenance time that varies based on the technicians' experience. Our proposed approach requires more inputs such as (1) number of components, (2) number of components not in working state (3) technician's experience level, and (4) time to fix a component based on the technicians' experience. For instance, input for (2) could be obtained from IoT sensors and diagnostics. We study the efficacy of the proposed model using computer simulations and statistically characterize the possible impact of technician experience on the parameters of the maintenance distribution.

**Keywords:** Maintenance · Maintenance time · Negative hypergeometric distribution · Technicians' experience

## 1 Introduction

Maintenance time consists of several steps: localize, isolate, adjust, disassemble, repair, interchange, reassemble, align, and checkout (return to normal condition) [1]. In many situations, especially for corrective maintenance, the process is composed of two different distinct tasks: to select which components to focus their attention; and the subsequent task is to check, repair or replace the selected components. For example, if technician removes the cover and finds out the selected component is in good condition, then he/she has to put the cover back and repeat the previous tasks until he/she successfully identify the problem. This process, which is similar to the trial-and-error


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process, contributes a large amount of time to the maintenance time and highly depends on technician experiences on fault localization (selecting which components to play).

How does experience impact the performance of maintenance? There are many different opinions in the literature. Cabahug et al. (2004) survey 105 respondents, including managers, training instructors, and directors in 2000. They consider 14 technician personal factors to examine technicians' proficiency. Their result shows up years of experience with equipment has a high correlation with technician proficiency [2]. Edwards et al. (2005) extend the research to 50 factors. They find that ten factors are significant for predicting maintenance proficiency including duration of training period and years of experience [3]. This study implies that experience is one of the instrumental factors in measuring technician proficiency. In Jørgensen and Sjøberg (2003), however, they claim that the experience has little impact on predicting problems in software maintenance. However, when they define technicians' experience, Jørgensen and Sjøberg only consider the number of years in general maintenance job but did not consider the time spent in maintaining the software [4].

With the growing adoption of networked sensors based on IoT, big data, and real-time machinery diagnostics using artificial intelligence, maintenance will be done more smartly even if a technician is inexperienced.

However, extant research for maintenance has perpetually lump-summed maintenance time and predominantly used the exponential distribution family such as exponential, gamma, phase-type and generalized-exponential distributions for modeling [1, 5–7]. It is primarily because of its analytical tractability. At the cost of fidelity, these models are, nevertheless, limited in ability to capture essential characteristics of maintenance such as technicians' experience. Based on our knowledge, no research had considered the experience of a technician when it modeled maintenance times. Hence it is inevitable to develop models with better fidelity for maintenance operations. Therefore, in this paper, we explore a model based on using the negative-hyper geometric distribution for maintenance time that varies based on the technicians' experience on the selecting task.

The rest of this paper is organized as follows. In Sect. 2, we propose to model maintenance times using the Negative-Hyper Geometric distribution, which has the following inputs: (1) number of components, (2) number of components not in working state and (3) time to repair/replace a component. In Sect. 3, we characterize the statistical properties of our model using computer simulation. Section 4 brings up our conclusions and possible works in the future.

## 2 Modeling Maintenance Time

Typically, maintaining a machine requires two different distinct tasks: (1) the first task is to select which components to focus their attention; and (2) the subsequent task is to check, repair or replace the selected components. The tasks repeat until the technician find all components that need to be repaired. In the model, we assume there are $N$ possible components which might cause a machine failure. The machine goes back to the working condition once all failed components are found and repaired. The time for the second type of task is varied by different failure types and components, so we model the time as a random variable $T_i$ (sub-task time), which is generally distributed, to describe the variation. In addition, we assume the operation time of the first type of task is negligible. Thus, the maintenance time $(MT)$, which consists of these two tasks, can be shown in Eq. (1)

$$\mathrm{MT} = \sum_{i=1}^{X} T_i \tag{1}$$

Given that

$T_i$ = time to check, repair and replace task $i$, is i.i.d. to $T_1$
$X$ = number of selected components to focus technicians' attention

## 2.1 Modeling Component Selection Using NHG Distribution

Practically, selecting which components to focus attention is a similar process to the 'trial-and-error' process. The technician selects a component then check whether it requires replacement or repair. A technician takes necessary actions and then checks the next components until every component is in working state. This process also can be explained as drawing all 'fail' from a finite population without replacement in which each sample can be classified into two mutually exclusive categories: pass/fail. Therefore we formulated the number of selections, $X$, using the Negative Hyper-Geometric distribution, $X \sim NHG(N, M, k)$ [8]. In this model, we assume that all components must be in working state to properly maintain a machine. Otherwise, technicians continue to select more components, thus $k = M$. So, the distribution of $X$,

$$\Pr(X = x) = \frac{\binom{x-1}{k-1}\binom{N-x}{M-k}}{\binom{N}{M}} = \frac{\binom{x-1}{M-1}}{\binom{N}{M}} \tag{2}$$

Where we define,

$k$ is the number of components that need to be selected;
$M$ is the number of components which are not in working order;
$N$ is the number of all possible components which are not in working state and $M \leq N$.

## 2.2 Modeling Experience Impact on Maintenance Time

Two different experience effects can be defined in the model: (1) a more experienced technician requires a smaller number of selections in order to maintain the machine properly compared to an inexperienced technician; (2) a more experienced technician needs less time to finish each task in a maintenance process. In this paper, we discuss the first experience impact. We believe that this is because technicians can exclude some components in the first place based on their experience. Thus, in order to formulate this effect, we defined $N$ as $N^*$ which is

$$N^* = N - EE_N \tag{3}$$

Where

$N^*$: number of possible components in technician's opinion
$EE_N$: experience effect of $N$, $0 \leq EE_N \leq N - M$

$EE_N$ can be expressed in constants or functions such as learning curves. However, it should be noted that the experience effect cannot be greater than $N - M$ since at least $M$ components should be checked even the technician is very talented and can find all failed components without any wrong selection.

# 3 Model Inputs Analysis Using Computer Simulation

In this section, we analyze the sensitivity of the model's two inputs: $EE_N$ and $M$ to its variation by conducting a computational simulation. The simulation setting is:

- Set $N = 20$ components and randomly assign $M$ failed components;
- Technician randomly identifies some components which they think it should be checked. All failed components must be identified.
- With experience effects $EE_N$, experienced technicians identify less components than inexperienced technicians
- A technician starts checking the components based on the order in step 2. The subtask time is constant and $T_1 = 10$.
- Maintenance time is collected after the technician repaired the last failed component
- 5000 maintenance times are collected (simulation iterations = 5000).

## 3.1 Input Analysis of $EE_N$

$EE_N$ plays a critical role in this modeling. Although directly measuring $EE_N$ is very challenging, one could estimate $EE_N$ by reviewing a maintenance log. For example, one can obtain two information from the maintenance log: (1) the number of all possible components that need to be checked based on the failure mode, and (2) the number of all components that were checked by a technician. With this two information, we can fit the distribution to find out the $N^*$. Then we can estimate the $EE_N$ for the technician. However, even one can estimate the $EE_N$ from the log, it is hard to estimate it accurately. Therefore, we simulated the model by only changing the variance of $EE_N$ to see how the variance of $EE_N$ affect the expected maintenance time. In this simulation, $M$ is set to be one. In addition, experience effects are followed by uniform distributions with three different intervals $EE_N \pm 1$, $EE_N \pm 2$, $EE_N \pm 3$.

Figure 1 reveals us that the expected maintenance time is not biased by the variance of $EE_N$. In addition, the squared coefficient of variation (SCV) of maintenance time is increased as the variance of $EE_N$ is increased. Therefore, if we want to consider the second or higher moment of $MT$, $EE_N$ has to be carefully measured.

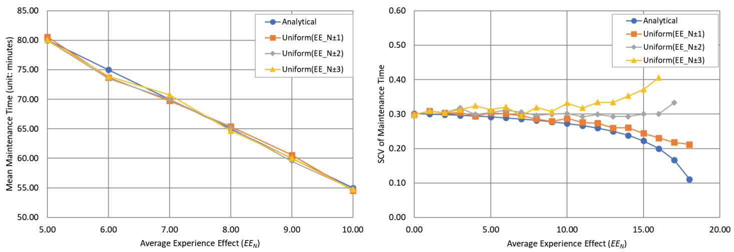


**Fig. 1.** Comparison of mean and SCV of maintenance time between analytical results and simulation results with uncertainty experience level

## 3.2 Input Analysis of *M*

One common challenge of analyzing maintenance log is that it is almost impossible to have enough data for acquiring information about one failure mode. Since a machine can have multiple failure modes and the frequency of each failure mode is so small, it takes a significant amount of time to collect the data. Therefore, it would be good if a model can estimate the expected maintenance time of a machine regardless of failure modes. In order to estimate the expected maintenance time of a machine, the number of components that are not in working state is treated as a random number followed by uniform distributions with three different intervals $M \pm 1$, $M \pm 2$, $M \pm 3$. In this simulation, we set $EE_N = 0$ and simulate model by changing $M$.

The results show in Fig. 2, we conclude that collecting data from different failure mode and using the average $M$ as the input of the model to calculate the mean and SCV of maintenance times is robust. Even the variation still impacts the values, the trend of the results is similar.

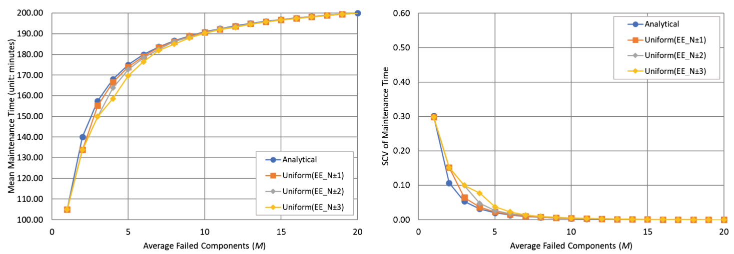


**Fig. 2.** Comparison of mean and SCV of maintenance time between analytical results and simulation results with multiple failure modes ($M$ is uncertain)

# 4 Conclusion and Future Research

In this paper, we explore a model using the Negative Hyper-Geometric distribution for maintenance time that varies based on the technicians' experience. Our proposed approach requires inputs such as (1) number of components, (2) number of components not in working state (3) technician's experience level, and (4) time to fix a component. The reason to develop this model is to explore the impact of technicians' experience on maintenance times which will be primarily affected in the future due to the growth of usage of big data, machine learning, and A.I.

From the simulation results, we discover that the estimated expected maintenance time is robust to the variation of $EE_N$. The maintenance time doesn't get biased even when the uncertainty of $EE_N$ is increased. Therefore, we believe that estimating $EE_N$ from maintenance logs is one of the methods that can be used to estimate $EE_N$. In addition, we simulated that whether the model is robust to the variation of $M$. The simulation result reveals that the mean and SCV of maintenance time is robust when there is variation in $M$. Therefore, the model we proposed can be used to estimate the expect maintenance time of a machine in general. In sum, modeling maintenance time with Negative Hyper-Geometric distribution require more inputs than traditional modeling methods. However, this modeling method allows us to capture the technicians' experience effect and gives the power to analyze the average maintenance time.

In future work, we will validate the model with human experiment results. In addition, the model will be developed to assess the impact of IoTs and A.I. on maintenance decisions. Even though Negative Hypergeometric well describes the process of selecting components, the distribution is not well-known and not many analytical properties existed. Thus, we will try to develop approximation method for the model to increase its analytical tractability.

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# A Thesaurus-Guided Method for Smart Manufacturing Diagnostics

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**Abstract.** The unstructured historical data available in the databases of Computerized Maintenance Management Systems represents a wealth of diagnostic knowledge. In this paper, a methodology for converting the maintenance log data into formal knowledge graphs is presented. The methodology uses text analytics techniques, in combination with human-assisted thesaurus development methods, for generating a formal thesaurus, or knowledge graph, that encodes the semantic relationships between multiple maintenance entities. The knowledge graph proposed in this work uses Simple Knowledge Organization System (SKOS) standard. A java-based tool is developed that uses the generated knowledge graph as the input and conducts light-weight reasoning to support smart maintenance diagnosis.

**Keywords:** Smart maintenance · Knowledge graph · Thesaurus · Natural Language Processing

## 1 Introduction

Manufacturing companies often strive to adopt advanced maintenance and control tools and methods to minimize their machine downtime and maximize the availability of their critical assets. In particular, Computerized Maintenance Management Systems (CMMS) are widely used in most industries to manage, plan, and organize preventive and planned maintenance activities [1]. The records of maintenance work orders and activities are often stored in the partially structured database of CMMS packages for archiving, reporting or analysis purposes [2]. The data in CMMS databases can be potentially used as a source of diagnosis knowledge. However, the maintenance log data is often under-used [3]. Enormous collections of historical maintenance logs, representing a wealth of diagnostic knowledge, can be found in most industries. As the number of reports related to maintenance issues in the CMMS databases grows, manual search and analysis of the reports becomes more cumbersome and less efficient. Without proper tools and techniques for analyzing, mining, and contextualizing that knowledge, the usefulness of these maintenance logs is severely limited. The underlying research challenge that motivates this work is to generate more structured and formal knowledge models, based on the unstructured and informal data available in the maintenance logs that can support smart and automated diagnosis process.

Advanced techniques supported by Natural Language Processing (NLP) and Machine Learning (ML) can be applied to extract useful patterns and rules from the raw


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text that are otherwise hidden in the historical maintenance work order data. However, most often the intervention of human expert is needed for validating the generated models and taxonomies. In general, full automation of taxonomy and ontology creation process is not a feasible approach to follow based on the current state of Artificial Intelligence technology.

The objective of this work is to introduce a hybrid methodology for generating more structured knowledge models from the unstructured maintenance log data. The methodology uses text analytics techniques, in combination with a human-assisted thesaurus development method, for the purpose of generating a formal thesaurus (i.e., knowledge graph). The resulting knowledge graph is intended to encode the semantic and lexical relationships between various entities in the maintenance domain. The proposed methodology uses Simple Knowledge Organization system (SKOS) formalism for thesaurus modeling and representation [4].

A Java-based tool is developed that uses the generated SKOS thesaurus as the input and conducts root cause analysis and diagnosis based on the observed symptoms in a given maintenance artifact (i.e., part or equipment).

## 2 Related Works

The body of work related to analyzing the historical maintenance data is rather sparse. Winker [1] developed a rule-based approach for cleaning the historical work order data available in CMMC databases. The objective was to improve the quality of the data in order to ensure that the data is fit and reliable for further analysis. Sharp et al. [5] used multiple Machine Learning and Natural Language Processing techniques, including unsupervised classification method based on Support Vector Machine (SVM), for automated clustering and tagging of maintenance data. Tagging maintenance logs with appropriate label results in creation of more structured and clean data and reduces the ambiguity in the data. The generated tags can also be used as controlled vocabulary. These works address the necessary steps for pre-processing the data and giving it more structure and semantics. However, the final product cannot be regarded as a formal knowledge graph that can support smart maintenance diagnosis.

## 3 Maintenance Diagnosis Thesaurus

As mentioned before, the *Maintenance Diagnosis (MD) Thesaurus* that is developed in this work is based on Simple Knowledge Organization System. The MD thesaurus provides a formal vocabulary of maintenance terms and at the same time serves as a knowledge graph. In this section, a brief introduction to SKOS is provided and the motivations for using SKOS as the thesaurus representation formalism are discussed. Also, the definitions for some of the key concepts of the thesaurus are provided.

### 3.1 Simple Knowledge Organization System (SKOS)

SKOS is a standard data model, published by, World Wide Web Consortium (W3C), that provides a structured framework for creating different types of controlled vocabulary such as thesauri, concept schemes, and taxonomies to be consumed on the web. A SKOS concept is any unit of thought such as an idea, an object, or an event.

Each concept in SKOS has exactly one *preferred label* (skos:prefLabel) and can have multiple *alternative labels* (skos:altLabel). For example, *Rusting* is the alternative label for *Oxidation* as it is used frequently for referring to the same concept. The broader concept of the *Oxidation* is *Chemical Reaction*, while *Homolytic Oxidation* and *Heterolytic Oxidation* are the narrower concepts; meaning that they are more specialized forms of *Oxidation*. The concepts that are *related* to Oxidation include Galvanization, Coating, and Rust.

The concepts are made *related* to one another based on some type of semantic connection between them. For example, the reason *coating* is a related concept to *oxidation* is that coating is the method that is typically used for preventing oxidation. The exact type of relation, however, is not specified in the thesaurus. Each SKOS concept can also have a definition provided in plain English or any other natural language. One major advantage of the SKOS thesauri is that they can be extended, enriched, and validated incrementally by community crowds and shared as linked open data due to their open and standard syntax and semantics. A SKOS thesaurus forms the nucleus of a knowledge graph that can be continuously enriched to support various data-driven and knowledge-intensive application such as semantic search and reasoning, text mining, data integration and alignment, and data analytic.

### 3.2 Corpus

The maintenance data provided by three manufacturing companies was used to build the text corpus associated with the thesaurus. The data across three companies contain a total of approximately 10,0000 Work Orders (WO) collected over a 10-year period. The logs are often organized into tabular format and include contextual data, such as the Affected Equipment, Description of Problem, Resolution of Problem, Time/Date Work order was issued, Time/Date Work order was completed, and Maintenance Technician Assigned.

### 3.3 Structure of the MD Thesaurus

Developing a SKOS thesaurus typically starts with creating the top-level categories of terms and further populating the lower-level categories by the terms extracted from the corpus. Currently the MD thesaurus has three main *concept schemes* (collections), namely, Artifact, Maintenance Problem, and Maintenance Treatment as defined in this section. The first level concepts under each category are called *top concepts*. Figure 1 shows the partial view of the top concepts in the MD thesaurus.


**Fig. 1.** A partial view of the concept hierarchy in MD thesaurus

**Artifact** (Concept Scheme) Def. = A physical entity such as individual parts, subsystems, or equipment can be the bearer of a failure.

**Maintenance Problem - Failure** (Concept Scheme) Def. = Event in which any part of an equipment or machine does not perform according to its operational specifications or does not possess its desirable qualities.

**Functional Maintenance Problem** (Top Concept) Def. = a state in which an asset or system fails to perform a specific function to the desired level of performance.

For example, leaking, as shown in Fig. 2, is considered to be a functional problem as it is considered to be an undesirable behavior of a system.

**Non-Functional Maintenance Problem** (Top Concept) Def. = Non-Functional Maintenance Problem occurs when a production equipment (artifact) or one of its parts have one or more undesirable qualities or attributes.

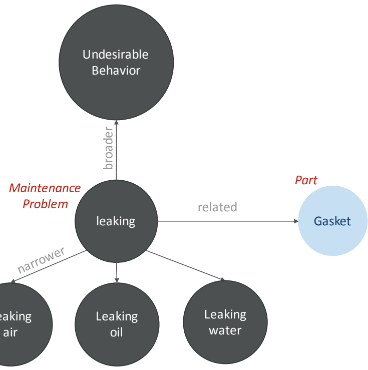


**Fig. 2.** Leaking as an example of a functional problem

**Maintenance Treatment** (Concept Scheme) Def. = A process in which the act is intended to modify or alter some other physical entity with the intention to resolve a maintenance problem. Different types of maintenance treatment include repair, adjustment, replacement, and rebuild.

The top concepts provide the necessary sub-categories under which more specific concepts, extracted from the corpus, can be classified.

### 3.4 ATP Sub-graph

The ATP sub-graph is a sub-graph of the SKOS graph that only contains the *skos: related* relationship between the concepts. The nodes in the ATP sub-graph are of types Artifacts, Problems, or Treatments. The ATP sub-graph describes how artifacts, problems, and treatments are related to each other (Fig. 3).

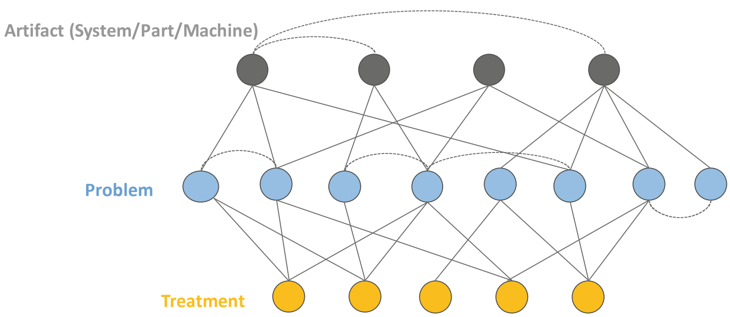


**Fig. 3.** The structure of the ATP sub-graph

### 3.5 Thesaurus Formation and Extension Process

A commercial tool, called PoolParty Taxonomy & Thesaurus Management system [6], was used for creating and extending the MD thesaurus. In PoolParty, each thesaurus can have a document corpus from which the terms can be extracted. In this work, each maintenance record is considered to be a document in the corpus. The MD corpus contained more than 10,000 documents at the time of preparation of this paper. There are two methods for extracting the terms form the corpus and converting them into thesaurus concepts. The first method is based on direct tagging of the relevant terms in the corpus documents. The tagged terms are later added to the collection of *Candidate Concepts*. A candidate concept is formally integrated with the thesaurus when its broader concept is specified by the thesaurus developer. For example, the phrase *broken gear* can be manually tagged in a document by the developer and then placed under *broken part*, as its broader concept. The second method is through automatically extracting a list of n-grams from the corpus and adding the relevant terms to the collection of candidate concepts. In this work, the first method was used.

### 3.6 Thesaurus Validation

The usefulness of the MD thesaurus highly depends on its level of completeness and accuracy. To validate and verify the thesaurus with respect to completeness and accuracy, it was used for *tokenizing* the maintenance records outside the corpus. The tokenization process entails splitting the text into individual concepts from the thesaurus. A maintenance record is considered to be *adequately tagged* if at least one artifact, one maintenance problem, and one maintenance treatment can be identified in the record. Table 1 shows an example of a maintenance records with complete tags.

**Table 1.** A maintenance record tagged with sufficient tokens

| Concept schema | Top concept | Concept (preferred label) | Freq. |
|---|---|---|---|
| Artifact | Part | Coil | 1 |
| Artifact | Part | Indexing valve | 1 |
| Maintenance problem | Functional maintenance problem | Not indexing | 1 |
| Maintenance treatment | Treatment action | Replace | 1 |
| Artifact | Part | Valve | 1 |
| Problem description: Table will not index<br>Resolution: Table indexing valve coil found bad and replaced | | | |

## 4 Diagnosis Guided by ATP Sub-graph

The ATP sub-graph can be used for identifying the failures related to a given artifact such as a gear or a pump or a hydraulic system. For example, for artifact A shown in Fig. 4, the related problems are P1, P2, and P3. Since P1 is related to P2 and P2 is related to P3, a loose causality relationship can be inferred. Also, because the links connecting the vertices are bi-directional, it is not possible to determine which problem is the root cause and which problem is the observed effect. But as mentioned before, the goal is to provide a lightweight model with simple semantics to enable some basic reasoning and approximate root cause analysis. For more deterministic and complex reasoning, more expressive ontologies will be needed. If the user picks a specific problem as the probable root cause, then the ATP sub-graph can point to the potential treatments.

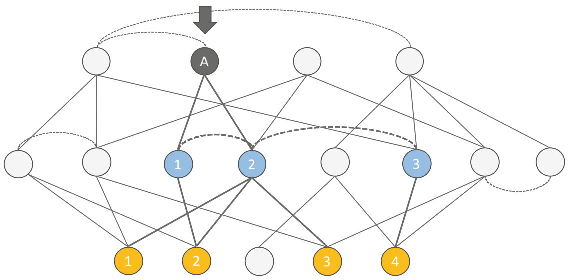


**Fig. 4.** The active portion of the ATP sub-graph when a specific artifact is selected.

## 5 Implementation

A Java-based tool, called *Smart Maintenance Diagnosis System (SMDS)* was developed based on the proposed methods. The SMDS tool uses the Apache Jena API for Java. The tool receives the thesaurus in RDF/JSON format as the input. There is a default thesaurus embedded in the tool. However, the user can always upload the most recent version of the thesaurus. Jena is used to parse the thesaurus and to create a map of systems, parts, symptoms, causes, treatments, and the relations between them. The map is then used to analyze and diagnose a selected system or part issue. In the first step, the user provides some contextual information regarding the diagnosis scenario. System type (e.g. landing gear) and part type (e.g. gear) comprise the contextual information in this implementation. Then the user selects the observed symptoms from the drop-down menu. The symptoms are filtered by the tool so that the user can only select from the symptoms (maintenance problems) related to the selected part.

After the symptoms (effects) are selected, then the tool provides the user with a list of potential causes. The potential causes are actually the maintenance problems that are related to the selected symptoms using *skos:related* relationship. Figure 5 shows the

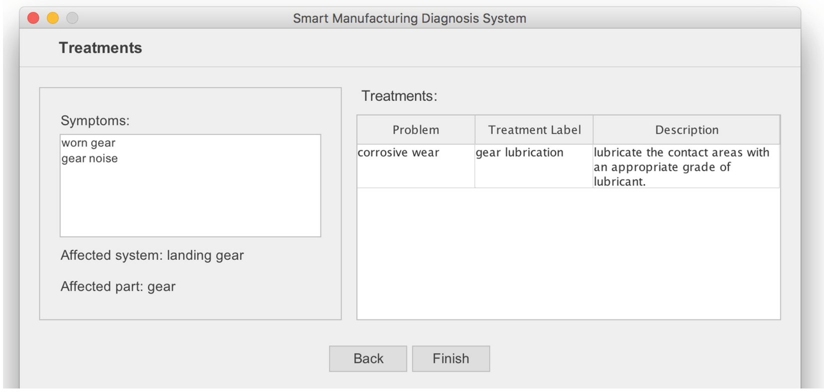


**Fig. 5.** SMDS tool screenshot (4): the tool suggests the treatments based on the selected root causes

screenshot of the final recommendations of the tool. In the provided example, *corrosive wear* is identified as the potential causes for the selected symptoms, namely, *worn gear* and *gear noise*.

As mentioned before, since ATP sub-graph is built based on the observations about the past failures, the resulting conclusions are always approximative based upon the evidence given. The textual description of the recommended treatments are extracted from *skos:definition* property of the concept.

## 6 Conclusion

In this paper, a thesaurus-guided maintenance diagnosis method is proposed. The thesaurus is linked to a text corpus extracted from the CMMS maintenances logs provided by three participating companies. A smart maintenance diagnosis tool was developed and tested based on the proposed method. The test results provided correct diagnosis based on the scope of the thesaurus. The proposed MD thesaurus uses SKOS standard. SKOS knowledge graph provides a solid basis for machine learning and cognitive computing efforts with an organization. SKOS is widely adopted and there exist hundreds of SKOS vocabularies on the web. Therefore, the proposed MD thesaurus can be linked and integrated with other vocabularies to enhance the semantic coverage of the knowledge graph.

One shortcoming of the proposed approach is that it ignores the type of the relations between two concepts and treats all relationships to be the same. This caveat can be countered by superimposing more expressive ontologies on top of the light-weight thesaurus to enable more advanced reasoning. However, developing and extending axiomatic and heavy-weight ontologies can be very costly and time-consuming. Light-weight SKOS thesaurus can be easily developed and extended to support a first-order reasoning process when diagnosing a maintenance problem. In the future, the ATP sub-graph will be augmented with probabilistic values to create Bayesian Networks.

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