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Product Lifecycle Management

Green and Blue Technologies to Support Smart and Sustainable Organizations

18th IFIP WG 5.1 International Conference, PLM 2021
Curitiba, Brazil, July 11–14, 2021
Revised Selected Papers, Part I

1 Part I

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Preface

The year 2021 was marked by the worsening of the COVID-19 crisis restricting our social lives and freedom of movement, especially in the city of Curitiba, Brazil, where the 18th edition of the IFIP International Conference on Product Lifecycle Management (PLM 2021) was held. The industry has continued to be hard hit, with companies closing down, reduction of working hours, and restriction of borders altering the world's traditional activities. On the other hand, this crisis has provoked conceptual changes in the search for innovative solutions, making society adapt to the new work model that has been mostly performed in a virtual way.

However, it was not by chance that this was possible. On the contrary, it was the result of continuous research and development during the last decade and, in part, of efforts to contribute to state-of-the-art research questions involving issues of green and blue technologies to support smart and sustainable organizations in the digital age. Since 2003, the IFIP WG 5.1 International Conference on Product Lifecycle Management (PLM) has brought together researchers, developers, and users of PLM. This event has always aimed to integrate business approaches to the creation, management, sustainability, and dissemination of product and process data in companies that create, manufacture, and operate engineered products and systems. In this context, approaches such as digital and virtual product development, digital twins, smart manufacturing, or artificial intelligence in a sustainability context were discussed and developed further. While these sustainability concepts seemed vague and visionary at first, the contributions from this year's edition clearly showed that these innovative concepts have maturity and are being addressed and implemented with relative success in industry. Virtual collaboration, agile and green supply chains, intelligent manufacturing, and interoperability of work are becoming of paramount importance for worldwide technological development. PLM systems based on cloud and web service technologies, oriented to the purposes of sustainable development and combined with Internet of Things (IoT) platforms, seem to be actors promoting smart or intelligent solutions for products, processes, and decisions.

PLM 2021 was organized by the Industrial and Systems Engineering Graduate Program of the Pontifical Catholic University of Paraná, Brazil. So, this edition was concerned with responses to environmental and energy crises involving and considering green and blue issues. The health crisis has been added to these issues, demonstrating the need to change industry practices at the heart of PLM's concerns.

Due to the continuing global impact of COVID-19, the conference was held for the second time in its history in a virtual edition (like the PLM 2020 conference in Rapperswil, Switzerland).

PLM 2021 was attended by 97 researchers from 22 nations across three special sessions (PLM Maturity, PLM Implementation and Adoption within Industry 4.0; Sustainability, Sustainable Development and Circular Economy; and Blockchain Integration with Enterprise Applications) and 22 parallel sessions with a total of 100 online presentations. PLM 2021 also included the following academic keynotes, industrial keynotes and open webinars:

i) Academic Keynotes

- Andreia Malucelli – Pontifical Catholic University of Paraná, Brazil;
- Luiz Marcio Spinosa – Fundação Araucária, Brazil;
- Robert Young – Loughborough University, UK;
- Rodrigo Lozano – University of Gävle, Sweden;
- Cecilia M. V. B. Almeida – Universidade Paulista and the Journal of Cleaner Production and Cleaner and Responsible Consumption, Brazil;
- Ubiratã Tortato – Pontifical Catholic University of Paraná, Brazil;
- Elias Hans Dener Ribeiro da Silva – University of Southern Denmark, Denmark;
- Marcelo Távora Mira – Pontifical Catholic University of Paraná, Brazil.

ii) Industrial Keynotes

- Domingo Ureña Raso – Mecanizados Y Montajes Aeronáuticos, Spain;
- Regis Ataides – Siemens Digital Twins, Brazil.

iii) Open Webinars

- David Berquelange – Renault, France;
- Renato Grottoli – Robert Bosch, Brazil;
- Alex Rogério Figueiredo – Volvo, Brazil.

The pre-conference program featured a virtual PhD workshop dedicated to young researchers. The main program was structured so that on each day of the conference we had at least one academic keynote, industrial keynote, and open industry webinar, freely accessible to all, followed by intense discussions with researchers and industry participants.

All submitted papers were reviewed in a blind review process by at least two reviewers (2.4 reviewers per paper, on average). In total, 133 full papers were submitted, of which 107 were accepted to be presented at the conference. The accepted papers are grouped into 25 thematic sections in this book, which is part of the IFIP Advances in Information and Communication Technology (AICT) series that publishes state-of-the-art results in the sciences and technologies of information and communication. In addition to this conference proceedings, the International Journal of Product Lifecycle Management (IJPLM) is the official journal of the IFIP WG 5.1. Selected papers from PLM 2021 might be published as extended versions in IJPLM.

We would like to thank everyone who directly or indirectly contributed to making the PLM 2021 conference a success, particularly under the difficult circumstances of the worsening COVID-19 pandemic.

November 2021

Osiris Canciglieri Junior
Frédéric Noël

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Impacts of the Sustainable Automotive Chain: Faced with the Perspective of Electromobility in Consolidated Markets in Germany, United States and Japan

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Abstract. Regardless of the global crisis due to the COVID-19 pandemic, the automotive industry is advancing through new and significant global renewals that arise at the heart of some directions of the automotive segment, especially with regard to electrification and vehicular hybridization, as an adaptive response to ongoing environmental issues. Automakers and automotive dealerships show concerns about these global megatrends that should impact the sector and are emphatic, especially regarding the rapid growth of solutions and business proposals that involve changing consumer behavior, especially regarding the sustainability aspect of the product, as well as the new concept of vehicle use, rather than the purchase of the good. The planet does not have the capacity to withstand current patterns of consumption and, consequently, production. Aligned with this need, the present work aims to analyze the impact of the sustainable automotive chain against the perspective of electromobility in the consolidated automotive markets in Germany, the United States and Japan. These countries have shown to lead research on electric and hybrid motors, where it is concluded that electromobility is fully inserted in the automotive industry of Germany and Japan, with a tendency to exclude fossil fuels in a very short time. In the United States there is a coexistence of technologies from internal combustion engines with electric and hybrid combustion, demonstrating that both technologies must coexist together and be improved over time, partially meeting socioenvironmental sustainability.

Keywords: Automotive industry · Resilience · Governance · Production chain · Sustainability

1 Introduction

The global automotive industry undergoes transformations with the implementation of new technologies, which confirm the trends of the sector, with emphasis on electric and

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hybrid vehicles, vehicle connectivity and autonomous vehicles. There is a revolution in the automotive product, which can significantly change the current business model, where distributors become centers of product experience and vehicles are customized to meet the needs of each consumer [1]. The transition from fossil fuel-based vehicles to electric and hybrid vehicle technologies is in line with the need to address current environmental problems by reducing exposure to various pollutants, especially those that cause the greenhouse effect. For experts, regardless of how electricity is generated, the electric vehicle emits less carbon dioxide than a hydrocarbon-powered automobile.

The benefits of electric vehicles are gradually being perceived, however, still their high costs restrict access to the majority of the population [2]. A new approach in the relationship between human beings and nature, within a complex conflict of interests, is necessary so that economic development does not preponderate under the triad of sustainability. Thus, there is governmental concern in the relations between industries and the environment that are fundamental to the sustainability of the planet as well as socioeconomic policies. Environmental impacts have increased incrementally, which causes pressure on industrial businesses [3].

The objective is to analyze the impact of the sustainable automotive chain against the perspective of electromobility in consolidated automotive markets in Germany, the United States and Japan. These countries are justified, as these have been demonstrating over the last few years greater attention to environmental aspects, including the option for electromobility, within the automotive chain, creating a parameter with the current Brazilian automotive reality.

2 Sociotechnical Theory - Innovation Systems

List's classical theory [4] describes the National Systems of Economic Policy as an important milestone for the development of the theory of innovation systems. The theories concerning the sociotechnical transition demonstrate an integrated vision with the systems of innovation and of the automotive sector regarding the transition from fossil fuels to electrification, presenting an overview for the development of this technology in the country. Several authors highlight the relationship between the various forms of energy, environment and social and economic development.

There is evidence that the space in which technical change should be addressed is that of innovation, in the convergence of technology, of the economy and of the institutional context, which is dynamic and which represents the pace and direction of the change of a given technology [5].

The National Innovation System stands out for the role of the system institutions that aim at the technological advancement of a nation and, thus, stresses the need for some reorientations in countries that need to catch up with regard to a particular technology, and, in the specific case, the use of electricity in motor vehicles, whether the automotive sector of pure electrification and/or hybrid technologies, which is still virtually nonexistent in several countries, including Brazil [6]. The author points out that to catch up efficiently, an Innovation System should be used that considers the necessary policies taking into account the current context each country.

In addition to this issue, there is the view that a Sector Innovation System can consist of a plurality of actors such as government research bodies, universities, manufacturers and suppliers, among others, which are related through cooperation, communication, competition and command, and such interactions are delineated by institutions through rules and regulations, which causes the system to modernize over time [7].

3 Transition of the Automotive Industry

After analyzing the grounds put forward by the various international automakers, based on the theoretical work of authors such as [8–14], and also through the information obtained in the sustainability reports of each automaker evaluated, it was possible to identify the main sustainability practices adopted in the transition to electrification process, which are based on four pillars, namely (Table 1): Environmental Regulation, Profitability of Electric and Hybrid Vehicles, Battery Charging Structure and Customer Satisfaction Index [15].

Table 1. Market situation of international electromobility.

 **Charging Infrastructure**	 **Environmental Regulations**	 **Customer Satisfaction**	 **Electric Vehicle Profitability**
- Availability of the charging network, especially fast charging.	- Regulatory sanction in many markets for not complying with current legislation.	- Low customer demand for electric vehicles.	- Lower profitability of electric vehicles when compared to combustion vehicles.
- The charging experience is not yet attractive to the user.	- Decreased incentives by governments as technology advances.	- Conversion of sales below 5% of the total vehicles sold.	- Lower after-sales revenues are few components that have wear and tear.
- The charging time of the batteries is an impediment.	- Legislation for installation of charging points.	- Electric vehicle buyers are more technological, have preference for digital channels and customization.	- High cost of batteries for replacement.
- Installation of residential charging plants.	- Appropriate legislation for reuse and disposal of batteries.	- The main concerns are batteries (durability and replacement) and charging.	- Network of distributors with little specific knowledge about electric vehicles.

It is important to highlight the main role of the automotive chain, starting from suppliers, through the automotive industry and its distributors until reaching the final customer. It is evident for the process of transition from fossil fuel to electrification the need for engagement between all links, creating a unit to ensure and meet the needs from the beginning to the end of the chain.

The competitiveness of companies in the automotive segment necessarily involves the effective development of their production chain, the so-called levels 1 and 2, but also the expansion of the production scale and the reduction of their costs. For most automakers, the supply chain follows the model called Global Sourcing, that is, few suppliers around the world who end up being installed near the automakers with dedicated supply to them - level 1, and national auto parts suppliers who can integrate the main chain or are responsible for the replacement of auto parts, called level 2 [16].

In this sense, it is important and urgent to evaluate the automotive chain in relation to the business model based on electromobility, through a business plan that takes into account not only the comparison between the effectiveness of electric models and to internal combustion models, but all the infrastructure necessary to make the project viable and also arouse the interest on the part of the consumer to purchase an electric vehicle at a cost, at this time, even greater when compared to combustion vehicles [17].

The principles of sustainability and social responsibility must go beyond companies, they need to be adopted throughout the value chain, ranging from the extraction of the raw material to the final disposal of waste, taking into account the life cycle of the products, and most environmental impacts from the automotive industry have direct influence through the production and use of the vehicle or indirect, by the distribution of the raw material and final disposal of the products, occurring diffusely and consequently reaching the whole society [18], as observed in the Fig. 1.

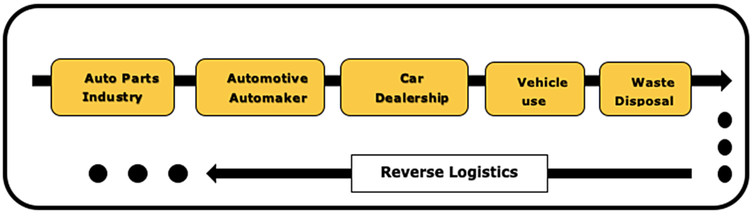

Fig. 1. Automotive value chain.

The environmental crisis is the epicenter of a great global transformation, in which the industrial era, within its economic and developmental rationality, has transformed the relationship between man and nature, opening an unprecedented crisis in the aspect of sustainability [19].

Currently the consumers are more demanding and enlightened about legislation that, in turn, is stricter, which suggests that automakers and their network of dealerships, suppliers, auto parts factories, carriers must innovate technologically to be able to meet environmental performance constraints, in addition to anticipating future trends, within legal limits [20].

This discussion deepens the theme of governance from the transition to sustainability, where, in order to achieve certain challenges, it is necessary to have a governance that can recognize the multiplicity of existing interests and their various spaces of dispute, in addition to public policies, in order to develop more sustainable innovation systems through a process of learning and experimentation [21, 22].

The national automotive chain has undergone changes related to electromobility and becoming a technological ecosystem due to the need imposed by the global concern regarding the environment, especially in relation to greenhouse gases and CO2 emissions, aiming to meet the commitments made by Brazil and other countries that are signatories to the Paris Agreement. The initiatives for national electromobility are at an early stage, however the experiences of innovation systems, especially in countries such as Germany, the United States and Japan, such discussions are at a more advanced stage, since eco-innovations are absolute realities and make up the so-called sustainable innovation systems, demonstrate the importance of this technological model for replacing fossil fuels for electrification [23].

The relevant role that electromobility has in the global automotive industry makes us come across a little of this industry in the leading countries in this area, as we will see below.

4 Demonstrative Experiences in Germany, United States and Japan

The need to develop new ways of reducing emissions of pollutants generated by conventional combustion engines, as well as improving energy efficiency, sustainable urban mobility imposes on the automotive industry the creation of different transport solutions, offering new services with several possibilities, including electromobility through the development of vehicles with electric motorization, called hybrid electric vehicles (VEH) or pure electric vehicles (VEP), as well as innovation in public transport based on the improvement of transport systems and carsharing, which is the rental of short-term vehicles shared by users [8, 9].

Electromobility is one of the most studied research themes in recent years [10, 24, 25] and, due to its complexity and importance on the world stage, it cannot be independently analyzed. It is necessary to discuss by the automotive industry with the various actors in the energy sector and public managers about the development of all recharge infrastructure, transmission networks, technical homologation and legal incentives for less polluting technologies.

The relevant role that electromobility has in the global automotive industry makes us come across a little of this industry in Germany, the United States and Japan, leading countries in this area.

4.1 Germany

Germany is the world's 4th largest market in car and energy commercial sales [26]. It's behind China and Japan, this one by a small margin. Its domestic market is equivalent to 1/4 of the American market and 1/5 of the Chinese market. In terms of vehicle density, it is the third largest market with 557 cars per 1,000 in habitants [27]. In eastern European countries that are part of the European Union, the presence of German automakers is significant, dominating the market with 60% of sales and 65% of production.

The annual report of the Verband der Automobilindustrie Association (VDA) - German Industry [28], shows that the electric vehicle market in Germany grew by 117% over the previous year, reaching the level of 55,000 battery electric vehicles and plug-in hybrids, increasing the share to1.6% of the total market. This share is still small, but it has been increasing significantly every year. The hybrid engine is able to increase the effectiveness of the drive system, thus reducing fuel consumption by around 25%, as well as CO2 emissions considering that the reduction is obtained mainly when using the vehicle in urban paths, due to the recovery of energy that is spent on braking through a fully electric driving, for some time, depending on the autonomy and performance of the vehicle. On the other hand, the internal combustion engine has been operating close to its ideal condition, which is why hybrid vehicles can only achieve moderate efficiency gains. However, global efforts to reduce CO2 emissions point to a clear trend of power train electrification making hybrid units the medium-term standard.

Germany does not practically perform R&D with alternative fuels, whether fossil or renewable, whether liquid or gaseous. In the country, the options are to stay in the current dominant design (ICE[1] + gasoline or diesel) or seek electrification/hybridization of engines. It seems that the main role that Germany will play, is the extended maintenance of ice powered by gasoline and diesel, in view of the experiments with gaseous fossils (CNG[2] and LNG[3]) do not exist in this country, a phenomenon that also occurs with Japan. Germany, as well as Japan, through its automakers, are surely revealing to the world their intention, if technologically advanced to the development of a new dominant design or the maintenance of the current one, it will be the next challenge between these two countries [27].

For several years, Germany has been the leading country in electromobility technologies, where demand for electric vehicles exceeded 200,000 units at the end of 2019, with the German automotive industry expected to reach 1 million units by 2022 with a diversity of more than 100 different passenger car models and investment of approximately €40 billion in this segment [29].

4.2 United States

The United States is the country whose strategies in technological development in motorization has been highlighted. Taking China as the world reference (base 100), it is perceived that the United States, the second largest market in the world, has 99% of the size of the Chinese market [30]. In 2018, 13.1 million cars and light vehicles were sold in the U.S., equivalent to 18% of all sales worldwide.

In this context, the United States is configured as a laboratory of robust experiments for strategic projects involving the maintenance of internal combustion engines. These figures attest to the greatness of the market and that American automakers are at the forefront of efforts to preserve the current dominant design in motorization. These automakers have unveiled a number of strategic actions such as: expansion of production plants and transmissions, investments in downsizing engine emission control

[1] ICE – Internal Combustion Engine.
[2] CNG – Compressed Natural Gas.
[3] LNG – Liquefied Natural Gas.

systems, fuel economy systems including stop-start systems, exhaust gas recirculation systems (EGR), new transmissions with higher speeds, introduction of different materials technologies such as powder metallurgy into engine blocks, turbocharging [30].

In fact, in the United States there is pioneering activity related to world industry with regard to motorization. There is virtually no technological movement around motorizations that is not taking place in the United States. Forty percent of the strategic actions focused on this sector, there is a predominance of internal combustion engines, and these are developed in the United States. This refers to a finding: that if there is a possibility of preserving this engine, this will be done by the effort made in that country and, from the companies that develop their technological mechanisms there. It is unlikely that other countries will find the conditions to preserve it in isolation. It seems essential that there is also the participation of other actors, such as systemists – manufacturers and suppliers of national and international auto parts, universities and government, as inducers of this scenario [30].

Several U.S. studies show that the vision of the development and dissemination of electric vehicles is part of an aggressive industrial strategy and the search for technological leadership [31, 32].

When it comes to electric vehicles in the United States, it is important to note that in the early 2000s, a vehicle manufacturer named Tesla Motors appears in the American automotive market [33]. Tesla produces and sells directly to end customers primarily through the online sales channel, and does not have dealerships representing the Tesla brand within the U.S. territory. Vehicles are produced in a system that seems to have a more sustainable basis and providing access to urban mobility solutions for more and more consumers [34].

According to Tesla's sustainability report [35], the organization's challenge is to accelerate the world's transition to sustainable energy, highlighting the full environmental impact, from the manufacturing phase of the products to the emissions generated by vehicles during their use.

4.3 Japan

Japan is considered the country that dominates hybrid (HEVs) and electric (EVs) vehicle technologies, which would allow one of its automakers to be the first mover when emissions standards become much more stringent globally. Japanese automakers have played a substantive role in the development of new motorization technologies [36].

Japan presents itself as a country in the search for technologies, especially in the area of alternative designs to the internal combustion engine, in which it is in 3rd place behind the United States and Germany. This makes Japan an important player in the international scenario of motorization technologies and a stage of powerful experiments in terms of strategic projects, involving technological alternation to the combustion engine [36].

Japan's investment in the electric vehicle segment is based on the problems related to CO2 emissions in the transportation sector, the constant concern with oil, from the economic and energy security aspects and, finally, the strategy of technical and economic development of the automotive sector in the country, transforming Japan into an industrial power and global technological innovation [37]. Japanese institutional actions aimed at

Table 2. Summary of outstanding actions related of electromobility.

COUNTRY	AUTOMOTIVE INDUSTRY	MAIN INITIATIVES	STANDALONE TECHNOLOGIES	ENERGY ECOSYSTEMS
GERMANY	VOLKSWAGEN	Electrification E-mobility program. By 2030: launch of 75 all-electric vehicles and 60 hybrid vehicles.	It does not have a specific program for the development of autonomous technology in vehicles. It develops semi-autonomous systems.	Development of technologies for the use of biofuels and improvements in hybrid systems.
	MERCEDES-BENZ	AMBITION 2039 Program. By 2020 - launch of 5 electric models and 20 plug-in hybrids. By 2039 - zero CO2 emissions in all vehicles.	Develops R&D program for autonomous technologies in its vehicles.	Strong research and development for biofuel use and also for new fuels from hydrogen.
	BMW	By 2021 - Forecast of 25% of all production in Europe will be electrified. By 2025 - Forecast of 33% is electrified. By 2030 - Forecast of 50% of vehicles produced are pure electric.	Development of autonomous and semi-autonomous technologies for vehicles.	Significant development to improve the efficiency of combustion engines, as well as improvement of electric motors after the year 2000.
UNITED STATES	GM	Development of electric, autonomous and connected vehicles. By 2030 - Zero emission and zero accidents.	Expressive development of autonomous technologies for electrified vehicles, especially the most popular vehicles.	Improvement of biofuel technology and significant improvements in electric vehicle batteries.
	FORD	Reduction of carbon emissions according to legislation. By 2050 - Completely carbon neutral.	Development of autonomous technologies for vehicles with strong concern with zero accidents.	Development of the combination of technologies from motorcycles to combustion with electric.
	TESLA	Development of low-cost electrical vehicles. Battery technology with longer service life than the vehicle itself. Direct marketing to the final consumer.	State-of-the-art technological innovation in autonomous vehicle systems, which are being implemented in other brands.	Continuous search for innovation in cutting-edge technologies, transforming concepts into reality, transforming the generation, storage and use of electricity in electromobility.
JAPAN	TOYOTA	Program: Toyota Environmental Challenge 2050. By 2030 - Reduction of 90% of Cos emissions through electric vehicles.	It does not present any specific autonomous vehicle systems programs.	Strong development of hybrid and pure electrical technologies, with mastery of higher performance batteries.
	NISSAN	Program: Nissan Sustentainability of CO2 until 2022 in Japan.	Develops an autonomous technology project with the objective of zeroing fatalities in traffic accidents.	Significant developments of pure electrification technology as well as vehicular hybridization.
	HONDA	Program: Vision 2030 Mobility, robotics and renewable energy.	It has been developing autonomous technologies through partnerships with other automakers.	Development of new technologies in electric and hybrid motors, as well as development of new fossil fuels.

electric vehicles have as a challenge the social-environmental development linked to the demands of society, such as energy efficiency, sustainability, safety and connectivity.

The Japanese automotive market is dominated by local automakers, and these automakers together currently have almost 80% market share, which operate in a society that will continue to be increasingly concerned about climate change, believing that the business model will accelerate through the sharing of vehicles in relation to 'private property and also by other forms of use. In this society, it will be possible to expand the effects of CO2 reduction by the use of electric and hybrid vehicles, which in turn will lead to an increase in business opportunities globally [37].

In this way, it is visible that the countries evaluated here (Germany, United States and Japan) have a more demanding manufacturing and consumer market from the product aspect and also more significant in global numerical terms. An international market analysis is important to position some strategic milestones, shown in Table 2.

In this context, the arrangement of the production chain in the countries studied has been facing different market situations in the face of the definitive establishment of the transition from fossil fuel to electrification. This is the panorama found in the countries listed, from the point of view of the technological development of electromobility, which has been treading a path to be followed by the majority of the world's automotive producers scattered throughout the planet.

5 Conclusion

All the evidence indicates that the countries covered here, which have more robotic automotive markets mainly in relation to socio-environmental sustainability, demonstrate a current scenario where hybrid or purely electric vehicle technologies have been consolidating mainly because they are considered countries with educational level and high per capita income, where consumers agree to pay more for new technologies through a process of replacing technologies, being more willing to take the risks inherent to technological advances in electric and hybrid motors, as well as the development of new batteries.

In this same view, these countries are more prone to the insertion of electromobility due to public policies regarding the use of new automotive technologies that seek to reduce greenhouse gas and pollutant emissions. Electromobility becomes indispensable for the mitigation of climate change, where the life cycle of the electric vehicle is relevant, from its production, through use to reaching the final disposal and reuse.

Facing the scenario presented, the automakers studied are adapting their electromobility strategies with internal analyses and market situations pointed out, defining procedures and goals that meet the needs of consumers, allied to the economic and financial balance of the entire automotive chain.

From this perspective of transition management, it is sought the best strategies for the sectors of innovation in renewable energies and, more specifically, in the automotive electrification sector, through a new technological arrangement that necessarily involves the transition from the fossil fuel powered engine to new propulsion systems using electric motors, being necessary the construction of technological integration networks to stimulate the entire development and learning curve of the most varied technologies in the development of electromobility [38].

Given the significant uncertainties of the automotive market, it is important that automakers develop strategies for electromobility focused on key issues, starting with a new brand positioning that explores where, how and when to compete, ensuring profitability in an increasingly electrified world.

The transition from fossil to electrification involves not only technological changes, but also policies and behavioral scans exactly in the convergence between energy use systems and production systems [39]. Therefore, the control of the actions of public and private actors is necessary to meet society's demand for sustainable urban mobility through the use and development of less polluting electric vehicles and greater energy efficiency.

Therefore, electromobility seems to be a global trend, but its implementation should occur differently in the most diverse countries, with Germany and Japan being a faster transition with the almost immediate replacement of combustion engines by electric and hybrid engines, or even more slow and gradual as the North American, where there is a prolonged process of coexistence of automotive technologies, still allowing significant use of fossil fuels. On the other hand, in several other countries and even in Brazil, there are numerous barriers to entry to new automotive technologies, and electromobility is certainly an agent of change, but not being able to define the time of these changes.

In Brazil, it is noticed that electric and hybrid vehicles have seen an increase in the last 5 years, but their absolute numbers still represent 0.35% of the total vehicles sold in the country, a percentage much lower when compared to other relevant countries in Europe, the United States and Japan. The lack of demand on the part of the Brazilian consumer for new automotive technologies still needs to be better understood, becoming evident the need to create public policies to encourage greater use of electromobility, as well as the development of all the loading infrastructure and technical support necessary for the users of this new technology.

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A Comparative Study on Material Selection for Designing an Electric Last Mile Vehicle for Parcel Delivery

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Abstract. Mobility and contamination are two major issues that affect expanding cities. Therefore, there is a need to assess the development of products that fulfill transportation needs while simultaneously reducing environmental impact. This paper presents a comparative study on the use of steel, aluminum, PLA, HDPE and PC, as part of the design process for a last mile vehicle. This vehicle was developed in collaboration with a parcel company, as a response to Mexico City's urban space problems, such as heavy traffic and lack of parking spots, which leads to delayed deliveries. The prototype was built using steel as the main material; however, the goal of the sustainable assessment was to identify other possible materials which could be used for the structural and case system of the vehicle. The results of this paper could be extrapolated to other products, in order to select materials that show similar levels of performance, while simultaneously reducing the impact on the environment.

Keywords: Product design · Sustainability · Material selection · Last mile vehicle

1 Introduction

Finding the right balance between performance, costs and sustainability has become relevant in recent years, due to the excessive use and overexploitation of natural resources. Single-use products contribute to the generation of waste, because of the difficulties in recycling or composting. However, engineers and designers can reduce environmental impact by assessing the materials chosen for the design of products.

The purpose of this article is to showcase the benefits of assessing different materials during the design process, in order to reduce environmental impacts. The specific case analyzed in this paper is the electric last mile vehicle developed in collaboration with a parcel company, for delivering packages in Mexico City. The paper is structured as follows: Section 2 explains the background with relevant information related to sustainability assessment, mobility in Mexico City and the chosen case study. Section 3

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explains the objective for the material assessment, while Sect. 4 explains the methodology followed during the analysis. Subsequently, Sect. 5 explains how the comparative study was made, as well as the results and comparisons among concepts, which led to considerations of redesign in future decision making. Finally, Sect. 6 presents the conclusions and perspectives on continuing the sustainable development of products and services.

2 Background and Related Research

2.1 Sustainability in Products

According to the U.S. General Services Administration [1], sustainable design seeks to reduce negative impacts on the environment by minimizing waste. McLennan [2] agrees that designers should "eliminate negative environmental impact completely through skillful, sensitive design", which involves disciplines such as product design, architecture and urban planning. When it comes to designing sustainable products, innovation shows a higher degree of complexity, because it incorporates environmental issues [3]. Moreover, the designs must be efficient, competitive and cost effective [4]. Therefore, conducting an environmental impact analysis is useful for identifying areas of improvement which could be helpful during the design process, not only for choosing materials or manufacturing processes, but also methods of disposal of the product, once its life cycle has ended.

A sustainable product is defined as a product that will have as little impact as possible on the environment during its life cycle [5]. The life cycle includes extraction of materials, production, use and disposal/recycling. As Lennart mentions, the impact cannot be zero, but it can be minimized, especially when compared to other products or services [5].

The Life Cycle Assessment (LCA) is a technique for assessing environmental impacts of products [6]. It is a useful method as it quantifies the impacts of products from cradle to grave [7]. In order to conduct an LCA, international standards such as the ISO 14040 [8] and the ISO 14044 [9], which contain both general and specific requirements for the assessment, are used [7].

This paper presents the process of conducting an assessment for material selection; however, it is not a complete LCA, as it includes neither the source or commercial modification of raw materials, nor the product disposal or recycling, once its life has ended.

2.2 Mobility in Mexico City

As the project scenario was Mexico City, it was important to understand mobility in this particular area. According to the Instituto Nacional de Estadística y Geografía (INEGI) [10], in the Metropolitan Area of the Mexican Valley, 34.56 million trips are made per day with 11 million people traveling to their workplaces, to educational centers or just for recreational purposes. Due to the extended infrastructure of the metropolis, there is an overuse of roads currently existing for private vehicles, along with a concurrent saturation of public transport [11]. As a result, the issue of mobility has assumed great relevance in

Mexico City, especially given the frequent environmental contingencies, forcing drivers to leave their cars at home, at least once a week [12]. In 2016, the high pollution levels caused by the saturated infrastructure, resulted in various studies classifying Mexico City as the most congested city in the world, with an estimated average velocity of 11 km/h in the central areas [13]. As a result, the use of motorcycles was popularized; however, this led to an increase in travel time and the exacerbation of environmental problems [14], since engines are one of the chief sources of pollution, contributing to 52% of PM10 particle emission, 55% of PM2.5 particle emission and 86% of carbon monoxide and nitrogen oxide emissions [14].

In 2019, the Strategic Plan for Mobility in Mexico City [14] was presented with the objective of improving the quality of life of its inhabitants. It sought to reduce the emission of greenhouse gases through the creation of an integrated system of mobility, with increased accessibility for the population. The action plan is structured around three complementary axes: integration of transportation systems, improvement in current systems for reducing travel time and protection of travelers' integrity. These axes not only consider sustainability, innovation and quality of service, but also seek to integrate electric transportation with the eventual incorporation of autonomous cars [14]. Hence, this proposal was supported and aided by the government, with the aim of faster and better transportation of people and commodities.

2.3 Case Study: Last Mile Vehicle for Parcel Delivery

This project was the result of the collaboration between the Mechanical and Industrial Engineering Division from the Engineering Faculty, the Industrial Design Research Center from the Architecture Faculty, and a Mexican parcel firm. It was conceived with the aim of overcoming the challenge of improving mobility within Mexico City. The mobility in the city was studied through observations, polls and interviews with the drivers of trucks, motorcycles and scooters who worked for the firm and delivered packages in different zones of the city. The methodology used to approach the challenge was the user-centered design method, which was improved by teachers and advisers from both the Engineering and the Architecture Faculty at UNAM [15]. The methodology was divided into five stages: Define, Know, Create, Test and Learn. It was an iterative process, wherein the order of the stages was defined by the needs of the project. This allowed flexibility for divergence, but concurrently narrowed the scope at the end of each iteration, with the help from new insights and user feedback, leading to redefinition of objectives for future iterations.

The project was divided into three stages: for the first one, the goal was to create a functional prototype for understanding the scenario and the user's needs. The result was VUM, which stands for Last Mile Vehicle (Vehículo de Última Milla), an acronym of the Spanish name. For the second stage, the goal was to develop a vehicle that could be transformed into a suitcase for delivering packages inside corporate buildings [16]. This prototype was called VUMi2, which stands for "Vehículo de Última Milla - innovación". Finally, the third stage was called VUMi3, and here the objective was to develop a solution for delivering packages in corporate and residential building clusters, using both bike roads as well as car lanes, in order to reduce delivery time [17] (Fig. 1).

Fig. 1. The first prototype is shown on the left. VUMi2 is shown in the center and VUMi3 is shown on the right.

VUMi3 was divided into eight systems: structural and case systems, which are related to the support and exterior design; vehicle steering, rear axle system and brake system, which are related to the directional and longitudinal dynamics of the vehicle; electronics system, which is integrated with the motor, battery pack, and other electronic components such as the accelerator and the controller; access and security system, which is integrated with safety components for guaranteeing the integrity of both the packages and of the entire vehicle; and the user interaction system, which integrates the footrests, the user seat and other interactive elements for the driver (Fig. 2).

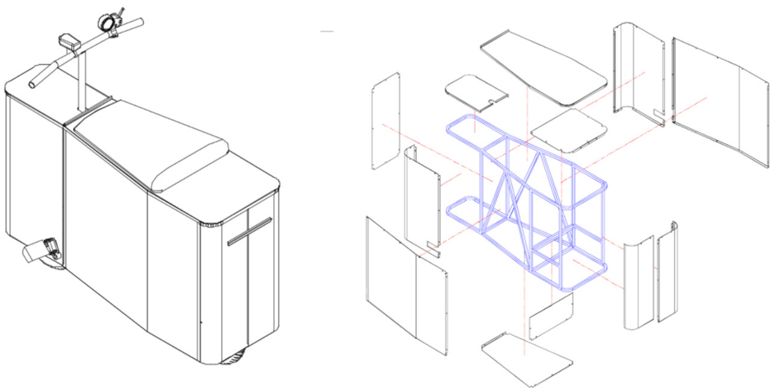

Fig. 2. Assembled VUMi3 is shown on the left. On the right, the structure system is shown in blue, and the case system parts are shown in black.

VUMi3 prototype was developed using steel, due to its mechanical properties, manufacturing processes, availability in Mexico City and low cost in small batches. However, the material selection for both the case and structural system was subsequently assessed, in order to identify the possibility of redesigning the prototype, while reducing the environmental impact.

3 Objective

The objective of the sustainability assessment was to evaluate the impacts of material selection for both the structural and the case systems, in order to define the redesign proposal for VUMi3.

4 Methodology

The evaluation of the product was made through the following the next steps:

- **Gathering product information:** Data cleaning and arrangement of the information in a single dataset called "Bill of Materials" (BOM) [18], for collection and future analysis of the information.
- **Tool selection for evaluation:** Definition of the chosen assessment tool is defined by taking into consideration objectives, software availability and product characteristics such as individual parts, assigned materials, weight and manufacturing processes.
- **Product Evaluation:** Consideration of BOM as the input for the assessment tool and the environmental impacts as the output at this stage.
- **Results Analysis:** Comparative Analysis based on the environmental impacts data collected for different materials and manufacturing processes.
- **Decision making:** Further decision making based on insights from the assessment, such as complete product redesign, partial modifications, material selections or even different approaches to the design process.

5 Assessment Development

As previously mentioned, the assessment was made by following the steps included in the methodology.

5.1 Gathering Product Information

The information was gathered from the parts which integrate the structure and the case systems, because they were not commercial parts. Therefore, decisions about changing their geometry, material or manufacturing process could be taken by the design team.

The second step was gathering the information from each part of the product. This step was executed by extracting data from the model created using Fusion 360 [19]. Using this program, it was possible to modify the materials, calibers and density for each part. Subsequently, using the OpenBOM tool [20], a table was created with the part number and name, assigned material, density, area, volume and mass. Other measurements which were not used during the assessment, were removed from the BOM. As densities of the materials provided by Fusion 360 were not the same as the ones taken from the suppliers in Mexico City, they were modified, in order to maintain data consistency for further analysis or decision making. In total, VUMi3 was integrated with 85 individual pieces, 15 of them as part of the case system and 36 of them as part of the structural system.

The following materials were considered for the structural analysis.

- **Steel** - Due its extensive availability and variety, it was chosen as the base material for the proposal. It is recyclable, possesses great durability and requires lower amounts of energy for production, in comparison with other materials [21].
- **Aluminum** - This material was chosen due to its light weight, which enhances fuel or energy efficiency. Moreover, it improves insulation and decreases heating and cooling costs [22].

Steel and aluminum were also considered as possible materials for the case system along with other materials described below.

- **Polylactic Acid (PLA)** - This material was chosen due to its biodegradable characteristics under a controlled composting environment: an industrial composting facility which heats PLA to 140 degrees Fahrenheit and feeds it to microbes. PLA is considered "carbon neutral" as it comes from carbon-absorbing plants, typically from corn [23].
- **Polycarbonate (PC)** - This material is widely used in automotive applications due to its lightness, strength and durability [24]. As it is a durable material, it helps to reduce the use of spare parts, thus lowering carbon emissions [25].
- **High Density Polyethylene (HDPE)** - It is a recyclable material [26], used in various applications such as food packaging, sports equipment and automotive parts [27]. It is flexible, easy to process, low cost and has good chemical resistance [28].

On one hand, the material selection process for the case system was made based on the availability of the product in Mexico and its commercial presentation in the form of sheets. On the other hand, the selection process for the structural system was based on the limited availability of aluminum in the market. While steel comes in a wide variety of forms both in bars and tubes, aluminum has a smaller range of presentations. Therefore, we decided to assess both materials using the dimensions of the commercial presentation of steel. However, possible future redesigns were to be considered, based on the results of the assessment for aluminum. Moreover, costs of the materials or the manufacturing processes were not taken into consideration at this stage.

5.2 Tool Selection for Evaluation

In accordance with the BOM and the objectives, the tool used for the assessment was Sustainable Minds [29]. It allowed comparison between estimated impacts associated with the materials and manufacturing processes of different concepts. Other softwares such as GaBi [30] were not considered because the complete Life Cycle Assessment (LCA) was beyond the scope of the project. For the project purposes, Sustainable Minds is a software which estimates environment impact [31] based on the equivalent CO2 impacts or milipoints [32]. A point (1000 mPts) represents the annual environmental load (i.e. entire production or consumption activities in the economy) in the United States divided up into the share of one American [33].

5.3 Product Evaluation

The first evaluation was made on the basis of the chosen materials, initially selected for building the VUMi3 prototype (Table 1).

Table 1. Assigned materials for VUMi3.

System	Material	Commercial presentation
Structural	Carbon steel	½ in, 18 gauge square tube
Case	Carbon steel	18 and 22 gauge sheet

The manufacturing processes that were considered differed according to each part. Most of the manufacturing processes involved sheet and bar rolling, saw cutting, welding and powder coating. Table 2 shows an example of how the processes were imputed into the assessment tool for two parts of the structural system.

Table 2. Manufacturing processes assigned on Sustainable Minds for part 041 and part 029 from VUMi3.

Name	Material/Process	Qty	Amt	Unit	mPts	CO_2 eq. kg	MS	Part ID
Pieza3_Predeterm		1	818.043	g	1.02	2.89	E	VUM041
Material	Steel, low-alloyed, market a		818.0430	g	0.906	1.42	E	
Process	Sheet rolling, steel		100	g	0.0134	0.0422	E	
Process	Saw cutting, metal		20	g	$2.28x10^{-6}$	$5.45x10^{-5}$	E	
Process	Powder coating, steel		275500	mm2	0.0955	1.43	E	
TuboDiagonal		2	136.142	g	0.351	0.696	E	VUM029
Material	Steel, low-alloyed, market a		136.1419	g	0.151	0.237	E	
Process	Welding, arc, steel		10	cm	0.0181	0.0146	E	
Process	Saw cutting, metal		10	g	$1.14x10^{-6}$	$2.73x10^{-5}$	E	
Process	Powder coating, steel		18710	mm2	0.00649	0.0968	E	

The results from the first analysis are shown in Fig. 3. These were used as the reference point for further comparison with the other concepts wherein materials were changed. It is considered that the vehicle could have a five-year time of use. Therefore, the total impact is approximately 41 mPts or its equivalent of 125 CO2 eq. Kg. In other words, the functional unit is defined as one year, and within that time window, its impact contribution is 8.2 mPts or 25 CO2 eq. Kg. The greatest impacts that the software identified, were associated with the material selection. The life cycle stage having the greatest impact is the manufacturing phase, as neither the extraction of the materials nor the disposal phase were considered for the assessment. However, it was decided to incorporate the transportation of the product, once it leaves the manufacturing facility to the final customer, which in this case was the parcel company located 21.7 km away. Nonetheless, the transportation stage was not representative as its contribution was 0.26 CO2 eq kg/func unit.

According to the total impacts by category, the largest contributions were from carcinogens that supplied 80.3% of the total impacts, followed by the non-carcinogens category that supplied 6% as a result of the chemical constituents of the chosen materials [34, 35].

The next step for this stage was to assess the other concepts by changing both material and gauge selection. Table 3 presents the concepts that were taken into consideration for the assessment.

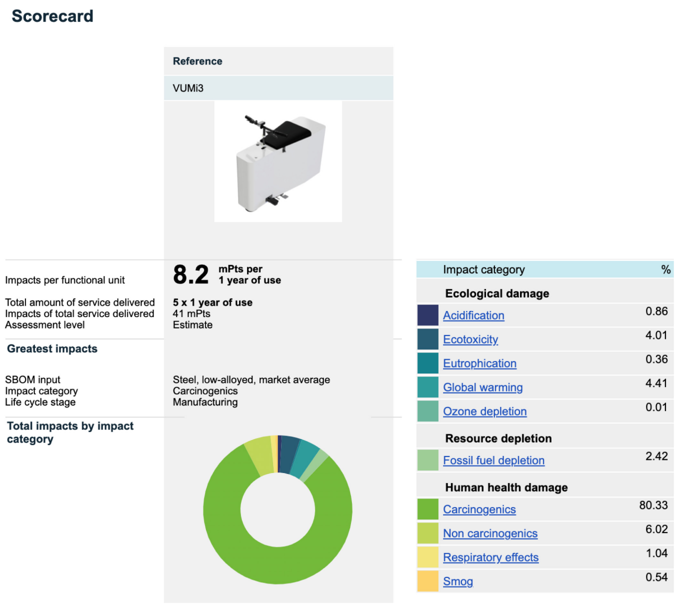

Fig. 3. Results for the base concept, considering steel for the case and the structural system.

Table 3. Concepts and materials assigned for the assessment.

Concept	System	Material	Presentation
CONCEPT 1 (Gauge modification)	Structural	Carbon steel	½ in, 18 gauge square tube
	Case	Carbon steel	22 and 24 gauge sheet
CONCEPT 2 (Case material modification)	Structural	Carbon steel	½ in, 18 gauge square tube
	Case	Aluminum	18 and 22 gauge sheet
CONCEPT 3 (Case material modification)	Structural	Carbon steel	½ in, 18 gauge square tube
	Case	Polycarbonate	2 mm thick sheet
CONCEPT 4 (Case material modification)	Structural	Carbon steel	½ in, 18 gauge square tube
	Case	PLA	2 mm thick sheet
CONCEPT 5 (Case material modification)	Structural	Carbon steel	½ in, 18 gauge square tube
	Case	HDPE	2 mm thick sheet
CONCEPT 6 (Case and structure material modification)	Structural	Aluminum	½ in, 18 gauge square tube
	Case	Aluminum	18 and 22 gauge sheet

Results for the environmental assessment are shown in Table 4, and the percentages of performance improvement for each concept are shown in Fig. 4.

Table 4. Impact results for each concept.

	Impacts/functional unit	Co2 eq. kg/functional unit	Performance improvement from reference mPts
Reference	8.2	25	–
Concept 1	7.8	24	0.37
Concept 2	7.2	31	0.93
Concept 3	5.4	24	2.8
Concept 4	5.3	20	2.9
Concept 5	5.1	18	3.1
Concept 6	6.9	34	1.3

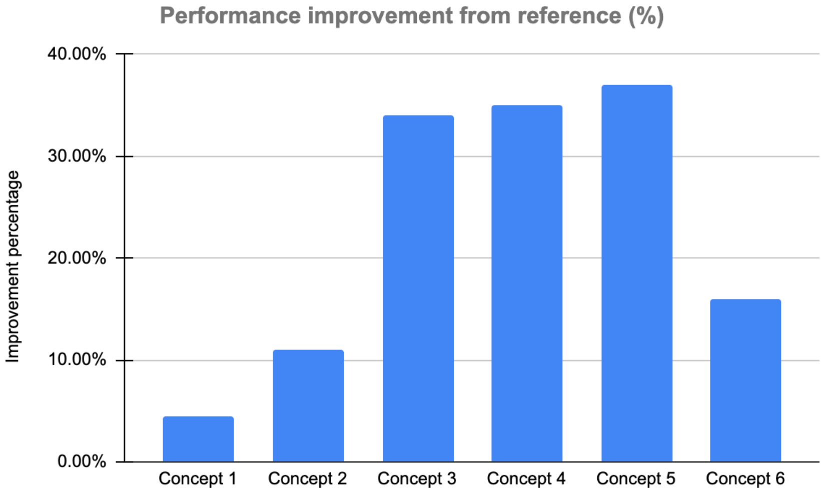

Fig. 4. Bar plot for comparing performance improvement from each assessed concept.

5.4 Result Analysis

Concept 1 had an improvement of 4.5%, due to the gauge modification of the material for the case system. Concept 2 had an improvement of 11%, upon changing the case material to aluminum. Moreover, the case system weight was reduced from 9.4 kg to 3.1 kg, by changing the material to aluminum, which represents a 67% percentage change. The three concepts which presented the maximum improvement, in comparison to the reference concept, were concepts 3, 4 and 5 with an improvement of 34%, 35% and

37%, respectively. These three concepts had polymer as the material for the case system: PLA, PC and HDPE. HDPE presented the best results, and also reduced 50% of the case system weight, from 9.4 kg to 4.7 kg. If the chosen material for the case was PLA, the weight improvement for the system would be 40%, while for PC it would be 45%. Finally, concept 6 had an improvement of 16% in comparison to the reference concept, as the structural material was modified. However, it is important to assess the potential consequences that the material change would have, on the static and dynamic analysis. Concept 6 had an improvement of 16% in comparison to the reference concept. It also showed an improvement of 66% in the weight of the structural system, by reducing it from 6.2 kg to 2.1 kg.

5.5 Decision Making

Based on the results, it was decided to conduct one last environmental analysis by using aluminum as the structural material and HDPE as the case material, in order to identify the potential reduction of the environmental impacts. As a result, 43% of performance improvement was achieved, with an annual contribution of 4.7 mPts.

6 Conclusions and Outlook

This paper presented the comparison between concepts including different materials, which were assigned to the structural and case systems of an electric last mile vehicle, that was developed as a solution for improving mobility in Mexico City. As this was the first environmental assessment, the batch of materials compared was limited. However, the results showcased the benefits of analyzing different materials such as metals and polymers.

Further decision making can take into consideration material costs, as it would define product competitiveness in the market. Moreover, modifications in the manufacturing processes could lead to major improvements. For instance, powder coating enhances steel longevity [36], but this process can be removed when a polymer is assigned as the material for the case system. This was identified as a result of the environmental assessment made while assigning HDPE as the material for the case system (Concept 5). Use of HDPE led to an improvement of 37%, by reducing the environmental impact from 8.1 mPts per year to 5.1 mPts per year (Fig. 5).

Even though the results showed reductions in both weight and environmental impacts when aluminum replaced steel, it is still essential that dynamic and static loads be analyzed, in order to guarantee that performance is not compromised due to material or gauge modifications.

Finally, this paper is a starting point for developing more sustainable products and for improving design practices. The next step is to build a platform that could be extrapolated to other markets, such as the transportation of people (for elderly population or for recreational purposes) as well as goods transportation (medical supplies, food and supermarket deliveries). As requirements change depending on the market segment, different materials should be assessed, in order to fulfill customers' needs while simultaneously reducing environmental impacts.

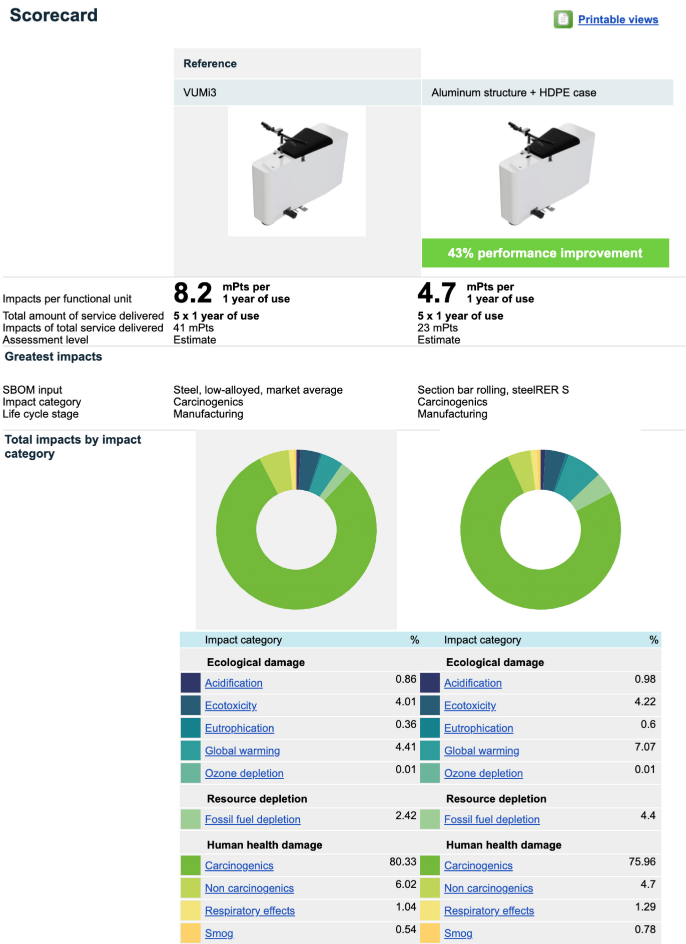

Fig. 5. Results for the redesigned concept, considering aluminum as the material for the structural system and HDPE for the case system.

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Methodology for Commodity Cost Estimation Through Production Line Analysis and Simulation

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Abstract. In a growing competitive environment, it is essential to have a clear idea of a product's total expenditure by estimating the component costs and correctly allocate cost drivers. Assigning exact commodity consumption costs is one of the most complicated aspects of cost engineering activities, which should be performed during the product design stage using Product Lifecycle Management (PLM). However, during the design stage, information is not complete, and it is not sufficient to guarantee the cost estimate's adequacy and reliability. Therefore, it is necessary to monitor the production process to identify each cost variable carefully. This article aims to propose a methodology to evaluate the proper commodity consumption during manufacturing activities for the assessment of the total part cost. Moreover, it helps to generate validated data useful for decision support systems. The proposed approach is studied by analyzing a machining production line of an Italian manufacturer of components for the automotive industry. It consists of three main parts: (i) description of the production line, (ii) definition of IT architecture, and (iii) asynchronous digital twin design. Thus, after the model's validation, the simulated data allows to analyze and estimate production expenditure accurately by the exact allocation of commodity consumption.

Keywords: Cost estimation · Material flow cost allocation · Production management · Production engineering · Discrete event simulation

1 Introduction

Sustainability is a growing concept for the nowadays society. For instance, in 1987, the report "Our common future" from the UN Commission for Environment and Development defined sustainability as a central pillar for humanity's development [1]. In 2015, the UN described the 17 Sustainable Development Goals (SDG) to transform our world, promoting prosperity while protecting the planet [2]. The latest definition of sustainability is given in [3, 4]. More in detail, according to Johan Rockström in [3], the "three pillars" approach (based on economy, environment, and society) has driven a fragmented assessment of the development process, where economic growth overcomes natural and

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human resources. On the other hand, according to [3], the economy is seen as a tool to reach social goals generating prosperity while remaining within the Earth's Life Support System (i.e., the finite natural resources and the limited capacity of the environment to absorb pollution). Different studies have been provided in literature for the assessment of the energy, cost, and carbon footprint metrics for the Life Cycle Assessment of a product.

Focusing on the cost metric, traditionally, cost management consists of defining which costs are generated by direct material cost, direct labor, and finally, all remaining charges are classified as overhead. Inside overhead expenses, it is possible to consider: rents, indirect labor cost, insurance cost, and utilities [5]. Material cost and direct labor cost are easily attributable to production, while assigning the correct overhead costs is more complicated. The traditional method consists of allocating all fixed costs considering the time spent in production, assuming that all different products need the same amount of every single overhead cost [6]. Thus, traditional allocation methods cause distortion on final product cost due to an incorrect definition of cost drivers. They fail to give correct insight to support the decision-making process [5]. Commodity costs are incorporated inside overhead expenses, and making decisions that improve the efficiency and sustainability of the process is problematic because it is not clear where energy, material, and other commodity wastage are made.

This paper provides a new methodology for cost management based on simulation. The proposed method allows keeping track of cost variations during the production phases compared to what was estimated in the design phase. The management of the product cost throughout its life cycle is a crucial phase of the PLM approach. This work aims to define a new costing method that considers both the theory concerning activity-based costing and the sustainability outlook of material cost flow accounting. We merged the process-based procedure of ABC, maintaining clear interest for the material and resources flow. ABC and MFCA are combined in a factory's simulated digital twin in order to provide insight into the actual cost of a single item produced. The proposed strategy emphasizes commodity consumption (electric energy, water, lubricant, etc.), cost-generating elements that are disposed of as NPOs, and their profligate waste has a substantial impact on the environment. This work fills a research gap by proposing a new standardized methodology for cost estimation using a line simulation.

This work is structured as follows. The second section offers a quick outlook of the current research state of the art in cost allocation. The third section describes the theoretical methodology we used to allocate costs. The fourth section presents an actual industrial application of the proposed method through a case study. The case study is presented in three different subparagraphs: (i) description of the production line, (ii) definition of IT architecture, and (iii) asynchronous digital twin design. The fifth section shows some preliminary results of the proposed model and discusses its goodness employing its validation. Finally, the conclusions section is dedicated to the discussion of future improvements.

2 Literature Review

This section evaluates the following topics: (a) activity-based costing, (b) material flow cost allocation, and examples of (c) simulation-based accounting procedures.

2.1 Activity-Based Costing

Fernandes et al. used activity-based costing to take into account correct energy consumption in manufacturing [6]. That process manages to transform the cost of energy consumed from overhead to a direct production cost, similar to labor and materials expenses. The activity-based method, also known as the ABC method, permits allocating indirect costs to search for actual relationships linking expensed to cost centers. The method's implementation follows three different steps: (a) Cost Center Identification, understanding which resources are used to produce the final good; (b) Activities Identification, analyzing all the activities that take place in the product creation, from its development to its selling; (c) Resource Driver Definition, a cost-driver of activity is a factor that directly explains how the operation incurs costs using resources (e.g., marketing activity uses staff, energy, etc.); (d) Cost Allocation through Activity Drivers Definition, the final stage consists of calculating the activity's share of the product's cost in proportion to the specific activity cost-drivers use [7]. That method requires a precise and complete understanding of the product, and it makes it possible to clearly understand where costs and, eventually, waste are generated. In literature, there are cases of the ABC approach used to assess system sustainability; for instance, Cagno et al. proposed an augmented ABC approach aimed at estimating the environmental impact, adding a flow analysis on the analyzed system [8]. A simple scheme of the ABC method [9] can be found in Fig. 1.

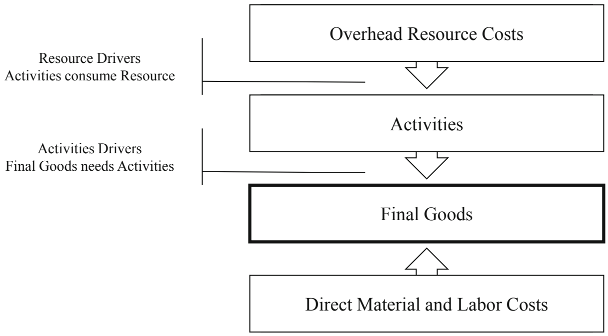

Fig. 1. Activity-based costing scheme.

2.2 Material Flow Cost Allocation

In the last decades, environmental management accounting (EMA) has emerged. EMA is a management accounting approach focused on physical flow. A business process can be described as a system that takes resources as input and transforms them into outputs. It can be possible to distinguish those outputs: product or value-added activities and wastes. Wastes are a cost for the company, and, on the other side, they have a negative impact on the environment [10]. An EMA approach uses internal information about the physical flows that pass through the firm's boundaries and evaluates the related environmental costs [11]. The EMA approach's main scope is to pinpoint the non-product output (NPO), generating many costs. It is possible to define two different kinds of non-product output. (a) Direct NPOs like raw material. These NPOs are usually disposed of as solid waste. Still, in some industries, they could be treated as wastewater if the final product is liquid or released into the atmosphere if the final product is a gas. In this category, it is possible to insert also auxiliary material like glue, paint, and packaging fabrics. (b) Indirect NPOs like energy and water; in this cluster, it is possible to categorize all resources and materials that are not directly part of the final good [11]. Generally, operating materials are considered not-product output since they are not incorporated in the product; there may be exceptional cases such as the beverage industry where only a water percentage is a waste [11].

One of the main tools of EMA is the Material Flow Cost Allocation (MFCA). According to Christ and Burritt, the application of a flow measurement system follows a series of steps. First, defining the analyzed system's boundaries; the second step consists of defining a flow model (a diagram capable of mapping everything that enters and exits the system). According to Kokubu and Tachikawa, this element is crucial to measure the balance of material and keep track of waste [12]. The third step is to determine the amount of input and output going in and out of the system in order to find a balance. The principle that guides this balance is that everything that enters the system, whether energy or material, is not destroyed but is transformed into other forms. Finally, The obtained physics values are converted in a monetary amount [13]. A simple scheme of Material Flow Cost Accounting can be found in Fig. 2. MFCA projects are generally defined and guided by academia; researchers have a direct consulting and expertise role due to the normative impact of research literature in this field [14]. In addition, there is a growing need for industrial applications to raise awareness of waste and unnecessary consumption during manufacturing activities.

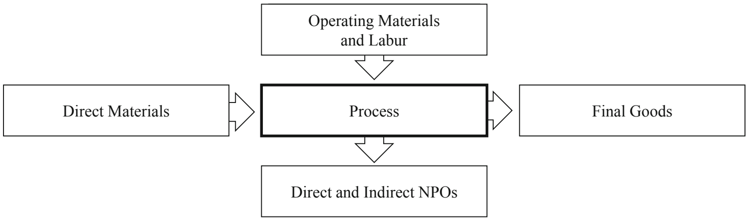

Fig. 2. Material flow cost accounting scheme.

2.3 Simulation-Based Accounting

In literature, there are some cases of published works on cost management based on simulation. Larek et al. proposed a Discrete Event Simulation Model to estimate a CNC machine's power consumption starting from the job's G-code. Their approach is flexible and usable for various processes, and the use of simulation can give a more precise insight compared to complex analytical models [15]. Spedding et al. proposed one of the first applications of a simulation-based approach for ABC accounting. Their methodology focused on manufacturing line surplus capacity. They allocate costs, both direct (i.e., direct labor and energy consumption) and indirect (i.e., asset depreciation), using the time spent in a workstation as a driver for allocation, and they calculate by difference all non-direct explainable costs. That methodology helps to focus on non-value-added activities, like idle time [16]. In recent days, Calvi et al. proposed a renewed process for an ABC approach based on simulation. They provide an in-depth detailed description of a simulator representing a re-manufacturing stage of a closed-loop supply chain for electronic devices. Also, in that case, the driver used to allocate cost is the time spent in each activity [17].

A simulation approach for cost management provides many advantages. (i) First of all, it is possible to have an exact value of the actual cost incurred during the activity. (ii) The activity-based driven modeling of discrete event simulation fits very well with an ABC cost analysis. (iii) Finally, this dynamic approach permits a what-if scenario analysis that can help managers during the decision-making process. In literature, it is possible to find a wide variety of simulation-based techniques to solve different issues. Despite the proven ability to deliver significant benefits, there are few examples of cost management applications [17].

3 Cost Allocation Definition

This paragraph defines a new methodology to implement a second-stage cost allocation. The first-stage allocation is the assignment of the costs on the activities. While, the second-stage allocation includes the attribution of the costs on the single produced elements, defining how much a single object has cost [18].

1. *System Perimeter Definition:* the first step of the proposed approach is to define the boundaries of the system, define what process is intended to be analyzed, where it starts, and where it finishes.
2. *Activity Identification and Flow Model Design:* the second step consists of identifying all activities involved in the project, both direct and indirect. For all single activities determined, a definition of the Flow Model Diagram is needed to keep track of all physical and non-physical resources that enter the system.
3. *Data Gathering:* the defined activities need a detailed data monitoring plan, starting from the designed model flow. A detailed analysis has to be pursued for each activity, and data collection points have to be identified, such as sensors or connected to central information infrastructure.
4. *Simulation Development:* it is possible to represent the activities by simulating them starting from the data obtained. The simulation model can be directly connected to the process's information system; it could be defined as the process's digital twin in such a case. In the alternative, the data could be inserted asynchronously, using an intermediary system. In such a case, the model could be defined as an asynchronous digital twin or an unconnected digital twin [19]. It would also be appropriate to explain what digital twins are and how the concept contributes to the study. According to [19], it is possible to define four categories of DT, (1) Unconnected DT, (2)

Connected DT, (3) Embedded DT, and (4) Aggregated DT. The first typology (1) is used when the digital model describes physical logics, but it is not feasible to connect the two interfaces (physical and digital world) directly. Indeed, the proposed methodology expresses the maximum potential when it communicates in real-time with the physical system (2, 3 and 4)

5. *Direct Item Cost Allocation*: it is straightforward to allocate all direct material costs. It is also possible to carry out a simple allocation based on time for all those operating costs incurred during direct work on the goods produced. The direct cost for a single product after this phase should be:

$$C_i^D = \sum_j \sum_k T_{ji} R_{jk} + M_i, \tag{1}$$

where C_i is the direct cost for the i-th produced item, T_{ji} is the time spent for the i-th item on the j-th activity, and R_{jk} is the time-related cost rate of the k-th operating resource (energy, water, depreciation, etc.) for the j-th activity. Finally, M_i is the direct material cost for the i-th product.

6. *Indirect Item Cost Allocation*: the second cost allocation step provides a quantified evaluation of all not-directly allocable expenditures. We can categorize Indirect Costs into two different types: (a) indirect costs from auxiliary activities (i.e., cost incurred during product design, administration activities, etc.); (b) indirect costs due to system overcapacity (i.e., worker idle time, idle consumption, etc.). The indirect cost C_i^I for a single product, can be written as:

$$C_i^I = \sum\nolimits_k \rho_{ik} A_k^{tot} + \sum\nolimits_j \sum\nolimits_k \frac{T_{ji}}{T_j^U} R_{jk} T_j^{UN} \tag{2}$$

where the first part of the equation represents (a) the indirect cost from auxiliary activities, A_k^{tot} is the overall cost of the auxiliary activity k, and ρ_{ik} is an allocation factor based on different conditions. The second part of the equation represents (b) the indirect overcapacity cost, T_j^U is the total utilization time for the activity j, T_j^{UN} is the time that an activity j-th spent in an idle state. $\sum_k T_j^{UN} R_{jk}$ is the total cost for the j-th activities in a non-value-added state. This total cost is allocated on the single item using the percentage of time which the item above passes in the phase T_{ji}/T_j^U.

7. *NPOs Evaluation*: all item has an assigned value C_i^S equal to the evaluated total cost spent to produce it at that stage:

$$C_i^S = C_i^D + C_i^I. \tag{3}$$

If a product is discarded due to a defect, all accumulated value should be redistributed as an NPO to the final goods. This value is firstly associated with the process that generates the failure if it is possible. This value is allocated to the final product in a second phase when it leaves the system's boundaries using a similar logic of the indirect overcapacity cost, seen in the previous step:

$$C_i^{NPO} = \sum\nolimits_j \sum\nolimits_n \frac{T_{ji}}{T_j^U} C_{jn}^S. \tag{4}$$

The cost C_i^{NPO} for non-product output allocated to the single i-th item is calculated as the percentage of time spent on the j-th process multiplied by the total cost of the n wastes caused by the j-th activity $\sum_n C_{jn}^S$. At the end of the process, all item has an associated cost equal to C_i^T that can be calculated as follow:

$$C_i^T = C_i^D + C_i^I + C_i^{NPO}. \tag{5}$$

4 Case Study

We applied the proposed method to a production line of an Italian developer and manufacturer of components operating in the automotive industry. The analyzed case study is described in this section.

4.1 Description of the Production Line

In this subparagraph, the production line object of this study is presented. The line's purpose is to manufacture wheel hubs for cars. The reader can find a simple scheme of the line in Fig. 3.

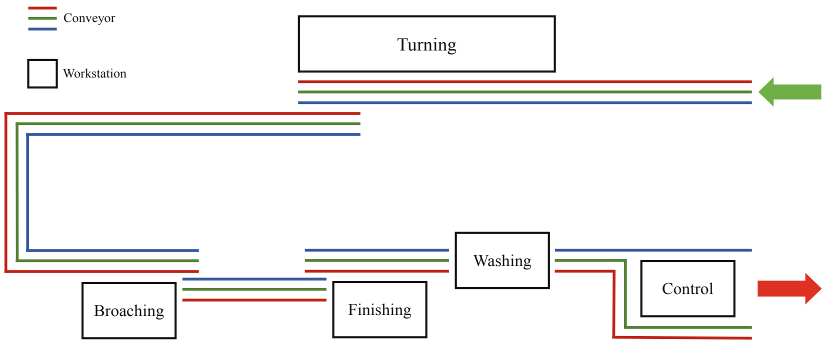

Fig. 3. Production line layout. (Color figure online)

The line could work on three different kinds of pieces (A, B, and C), two of them (B and C) with the same diameter. The parts are transported by three different conveyors, represented by three lines in Fig. 3, pieces of the same kind are always placed on the same conveyor. The line could be reconfigured in order to produce diverse mixes of the three parts by changing the conveyors' destination. The semi-finished products that come from the foundry are placed on boxes at the start of the line. Here an operator feeds the line setting the semi-finished at the beginning of the correct conveyor. Unless there is a case of operator negligence, the conveyors are filled with pieces, so it is possible to consider this buffer virtually infinite.

Turning

The first workstation consists of five parallel machines; all of them are in charge of doing two operations on each side of the piece. When a pre-product arrives from the conveyor, a robotic arm places it in a shuttle (position alpha). The shuttle brings the object inside the CNC machine. Here, the first operation (OP1) is performed. Meanwhile, if a second piece is waiting in the queue, the shuttle leaves the working area to take it. As the first operation is finished, the CNC machine drops the part inside the shuttle (position beta), and it takes another piece from position alpha to perform OP1. Before placing a new object inside alpha, the robotic arm turns the piece from position beta to position gamma. Suppose two different items inside the shuttle, one in position alpha and one in position gamma. In that case, the CNC machine will perform two separate operations: OP1 to the pieces in alpha and a second operation (OP2) on the parts in position gamma. After OP2 is finished, the CNC drops the item in position delta from where the robotic arm takes it and places it inside the conveyor. A scheme of the combination of the two first operations can be found in Fig. 4.

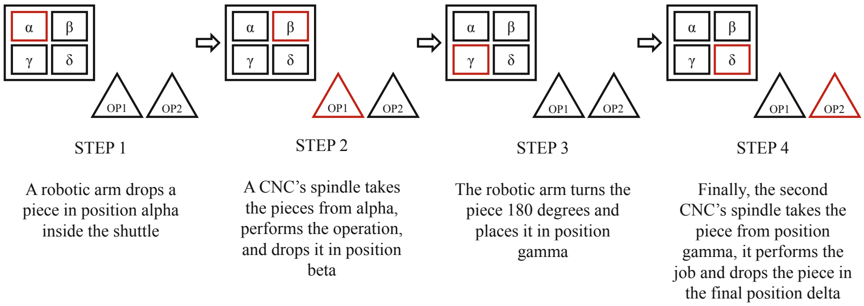

Fig. 4. Logic description of the two first operations (OP1 and OP2) on a single piece. (Color figure online)

Broaching and Finishing

Three different broaching machines compose the second workstation, any of them is in charge of a single kind of product. When a product arrives from the conveyor, a robotic arm takes it and places it inside the corresponding broaching machine. Here the third operation (OP3) is performed. When OP3 is finished, the robotic arm takes back the piece and place it inside the corresponding conveyor. The two objects with the same diameter (B and C) require the same type of processing and time. Therefore, each broaching machine can process the kind of pieces based on the line set for a specific day. Finally, two parallel lathes carry out the finishing operation (OP4). Both machines can be set according to the daily production planning, but they tend to be programmed identically to machine all types of wheel hubs (A, B, C).

Washing
The fourth operation (OP5) is piece washing; a washing machine performs this procedure following four different steps: (i) pre-wash, (ii) wash, (iii) rinse, and (iv) dry. In order to evaluate the procedure's total cost, it is crucial to define process times and the use of water and solvents. Generally, a mixture of water and oil is used to prevent the parts from rusting.

Geometric Control and Laser Marking
Finally, at the end of the line, two parallel tools complete the pieces' geometric control (OP6). The first instrument checks the A parts, and the other controls the pieces B and C. Scrap are placed in a box and subjected to a second wash; if the machine notifies a second measure error, the piece is rejected. A laser machine marks all not scraped parts (OP7). This mark makes it possible to trace geometric information and its position inside the process.

4.2 Description of the IT Infrastructure

One of the project's central parts is the IT infrastructure needed to gather data from the production line. An industrial edge gateway manages the plant infrastructure, controlling the line's PLC through internal software (SINTRA). Any workstation is equipped with sensors to measure electric energy, water, compressed air, and lubricant-coolant liquid. All sensors are connected with SINTRA via an I/O link module. In order to measure ambient variables (e.g., external temperature, barometric pressure, etc.), we add to the system a sensor box. All data generated by the line are collected and managed by software developed ad hoc for this project (HOME). Data collected in a network attached storage includes machines' status from PLC, commodity consumption from sensors, and ambient value from the sensor box. This data is directly accessible by internal users or through a VPN by external users. Due to the company's confidentiality requests, the simulator has been designed externally and fed by data asynchronously. Figure 5 shows the architecture scheme of the previously described infrastructure.

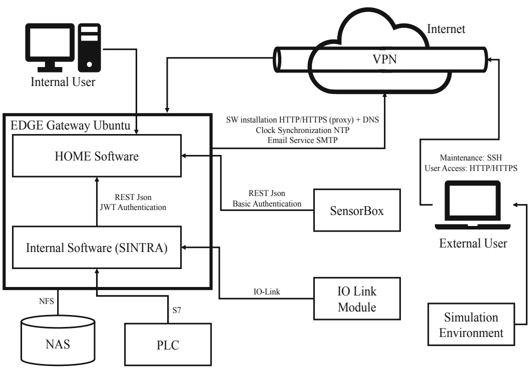

Fig. 5. Architecture scheme.

4.3 Asynchronous Digital Twin Design

Using the accounting theory described in the second paragraph, we developed a digital twin prototype able to ideally copy the line's behavior described at the beginning of this third section. Due to the project still in its early stages, we decided to focalize only on the line's electric energy consumption, and we considered it as a generic commodity able to drive direct costs C_i^D (i.g., direct machining consumption), indirect costs C_i^I (i.g., idle consumption), and non-product output costs C_i^{NPO} (i.g., electricity used to produce waste parts). Our approach can be easily extended into a more complex context, evaluating different sources of direct and indirect costs, such as other commodity consumptions (e.g., water, compressed air, and lubricant-coolant liquid, etc.), amortization of the machines and overheads, and adding costs generated by ancillary business units. Moreover, focusing on a single variable makes more explicit the novelty aspect of this work. The proposed approach diversifies a cost such as electric energy consumption into three different components. Each component provides additional information on the process, highlighting its effectiveness or inefficiency. The simulation model is developed using FlexSim, a discrete-event simulation model software. It replicates the actual line in detail; the user sets the productive mix (A, B, and C products), and he assigns each machine's task before launching the simulation (see Fig. 6). Before the run, the software requires two parameters: the update frequency and a flag variable whose outcome is a detailed electric energy report. When the simulation is finished, the user receives three separate outputs. The first one is a general aggregated dashboard with the following information: total produced pieces, total wastes, total direct electric energy consumption, total indirect electric energy consumption, and electric energy consumption dissipated in waste products. The second one is the first stage cost allocation report, and it describes energy consumption for each workstation divided into the three defined components (C_i^D, C_i^I, and C_i^{NPO}). The third document is the aforementioned detailed electric energy report with a second stage cost allocation. Finally, the third dashboard

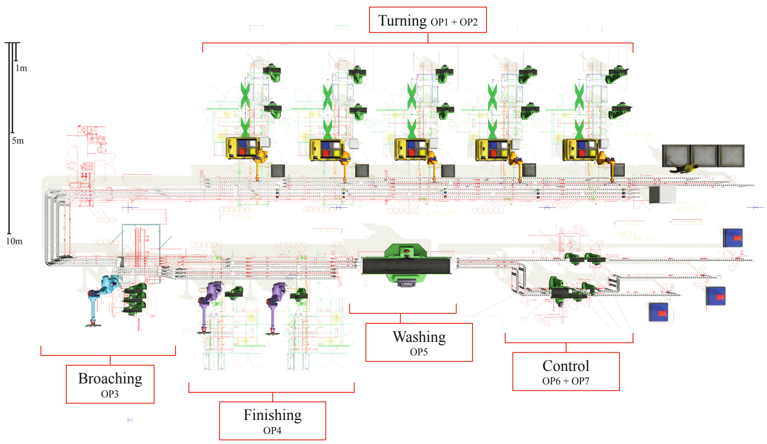

Fig. 6. Simulated model of the production layout. (Color figure online)

presents the precise cost of any single piece produced by the line, and again the report emphasizes the cost breakdown.

The simulation model is built on a scale of 1:1 starting from the production line CAD drawing. The parameters used in the simulation environment are based on internal references and machine nameplates. We decided to focus this work on product A. Therefore, from now on, all data are referred only to it. Product A is the main one: in about three observed months, product A consists of more than 91% of produced pieces while product B 6% and C are less than 3%. The reader can find a summary of the main line's time and speed parameters in Table 1. Process time for products B and C is longer due to the greater diameter and the general more significant dimensions. Table 2 displays the electric power requested by different machines during three phases: processing, idle, and scheduled down. We assumed that the machine tool is turned off if it is not working due to shifts or organizational reasons, so the scheduled down requested power is 0 kW. Finally, we insert a probability of 10% for every piece to have dimensions out of control during the geometric control and be rejected as waste; this value aligns with the company's historical information.

Table 1. Time and speed parameters.

OP1/OP2 processing time	93 s
OP3 processing time	56 s
OP4 processing time	43 s
OP5 processing time	6 s
OP6 processing time	24 s
OP7 processing time	19 s
Conveyor speed	0.67 m/s
Shuttle speed	0.25 m/s
Robot operation time	3 s

Table 2. Electric power parameters.

	Processing	Idle	Scheduled down
OP1 + OP2	65 kW	25 kW	0 kW
OP3	25 kW	14 kW	0 kW
OP4	45 kW	25 kW	0 kW
OP5	10 kW	1 kW	0 kW
OP6	1.5 kW	1 kW	0 kW
OP7	3.5 kW	1.5 kW	0 kW

The line works in a continuous cycle during the 24 h. On the weekend, the line is stopped at 6 a.m. Saturday and restarts at 6 a.m. on Monday. The line operates on three continuous shifts: the first from 6 a.m. to 2 p.m., the second from 2 p.m. to 10 p.m., and finally the last from 10 p.m. to 6 a.m. During shift changes, production slowdowns have been included in the simulation model, and this information is obtained by the company and from the direct analysis of production data. Generally, this slowdown has an impact on the half an hour before and after the shift change. We mimic the downturn with a machinery pause of 60 min. We also inserted a time break in the middle of each shift (10 a.m., 6 p.m., and 2 a.m.); this behavior is realistic and partially confirmed by data.

5 Results and Discussion

5.1 Production Output

To test and validate our model, we ran the simulation for about two months: from the 5th of October 2020 to the 19th of December 2020. We compare the obtained simulated results with the actual production output extracted from the line's PLC. We eliminate from our analysis the days 7th, 8th, and 9th of December: in these three days, the plant was closed due to an Italian public holiday. We also deleted the 30th of November; on this day, the IT system aggregated the data in a wrong format.

The first step was to validate different machine processing times. Table 3 displays the comparison between simulated processing times and the company's actual processing time.

Table 3. Validation of the different process times for the production of the single component A.

	Avg. sim time	Sim Std. dev.	Actual time
Turning time	04:19 s	00:04 s	**04:21 s**
Broaching time	00:58 s	00:01 s	**00:58 s**
Finishing time	00:45 s	00:01 s	**00:45 s**
Washing time	00:06 s	00:00 s	**00:06 s**
Quality control time	00:24 s	00:01 s	**00:24 s**
Laser marking time	00:19 s	00:01 s	**00:20 s**

After processing time validation, we examined the simulated total production output to evaluate if it correctly predicts the real one. During the two months, excluding the four outlier days, the line produced 86.029 pieces while the simulation produced 87.203, an error of 1.36%. We calculated the average and sample standard deviation of produced pieces for all combinations of hours and days to have more detailed information about this error. Figure 7 displays the average production of a week for the real manufacturing plant (green line) and the simulated model (brown line). Each value is calculated as a mean of the same day's production in the same hour for the considered sample. On Saturday after 6 a.m., Sunday and Monday morning, before 6 a.m., when the plant is closed, the two lines are perfectly overlapping, and on weekdays (120 h in total), the two lines are similar. The simulation model correctly represents the breaks during and between shifts. However, simulation systematically overestimates the production rate as shown by cumulative average week production reported in Fig. 8. On average, the simulated manufacturing line produces 88 pieces a week more than the real line. The nature of this error can be easily discovered by analyzing raw data: the hourly production in the real world has a more significant variability than the simulated. Frequent line interruptions cause this variability (e.g., breakdowns, periodic maintenance, stops asked by management, etc.). These interruptions drastically drop down the production rate and generate variability. Despite this, the line's digital twin replicates production without interruption quite well. However, it will be necessary to collect data for more extended periods in order to try to model the distribution and frequency of outages in the simulation model.

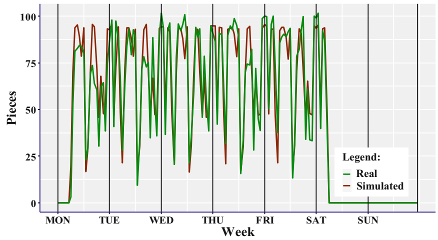

Fig. 7. Mean hourly production. (Color figure online)

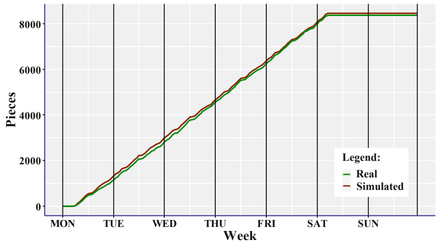

Fig. 8. Cumulative mean hourly production. (Color figure online)

Figure 9 shows the difference between the week average actual hourly production with the simulated one. The systematic error is emphasized in the image by a red line: the simulation model overvalues the real output of 0.732 pieces per hour; the average is calculated considering only the 120 working hours a week, an average relative error of 1.05%. On the other hand, the actual process is more variable than the simulated one: on average, the real standard deviation is 87% more than the modelized one. The average relative error committed for every hour of the week is represented in Fig. 10. As aforementioned in this section, this more significant variability is caused by frequent breakdown and maintenance periods. This behavior is not described in the simulation model due to a lack of knowledge of the complex phenomenon.

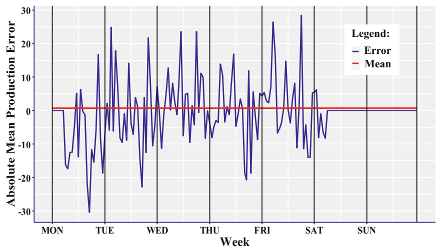

Fig. 9. The difference between simulated and real mean production. (Color figure online)

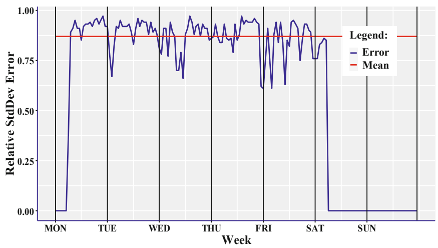

Fig. 10. The relative error between simulated and real standard deviation. (Color figure online)

5.2 Energy Consumption and Cost

We use the designed model to calculate the line cost for a generic production week due to its electric energy consumption. A cost of electricity equal to 0.17 €/kWh has been used. This value is the declared electricity cost for the examined company. It is in line

Table 4. Energy consumption dashboard after a generic week.

Production	8475 pcs
Direct cost	4462.88 €
Indirect cost	850.56 €
NPOs cost	590.84 €

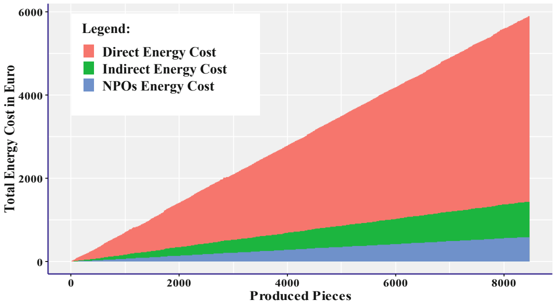

Fig. 11. Production costs divided into three components (C_i^D, C_i^I, and C_i^{NPO}). (Color figure online)

with the average Italian electricity cost (0.15 €/kWh) considering the Eurostat report indicating the electricity cost for non-household users in Italy consumption up to 2000 MW per year [20]. The final results are presented in Table 4. The digital line produced 8475 pieces during a production week, with an overall energy cost of 5904 €. Only 76% of the total cost is spent on value-added activities (C_i^D). The 14% is paid in idle (C_i^I), and another 10% is consumed due to waste (C_i^{NPO}). Figure 11 summarize the results showing the overall estimated cost incurred by the company during a generic week.

6 Conclusions

In this paper, we proposed a new simulation-based accounting model. The novelty of the approach consists of allowing a better classification of costs and commodity consumptions to evidence manufacturing wastes and inefficiencies. This work has several limits, which can be improved under different aspects. (a) The performed analysis has been limited to a single product. However, the study of a more diversified product mix would have given more realistic results. (b) We limited our work to the study of electrical energy consumption. In the future, we can use more complete data gathered from the information system. New data could help to improve our simulation model and permit the forecast consumption of water, compressed air, and cooling liquids. (c) We validated our model, collecting production data for less than three consecutive months. This factor represents one of the most significant limitations of our work. Therefore, we are planning to collect data for a more extended period. (d) Moreover, a more realistic description of the line is needed to create a more reliable digital twin. Future works will focus on developing a sensitivity analysis to estimate cost driver variables and eventually give insights to companies aiming to improve their processes. Once validated, the model could be used to forecast scenarios and provide "to be" configurations. As discussed in the methodology section, the proposed approach provides more significant value when integrated directly with sensors to build a connected digital twin. In the examined case study, such integration was not possible due to corporate security reasons. In the future, we hope to find collaboration from companies to develop a case study of our complete methodology to appreciate all the advantages. Suppose the simulation model would be directly connected to the process's information system. In that case, more information could be collected, and new challenges would be raised, such as how to keep Digital Twin consistent data consistent.

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Conceptual Design Methodology for Knitted Fabrics

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Abstract. This paper proposes operational systematics for the design phase, specifically the conceptual design, considering integration with manufacturing variables, promoting the concurrent engineering in the knitted industry. The bibliographic references are analyzed to compose a theoretical framework about models for the product development process (PDP). In order to understand the PDP practiced in the knitting industries, field research was conducted in four large companies located in Brazil. The PDP models identified were compared with the theoretical frameworks for generic products. Based on this analysis and the contribution of three specialists in knitting development, a methodology is proposed to support the conceptual knitting design, considering manufacturing aspects and including some tools. This methodology is evaluated through a simulation, where two groups use the proposed methodology, and the indicators are compared with the third group with a high experience that does not use it to develop a conceptual knitting project. Among the results, the article proposes and evaluates a systematization, adapted to the Brazilian local reality and needs, considering the integration between product design and manufacturing phases.

Keywords: Product development · Conceptual design · Methodology · Textile · Knitted fabric

1 Introduction

The textile industry has great importance in the Brazilian economy, since Brazil is among the largest producers in the world [1]. In order to continue making progress, the textile industry needs to produce differentiated and greater value-added articles, nearing the market needs. However, it observes a shortage of qualified staff and development sectors with appropriate methodology, using a development process based on trial and error, supported by the experience of experts [2, 3]. Still in 2021, [4] discuss about needs for knowledge transfer in conservative production processes such as the textile industry. This kind of process still rely heavily on implicitly available experience-based (tacit)

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knowledge, make the process vulnerable. There is not design models with manufacture parameters in details and explicit. To help in this task, they suggest the "Internet of Production (IoP)", aiming to provide a framework to be incorporated within the textile industry.

Despite the numerous approaches to product design, providing many theoretical frameworks [5], the publications related to this specific problem are rare [6]. A brief search with some keywords was conducted in order to identify some contributions in literature, related to the subject in question, without restriction of periods. This research considered peer reviewed articles, in the engineering area and published in English, taking into account the main academic databases. The key words are "integrated", "conceptual design", "method", "textile industry", "and manufacturing". This search has resulted in 28 articles. However, analyzing the title and the abstract of these articles, only four presented a similar focus.

[7] comment that the literature clearly documents the importance of new product development to success of a manufacturing firm. Many examples of generic models of the process can be found, including sequential, concurrent, and multiple convergent models. However, these models have insufficient details to provide an adequate foundation for redesigning the development process of apparel products. This article proposes an operational systematics for conducting the project, although focused on clothing, and not on knitted fabric.

[8] analyzes the potential for developing novel methods of generating material and for creating new fabrics, useful for both fashion and decorative art, as well as exploring the potential uses of the newly generated fabrics. This study demonstrates the possibility of approaching artistic fashion by manipulating overstitching and the feasibility of conducting a fashion design process in which product aesthetics is generated from yarn texture, fabric structure, and garment construction. However, this article does not suggest a structured design methodology in order to create the fabric; it rather extrapolates creative solutions, through differentiated combinations of thread interlacing, aiming at creating innovative aesthetic solutions.

[9] use interviews, direct observation methodology, and theoretical argumentation to obtain the expert's knowledge on describing the problems in the garment design process. The purpose is to generate a methodology so that the expert in this field will become highly specialized, supporting them with the TI methodology and the design management model. It is a generic methodology, whose production knowledge prevails as a knowledge representation technique, making possible to acquire knowledge domain in complex problems such as in the garment industry. The proposal is based on the mapping of problems during the garment design, aiming to identify its origin, reducing the situation complexity. In other words, it is not a methodology for the garment creation, and has not been applied to fabric design before.

[10] reviewed the design processes used in the fields of architecture, engineering, industrial product design and clothing, and translated these methodologies in three major steps: (a) problem definition and research, (b) creative exploration, and (c) implementation. Based on these steps, a design process was proposed and tested to facilitate a

cooperative industry-university project in the redesign of an athletic ankle brace. However, the method does not address the design parameters of the fabric that makes up the product, and it was not tested for this purpose.

Some studies show the importance of the phases of a fabric design in containing the functional description of the product [11]. Others show the project planning, starting from a market research, including computational tools to support the development of the fabric design [6, 12].

[13] present a review about the evolution of Engineering Design, in the Industry 4.0 context, considering smart and connected products, end-to-end digital integration, customization and personalization, data-driven design, and intelligent design automation. The digital innovations allow improvements in product design because promote data collection from the field to feed new designs. The creation of these engineered systems must consider management systems that makes it possible to store, share, and use data collected in the field and ensure proper information throughout the PLM.

[14] reviews recent articles about digital technologies in textile manufacturing, concluding that these technologies could optimize production, reducing cost, and increasing profitability. However, its application is not common yet in textile manufacturing. The author suggests an example with an automatic model of knit fabric defect detection based on image classification and neural network that could refeed and improve the design phase. However, there is still the need of initial design model to start this process of improvement.

The researches show a lack of models that detail how to execute a design including all phases of knitting development, considering all aspects of manufacturing parameters. This is also true when analyzing the generic bibliography of the product development; the methodological focus for its management deals with isolated phases, not presenting a systemic integration of the development process, which directly relates the design to the manufacturing [5, 15, 16].

The purpose of this work is to develop a systematization in order to operationalize the conceptual design phase of the knitting fabric, taking into account the manufacturing aspects, promoting the concurrent engineering. To this end, a bibliographic review on the product development process (PDP) is presented, as well as its integration and systematic approaches to conduct it effectively. Next, a survey is conducted in four large-scale knitting companies located in Brazil, aiming to identify the methodologies applied in the development of their products. This result is compared with the design methodologies suggested in the literature, aiming at diagnosing the deficiencies of the industrial practices. Based on these deficiencies, a systematization is suggested, with the purpose of supporting and guiding the knitting developers in the conceptual design phase. In order to compose this systematization, the particularities of the textile industries were considered, aiming at identifying the best methods and tools to perform each design activity, also considering the manufacturing aspects involved in the knitting production. This methodology was evaluated through an empirical simulation and an evaluation simulated by experts in the industrial knitting area.

2 Material and Methods

In order to achieve this study's objective, it started with an understanding of the subject and a data collection in an industrial field, aiming to understand the way the product development occurred and its integration with the production, in a general manner, and in the knitting manufacturing industry, in a specific way.

The bibliographic review addressed the product development, its integration and systematic approaches on how to conduct it. The review structure is based on the approach developed by [17].

Despite the numerous approaches to product design, providing many theoretical frameworks [5], the publications related to this specific problem are rare [6]. A brief search with some keywords was conducted in order to identify some contributions in literature, related to the subject in question, without restriction of periods. This research considered peer reviewed articles, in the engineering area and published in English, taking into account the main academic databases. The key words are "integrated", "conceptual design", "method", "textile industry", "and manufacturing". This search has resulted in 28 articles. However, analyzing the title and the abstract of these articles, only four presented a similar focus.

The search was performed with the following keywords, considering the "industrial engineering" area: "product development model"; "Integrated model of product development"; and "integrated product development process". The articles found were selected from the reading of the title, keywords and abstract, according to the topic relevance.

Considering the rating of 27 selected papers, 48% of which correspond to books, 15% to MPhil thesis, 11% to PhD thesis and 26% to articles with SJR (Scientific Journal Rankings) – the latter have relevance of Q1 (86%) and Q3 (14%).

After the analysis of the bibliographic references and selection according to the affinity of the topic discussed, a study was conducted in four large companies, aiming to understand the practices used during the development of the knitting product. These companies were chosen for having a specific department of knitting development. They are located in the southern region of Brazil, in the State of Santa Catarina, known as a producer of knitwear.

In order to collect data, this study used a questionnaire with 26 questions, containing: (1) 4 questions to identify the company and interviewee characteristics; (2) 18 questions to understand the different phases of this process and how they occur — among these, 6 questions on informational design, 5 questions on conceptual design, 4 questions on preliminary design and 3 questions on detailed design, considering the methodology of [16]; (3) and finally, 4 questions related to rework during the PDP process and its causes. The interviewees have more than ten years of experience in knitting development and are responsible for the PDP management.

With the aim of analyzing the previous collection and obtaining a diagnosis of the industrial situation, the data collected in the industrial field were compare with the design methodologies studied, identifying the inefficiencies of the processes conducted by the industries.

The creation of the model considered the points of failure previously identified, aiming at establishing a model that would address these failures with literature proposals, including methods and tools identified as potential to operationalize some activities and considering the integration of manufacturing data. The model focused on the conceptual design step of fabric knitting and considered the interface to manufacturing. In order to construct the model and considering the best alternatives for the actual industrial situation, three instructors from the Technical Knitting Course of the Santa Catarina Federal Institute of Education, Science and Technology – IFSC were consulted, bringing their knowledge about the features of the knitting design. Aiming to present the model concept in a clearer way, this study presents an application simulation, whose preparation was based on the experience from one of the authors of this work who, besides acting in the academic area, has more than 10 years of experience in knitting projects.

In order to evaluate the performance of the proposed model, this study conducted an experiment with six technicians in knitting development (four with more than 10 years in this area and two with less experience) and divided into three groups: G1 (2 experienced technicians), G2 (2 technicians with little experience) and G3 (2 experienced technicians as a control group). The G1 and design G2 groups had a training whose purpose was to present the theory of the product development, the proposed model and its use. The G3 group did not receive this training because, as a control group, it was responsible for being a reference for the other groups. The proposal was to compare the conceptual design elaborated intuitively by the G3 group with the conceptual design developed with the methodology proposed and passed on to groups G1 and G2. In order to evaluate the performance of the groups that used the proposed methodology, the results obtained and the execution time between (G1 and G2) and G3 were compared. The evaluation considered as a key performance indicator (KPI) the design performance, considering the number of principles of solutions, the number of conceptions (as it is associated to product differentiation), and the quality of the records in the design step.

3 PDP and Product Design

The PDP process involves the design of systematic products and processes, integrating approaches in order to minimize costs and maximize the quality and performance of the development and the final product [15, 18–20]. The evolution of the PDP management, some approaches and the main characteristics are: Sequential product development, Integrated development of products (Simultaneous engineering, Stage gate, Funnel model) and new approaches to improve and integrate product development process (Lean Manufacturing, Design for Six Sigma, Maturity models, Management of product lifecycle).

For [21], the integrated development of products has determinants at the strategic and design levels. At the design level, it includes the overall process of product development, the design structure, the cooperation between departments and the involvement of suppliers and customers in the product development. In addition, it also uses multidisciplinary teams to share knowledge, aiming to facilitate problem solving and reduce failures [22, 23]. Considering its complexity, the companies need a reference model, from which they can guide the activities and decisions taken during product development.

3.1 PDP Models

[24] define a reference model as the union of the best practices related to a particular development process, these practices being clearly represented to any user of this process.

The models include the key decisions, activities and tasks required to the product development, providing a framework from which the companies can conduct, control and assess their PDP process. For [24], the models also facilitate the understanding and communication between the product design coordinators, helping in their planning and organization, and generating a unique view of the PDP process, as well as serving as reference for companies and professionals to develop products according to an established standard.

Several approaches or strategies can be adopted in the PDP process, whose characteristics make up different types of models; some of them are limited to the design process, while others address the integrated PDP as a business process, moving beyond the technical specifications of the product [25, 26, 51, 52]. For example, the models with a simultaneous approach address some elements such as: parallel activities, information flow between activities, integrated development with several areas of the company, use of supporting tools, multidisciplinary teams, product life cycle and management of product development [5]. The involvement of work teams from all areas included in the process contributes to a more holistic view of the product [25, 26].

The PDP process must be adapted in accordance with the environment influence and the market pressure to which it is subject. These factors determine the degree of success, the market recognition, and competitive advantage achieved by new products. This way, the PDP process must be cost-effective and aligned with the clients' needs [27]. One possibility to address this challenge is to incorporate a strategy that integrates the production technologies and manufacturing characteristics into the early phases of the project, as these phases are essential for the efficiency of the PDP process and product innovation level. This enables the generation of optimized products, with functional benefits, and reduces the complexity of the parts [28]. According to [29], this integration demands new skills from the product engineers, covering both design and manufacturability issues. It also demands technical skills related to product design and the analysis of its manufacture, as well as behavioral skills such as teamwork and communication between different areas.

However, there are still gaps when dealing with design and manufacturing; the PDP process uses the construction of a system and the function of the product, while production uses the process, operation and tools. In addition, it is necessary to form both models in such a way that the relationships between them can be expressed even in different domains [30]. [31] have identified significant differences between manufacturing and design operations. While sequential processes, executed several times in similar ways, characterize manufacturing operations, the design operations are not linear; tasks such as design, testing and redesign are performed cyclically and interconnected through functions at different hierarchical levels. In addition, the authors identified other barriers to integration and cooperation between design and manufacturing: manufacturing has a shorter time horizon than design and, in contrast to manufacturing tasks—these are well defined—, design tasks are often abstract. Additionally, there is a lack of knowledge about the operations of other functions, as well as the difficulty in allocating resources and predicting costs, even in the initial phases of the project.

Thus, to better understand this operational dynamic, it will be presented some reference models for the PDP process. According to [32], the models emphasize the process systematization and are oriented through phases, ranging from generation of ideas or identification of needs to the detailing of the proposal, new product development, its production, launching and product monitoring on the market, until its withdrawal. For the author, many of these phases are repeated in the models, with differences only in their terminology, since each author has his own point of view of the PDP interpretation, considering a particular application.

After reading 27 papers found in the bibliographic review about PDP models, this study developed a chronological structure in accordance with several authors, considering the complete life cycle of the product, which includes the pre-development, development and post-development.

Some authors attribute different qualifications to these steps but, when analyzing the operational activities, it can be observed only different forms of grouping. It seems to be the case of [15], who did not mention the expression “preliminary design” in his model; however, the author considers these step activities together with the “detailed design” activities, both under this same step.

An analysis of some works read allows to identify that most of them do not consider the complete product development cycle, including the product launch and its maintenance in the market. The implementation of the discontinuity phase is very important for the company’s competitiveness, since it takes into account the end of the product life cycle, such as recycling, reuse, among others, making the company more sustainable. This phase was identified in a few studies and requires more elaborate studies. Some papers describe the production preparation, but do not align it with specific projects for the production itself, which is a relevant sector to maintain the designed requirements and specifications for the final product. In the last decades, the traditional approaches that include and integrate the final activities of the product life cycle in the PDP process define the assembly sequences after the detailed design phase [33]. Most of the works focus on the design steps and present their final phases in a fragmented way.

After the reading and analysis, this study selected 17 works, which were chosen as they approached the model in more detail and included the last phases of the PDP process. The 17 papers selected were: [4, 5, 13–16, 32, 34–43]. Of these, some use life cycle approaches, integrated development of products and stage gate, simultaneous engineering approach, and the newest ones, suggest inserting technological tools like artificial intelligence, to collect and improve data, and other to make the process more autonomous. Only the studies presented by [32, 15] use all approaches in their models; the other authors use them partially. All authors integrate the manufacturing process at some stage of design, but not the complete product life cycle, and the most connected phases are the preliminary, conceptual and production design phases. Only three authors do not mention the connection between manufacturing and another specific phase. In spite of this, there is still no consensus on how to integrate manufacturing with the prior and subsequent production phases, considering a complete and operational life cycle.

In an analysis of selected papers, the models defined by [34] are very similar and use the production and consumption cycle to describe the model phases, differing only in the nomenclatures and in the form of presentation. However, they do not use approaches like concurrent engineering and stage gate because these are works developed before the popularization of these approaches or are very recent. The three models are related to the production and consumption phases and with the withdrawal options of the product from the market, but in a simple way, without using any tools or approaches.

The models presented by [16, 35, 36, 41] conclude the development cycle in the detailed design, production preparation or product launch on the market. The focus of these works is on product design, not addressing the production and post-development phases (product monitoring on the market and discontinuity). [37] also complete their model in the launch phase, presenting a step called "supply chain design" that addresses the type of process to assemble the product; however, they do not describe this topic at the production phase. [5, 38–40] conclude their models in the market-monitoring phase; however, [39] does not present a phase for this step; these decisions are taken at a phase prior to the production preparation.

[15, 32] present models for the complete PDP cycle, including the company's strategy, development projects and product discontinuity. Their models address integrated development of products, concurrent engineering, stage gates, and some decision-making methods. It is important to highlight that, from the 17 papers selected, most suggest a model applicable to a generic product.

Considering that this study's focus is the operational systematization for the knitting design, the way the product design step occurs in the textile industry will be analyzed.

3.2 Textile Product Design

In order to plan a textile product, various design methodologies could be adapted and used. However, among the most widespread methodologies in Brazil, there are those defined by [5, 15, 16], which are very similar in their descriptions and objectives. The phases are:

1. Task planning and clarification/Information design: it aims at understanding what is required by consumers and transforms this information into technical specifications;
2. Conceptual design: it proposes solutions from a functional structure of the product, evaluating the principles of solutions generated and composing several solutions for the same problem. The best design is compared and selected in order to meet consumer expectations;
3. Preliminary design: from the concepts generated, the constructive structure of a system is determined according to the technical and economic criteria;
4. Detailed design: it deals with the documentation for the production, with detailed drawings, parts lists, instructions for the production and assembly.

Of all the phases previously mentioned, the conceptual design is the phase where the product concepts are developed, and it is of vital importance for the creation of an innovative product. After all, it is at this phase that you have the opportunity to find innovative solutions, aiming at a better solution for the problem. However, some researchers conducted in Brazil show that it is the conceptual design phase in which the companies that develop knitwear have greater vulnerability [3]. The activities of the conceptual project, as well as the methods for accomplishing them, was based on [3, 5, 15, 16]. They are: Function structure (Describe the global function that the product must perform and all its subfunctions, including the connections between them - Method: Functional synthesis); Alternative conceptions (Generate alternative solutions for previously defined functions - Method: Brainstorming, Attribute Listing, Morphological matrix, 635 method, Triz, The Delphi technique, Synthetic Method); Selection of conceptions (the choice of solutions previously generated, to identify which are the ones that better meet the general qualitative criteria - Method: Compliance with the functions, Pugh's Method); Assessment of the selected conceptions (The evaluation must follow a technical and economic nature, verifying the production flows required by the design and its costs - Method: Pugh's Method).

With the purpose of observing the industrial reality, in order to contrast with the analyzed theory, the study starts by exploring information in the field; however, it has with a product focus: the knitting development.

4 Model for Conducting the Conceptual Knitting Design

In order to analyze the systematic that has been applied by the knitting industries in their product designs, a study was conducted in four large knitting producers (called A, B, C and D) that presented a knitting development department (design). The collection used a questionnaire, filled via interviews with workers with more than ten years of experience, responsible for managing the knitting developments.

The questionnaire has 26 questions, containing: (1) 4 questions to identify the company and interviewee characteristics; (2) 18 questions to understand the different phases of this process and how they occur—among these, 6 questions on informational design, 5 questions on conceptual design, 4 questions on preliminary design and 3 questions on detailed design; (3) and 4 questions related to rework during the process and its causes. The objective was to understand how the "Design step" is developed; this step is composed by the "informational, conceptual, preliminary and detailed design", belonging to the Macro phase "Development". Subsequently, the goal was to identify the most critical phase of the project, considering the systematization used in the industry, even without a structured model or script. A detail of this collection is shown in [3]. Analyzing the answers, it was verified that the development of alternatives and their formalization were the most critical steps, because they were not verified in any of the companies. This finding indicated that the conceptual design phase was neglected in the four companies analyzed. A detail of this collection is shown in [3]. Analyzing the answers, it was verified that the development of alternatives and their formalization were the most critical steps, because they were not verified in any of the companies. This finding indicated that the conceptual design phase was neglected in the four companies analyzed. Based on this observation, the systematization for the conceptual phase of the knitting design started, following the previously steps described. In addition to biblio-graphical references and deficiencies found in the analyzed industries, two instructors working in this area contributed to indicate which resources (methods and tools) could contribute to the execution of the activities.

Considering the specific knitting development, the generic model was adapted, taking into account the real needs of the industry. This adaptation is described in the operationalization of each activity that make up the conceptual design, as can be seen in the description below:

- List of requirements: originated from the informational design, it contains the necessary requirements for the product to meet the customer's needs and have a good performance. In the industries that produces clothing knitting, some functional requirements such as protection, comfort, thermal comfort, among others, are already intrinsic to all products. The list of requirements for knitting development should be more technical, preferably indicating units of measurement, thus providing greater assertiveness in development.
- Functional structure: it determines the functions that the product must present, identifying which functions and sub-functions the product must implement to achieve the product requirements defined in the previous activity. Depending on the affinity of these requirements, a function may be sourced from more than one requirement. For knitting developments intended for clothing, it is not necessary to define intrinsic functions, such as, protect the body, accommodate the shape or provide comfort—these are obvious functions. The functions established at this stage may contain indications of raw material or industrial processes in a generic way. The functions for knitting are usually independent, leading to a set of functions to meet a single product. After defining the product functions and sub-functions, the process evolves to determine the principles of solutions.
- Generation of alternatives: This activity can use the "morphological matrix" method to help in the exploration of solutions for each sub-function previously identified, allowing a systematic examination of all the combinations among the different solutions, creating some solutions that meet the global function of the product. This way, the mental processes of a knitting developer are implemented and improved. In the case of knitting development, the principles of solution should be used in the form of a verbal description. In order to generate conceptions of viable products from the morphological matrix, the combination of the different principles of solutions must respect two criteria, called filters. These filters are described below:

    a. Technical compatibility between the principles of solution;
    b. Meet the technical requirements.

- Evaluation and selection of conceptions: The selection of the best conceptions is conducted by using the Pugh's method [44]. In this selection, the conception considered more usual in the knitting shops is used as a reference for the comparison of the other solutions. The following criteria are evaluated:

    a. Compliance with the requirements: the number of product requirements met by the design under analysis is verified, comparing it with the referential design. If the number of requirements met exceeds that of the reference, the symbol (+) is assigned; if it is equal, there is the number (0) and if it is lower, the symbol (−) is assigned;

b. Estimated cost: the estimated cost of the design under analysis is verified, comparing it with the referential design. If the cost is higher than the reference, the symbol (−) is assigned; if it is equal, there is the number (0) and if it is lower, the symbol (+) is assigned;
c. Reliability: it is related to the good performance of the product during a certain time. In this criterion, the useful life of the design under analysis is compared to the reference design. If the useful life is higher than the reference value, the symbol (−) is assigned; if it is equal, there is the number (0) and if it is lower, the symbol (+) is assigned;
d. Appearance: it is related to the visual quality of the product. In this criterion, it was comparing the good image of the conception under analysis to the referential conception. If, according to the evaluators, the characteristics of the design evaluated generate a visual quality superior to that of the reference, the symbol (−) is assigned; if it is equal, there is the number (0) and if it is lower, the symbol (+) is assigned.

- Technical and economic evaluation: The best design previously defined receives a refined technical assessment, taking into account its manufacturing feasibility. Considering the projection of volume to be produced, the productive capacity of the company is verified and, if any process demands outsourcing, it is necessary to verify if other companies are able to meet this demand. The raw material supplier and its delivery capacity is also verified. The costs involved are detailed, in order to verify if it meets the "end product cost" requirement. Since the detailed product design is not yet available, the values established in this phase are subject to variations, for the knitwear is established only at the conceptual level.

This study presents a practical simulation in [3]. The process begins with the list of product requirements, including the "cost", which is the most responsible for rework. From this list, it is determined the functions of the product. The development team should analyze these functions, and then the group proposes some principles of solution for each function. For each function, different principles of solutions were described, generating a matrix of concepts. These solution combinations of the product, respecting the restrictions of compatibility and the compliance with the requirements, which are: Synthetic and elastomeric fibers are not mercerized; The resin application increases the grammage, and does not meet the initial requirements; Mercerization does not provide elasticity; The high degree of tightness decreases the elasticity. From the matrix of concept generation and taking into account the restrictions previously described, it was defining the possible product conceptions.

In order to define the best conception, one of them is defined as a reference (probably, the winner) and compared with the others, in order to identify if other possibilities are better than the one chosen by the group of designers. The best conceptions undergo a technical and financial evaluation, identifying the winning solution and verifying its real manufacturing viability.

With the purpose of testing the systematization in the field, 6 technicians used it in simulated projects, in order to verify the functionality of the proposal [3]. This study verified that all participants found a significant number of functions and principles of solution, indicating that the systematization provides the generation of functions and their respective principles of solution, independent of any experience. However, although the tool conducts the process, the user experience influences the generation of principles of solutions when more skill and knowledge in the area is required. Still, all groups have achieved very close product design results. This way, it can infer the systematization efficiency, by allowing inexperienced technicians to have results similar to those of very high experienced professionals. One group provided a list of raw material data, machine settings and process flows, using approximately 1.5 h to perform the experiment, that is, they did not explore or present principles of previous solutions. This proves that the conceptual step has been neglected in the knitting industries, trying to reach final solutions without exploiting other opportunities. Starting from the product requirements, the developers migrate directly to the detailed project, mentally evaluating alternatives, without producing records. This makes it difficult to transfer experience to new designers, as it can compromise the technical detailing of a given knitwear when a technician, who possesses this knowledge, leaves the company. In any case, the model shows that, in addition to assisting designers with little experience of the conceptual knitting design, it also helps to keep records of the conception evolution and the technical details associated.

5 Conclusion

The review presented about PDP process found that there is little operational systematization to integrate design data with manufacturing process, considering the whole development life cycle. The papers address integration only within specific steps or suggest the use of new technologies to improve design from manufacturing data. There is a lack of methodologies to operationalize the conceptual and preliminary design phases, integrating manufacturing aspects, especially in knitting fabric design [45–47]. So far, knitwear companies continue to rely on the tacit knowledge of some experienced technicians. Recent reviews point to the tendency of incorporate tools of industry 4.0, which could contribute to operationalize the PLM. After all, the data collected in the field could feed and improve mesh designs, contributing to making these data explicit and shared, reinforcing the aims of the PLM proposal [48–50]. Despite this, it was found that few industries in the sector adopt technologies from industry 4.0 and the designs follow dependent from the experience of some employees, without sharing information and without formalizing its development. Based on the field research with four large knitting industries, this study found that the conceptual design phase is ignored in knitting development and that there is no systematics for the PDP process, involving the entire development cycle. This work proposed a systematic for knitting conceptual design, integrating manufacturing aspects. The proposal could use to initiate the design parameters and, in the future, with news technologies, could be improved with manufacturing data, improving the PLM. Through an empirical simulation conducted by a specialist in knitwear development and an assessment simulated by specialists in the knitwear sector, it was found that the proposal allows to generate products with a greater degree of assertiveness when compared without use of the methodology, meeting the customers' needs and reducing manufacturing reworkings. Both experienced specialists and novices were able to obtain satisfactory results following the methodology. However, in a first moment, the model demands a seek for information on raw materials and textile manufacturing processes with experts in these areas. Due to the peculiarity of the textile sector, the same systematization could be adapted for the development of woven fabric, non-woven textile, and yarn, remaining as a suggestion for future studies.

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Management of Laser-Cut Sheet-Metal Part Using Collaborative Robots

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Abstract. Small-medium enterprises (SME) specialized in laser cutting and sheet metal working area join the Industry 4.0 (I4.0) revolution in order to preserve their competitiveness in the global market. This study aims to integrate new I4.0 enabling technologies into the design and implementation of the laser cutting process for sheet metal parts in order to improve the working conditions of the operators, enhance the product quality, and increase the SME's productivity. The paper proposes a human-robot collaborative workspace for the detaching, removing, and disposing of the metal sheet parts after laser cut.

Such activity is typically performed by human operators because it is difficult to automate. Moreover, such activity is always tedious, sometimes dangerous, and often it is ergonomically heavy.

The paper presents a new approach using collaborative robots for the management of sheet metal cut parts, specifically for developing the removing and sorting tasks of the cut sheet metal parts from the blank skeleton. The proposed solution integrates both the design tools, specifically the CAD/CAM environment where the sheet metal parts are modeled and the laser cutting process is defined, and the production tools, which are the Cobots automatically programmed to carry out the sheet metal parts removal. The study proposes both a simulated solution and real case applications.

Keywords: Cobots · Human robot collaboration · Laser-cut sheet metal removal

1 Introduction

SME specialized in sheet metal working are approaching a revolution by following an I4.0 path. The main objective of this trend is to integrate new enabling technologies to improve working conditions and increase the productivity and product quality of the SME. Obviously, the main aim is not to eliminate human intervention for financial purposes only, but mainly to optimize the production process and improve the ergonomics of the human operator workcell.

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The integration of a collaborative robot (cobot) into the working station, where the human operator performs detaching, removing, and disposing of the metal sheet parts after laser-cut, could improve ergonomics of the working condition, shorten the process time of the operator and reduce repetitive tasks of the human operator.

Automation of detaching, removing, and sorting processes of the metal sheet parts after laser-cut can lead to increased productivity and flexibility and reduced setup and tooling costs. Possible automated solutions for loading/unloading processes and for detaching activities metal sheet parts after laser cut are provided by the TRUMPF company [10]. However, existing solutions do not consider human operator interventions. Cobots are one of the enabling tools of the I4.0 [1]. The cobots have a compact shape, they occupy not so much space and can be easily collocated in different positions, rather than a traditional industrial robot. There are not safety barriers around them, because in terms of safety they are provided with some sensors that can immediately and automatically stop the robot if they detect some obstructions or errors.

Human Robot Collaboration (HRC) is a form of interaction between human and robot. In the HRC environment, cobots are intended for direct human-robot interaction, within a shared space of the workplace, or where human and robot are in close proximity. This kind of environment is then more inclined to a combination of human skills and robot skills and the scientific literature provides numerous researches and interesting results.

Authors already analyzed the applicability of the human-robot interaction in SME and the evaluation of the ergonomic risks of the worker during the detaching process using ergonomic assessment worksheet (EAWS) tool [2].

Other researchers proposed an automatic framework for designing the human-robot physical interaction [3]. The operator programs a collaborative robot by demonstrating a task and the robot autonomously performs pick and place repetitive movements after a number of demonstrations. Such research has been demonstrated with a prototype at the laboratory level but its implementation in a real manufacturing scenario is still pending.

To evaluate HRC workstation in different profiles conceptual evaluation framework is proposed by authors [4]. The integration methodologies of cobots to the human workspace to perform collaborative tasks with a human operator in an assembly workcell are proposed by [5, 6]. HRC manufacturing assembly cell is designed and developed in [7]. They proposed a task model approach to plan the collaboration and task execution based on human considerations. HRC prototype system is evaluated for five safety designs and risk assessment is conducted to verify the safety design.

The authors of [8] claim that it is possible to implement and design HRC workcell through lean thinking approach. The proposed methodology is adopted using industrial case studies that are focused on the steps of the HRC design process such as task allocation and scheduling.

In contrast to the above mentioned papers, this research provides a design and integration methodology of cobots to the human operator workcell where a worker performs the detaching, removing and sorting activities for the cut sheet metal parts. Moreover, in a newly designed human-robot workcell, a human operator can perform all tasks through the use of a cobot (UR3) automatically or in collaboration. The study demonstrates the integration of real and simulated tools to the designed human-robot workspace environment. Designed human-robot workstation receives CAD/CAM model from laser cutting machine with all specifications of the laser cutting process of metal sheet. Afterward, in the human robot workstation, a cobot with a special gripper performs detaching of the workpiece components.

The paper is organized as follows: first sheet metal laser cutting process flow is described, then the proposal of the human-robot collaborative workstation to detach metal parts is presented, and finally simulated and real case framework of the automated detaching system and results are discussed.

2 Sheet Metal Laser Cutting Process

The integration of I4.0 technologies and, specifically, the introduction of robotics for the automation of sheet metal laser cutting lines, requires a deep knowledge of the production process.

The laser cutting process in SME is mainly composed of five phases that are roughly illustrated in Fig. 1.

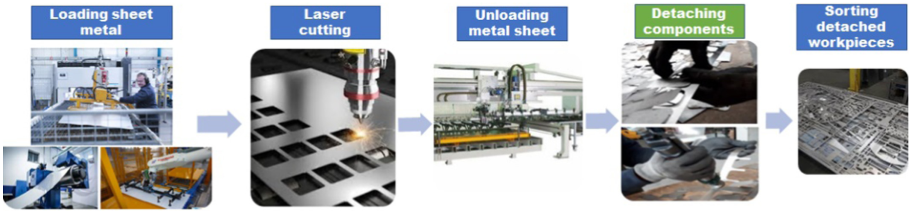

Fig. 1. Laser cutting sheet metal process flow

Loading sheet metal is the first procedure of the laser cutting process as illustrated in Fig. 1. The manual sheet metal loading can be carried out by human operators, but completely automated loading systems are commonly available in laser cut workstations by integrating an automated loading machine and the laser cutting machine. The utilization of industrial robots allows for the appropriate level of flexibility and productivity in sheet metal loading thanks to the reconfiguration of industrial robot tasks.

In the manual loading mode, one or two operators feed the laser cutting machine by putting one sheet metal on the laser machine bed, which is then moved to the laser cutting area.

In the automated loading mode, the metal sheets are stored in a stocking area and an automated system gets the sheet metal and moves it to the laser cutting area.

Laser Cutting. Once the localized heating, melting or vaporizing has started, the machine moves to the area of material removal across the workpiece to produce the full cut. The machine performs the movement either by adjusting the reflective mirrors, controlling the laser cutting head, or manipulating the workpiece. There are three different configurations for laser cutting machines, according to the laser beam control system: moving material, flying optics, and hybrid laser cutting systems.

– *Moving Material.* Moving material laser cutting machines feature a stationary laser beam and a movable cutting surface. The workpiece moves mechanically around the fixed beam to create the necessary cuts. This configuration allows for uniform and consistent standoff distance and requires fewer optical components.
– *Flying Optics.* Flying optics laser cutting machines feature a movable laser cutter head and a stationary workpiece. The cutting head moves the beam across the stationary workpiece in the X and Y axes to produce the necessary cuts. The flexibility of flying optics machines is suitable for cutting materials with variable thickness and sizes, as well as allowing for faster processing times. However, since the beam is continually moving, the changing beam length throughout the process must be considered. Collimation (alignment of the optics) can control the changing beam length, using a constant beam length axis. Adaptive optics or capacitive height control systems are capable of making the necessary adjustments in real-time. This system is the most common one.
– *Hybrid.* Hybrid laser cutting machines offer a combination of the attributes found on moving material and flying optics machines. These machines feature a material handling table that moves on one axis (usually the X-axis) and a laser head that moves on another (usually the Y-axis). Hybrid systems allow for more consistent beam delivery and reduced power loss. Hybrid systems have greater capacity per watt compared to flying optics systems.

Unloading Sheet Metal. As for the loading case, this operation could be done manually or automatically. In Fig. 1, an automated machine that performs both the operations (loading and unloading metal sheets) is presented as an example. Nevertheless, the unloading process is more complex than the loading process because of the number of different parts embedded into the sheet metal and their sorting and storing.

Detaching Components. Detaching process changes according to the presence or absence of micro-joints. The micro-joint is a small uncut area that links the cut part to the blank. The micro-joint prevents the detaching of the cut part from the blank and it facilitates the transportation of the laser cut sheet metal but makes the detaching of the laser-cut parts more difficult. Only the detaching of some reasonable large cross sectional components without micro-joints are automated while the other situations are usually performed manually or with detaching instruments.

Sorting. Sorting is directly linked with the detaching process. After detaching process human operator sorts detached components into the boxes. A manual sorting process performed by the operator is not ergonomically comfortable and automation of detaching process gives the possibility directly automate sorting process as well.

In the next chapter, we focused to develop a human-robot workstation to investigate different ways of detaching process and sorting processes of laser cut pieces since it can be ergonomically improved by integrating enabling technologies of I4.0.

3 Development of Human-Robot Workstation Design

A human-robot workstation has been designed Politecnico di Torino (POLITO) using tools and technologies available at the Laboratory of Economics and Production (LEP). The proposed workstation comprehends a collaborative robot from Universal Robots (UR3), an electromagnetic gripper, a laser-cut sheet metal with dimensions 500 × 500 mm, and stocking boxes.

Collaborative robot UR3 belongs to the CB series with capabilities of a 3 kg payload and a 500 mm extension range from its base. There are other products from Universal Robot that allow more payload and extension due to a more robust mechanical structure (UR5, UR10). UR3 is a 6-axis robotic arm and its workspace is spherical. To identify reachable components it is important to investigate the working area of UR3, which ranges from the 200 mm radius to the 450 mm radius around the robot base, as illustrated in Fig. 2. If the workpiece is located in the unreachable zone the robot arm cannot reach the target workpiece and the removal process fails.

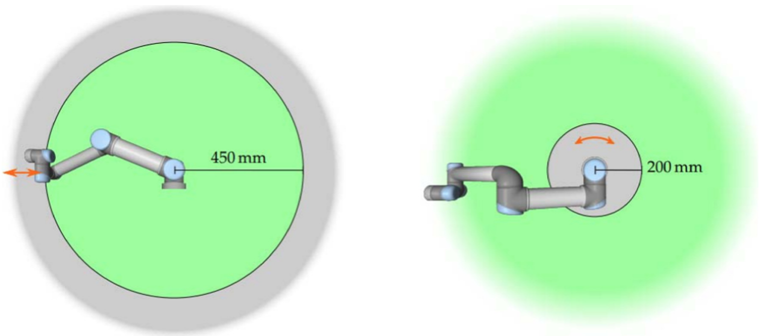

Fig. 2. UR3 working range [9].

Electromagnet Gripper. In order to perform grasping action on the surface of the metal components and to perform detaching actions to remove workpiece components from the metal sheet, a gripper to grasp metal components is required. For the proposed collaborative workstation, we developed an electromagnet gripper as shown in Fig. 3. The electromagnet gripper can be mounted to the existing mechanical gripper RG2 from OnRobot that is installed on the UR3.

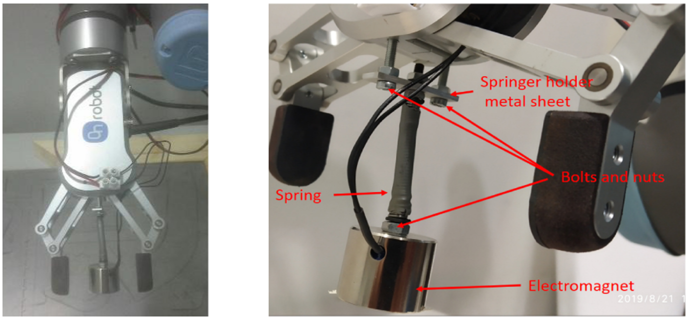

Fig. 3. Mounted electromagnet gripper to the end effector of the UR3.

The laser cut metal sheet has a square geometry with dimensions 500 × 500 mm. There are 7 different shapes for 33 elements in total, but only 27 of these elements will be detached and removed from the blank skeleton and put in the corresponding boxes. In Fig. 4(a) detachable metal sheet parts are colored with white and not reachable parts are colored with red color. Figure 4(b) shows all components on the CAD file, red arrows are reference points of the sheet metal.

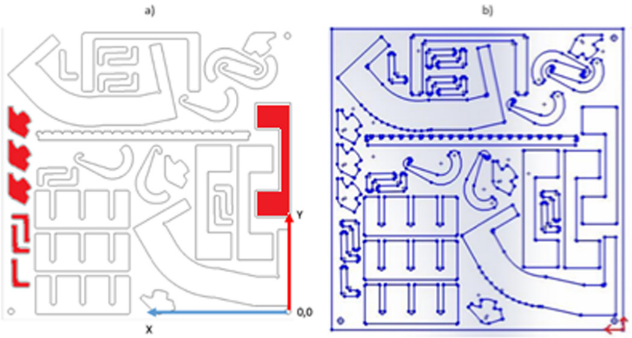

Fig. 4. Laser cut metal sheet: a) not detachable parts are colored with red color; b) CAD view of the metal sheet (Color figure online)

In order to place the metal sheet into the working area of the collaborative robot after the laser cutting process a *supporting system,* shown in Fig. 5, is required. The support system is located in the working area of the UR3. The dimensions of the supporting system are 500 × 500 × 45 mm. The supporting system is made of aluminum profiles with 90° connectors and special bolts to fix the assembled support.

For the sorting processes of the detached components, different *stocking boxes* are designed and integrated into the workspace of the UR3. The stocking boxes serve to store the detached components after the detaching operation. UR3 makes sorting and ordering by placing the components into the boxes.

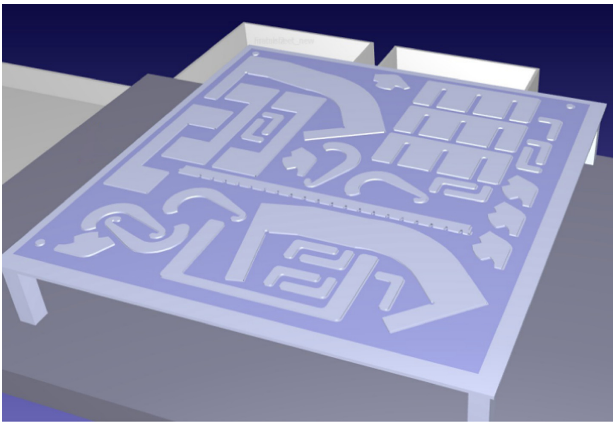

Fig. 5. Supporting system to place sheet metal.

Figure 6 depicts 2D drawings of the human-robot workstation with UR3 reachable area to detach laser cut parts. On the right and downside of the workcell, stocking boxes are located for sorting and placing the detached components.

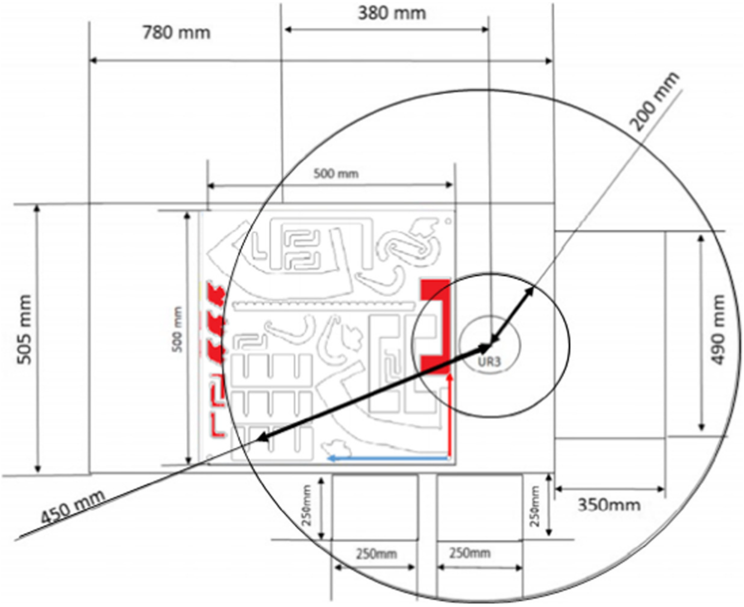

Fig. 6. UR3 with the reachable area and metal sheet on the human-robot workcell.

Figure 7 illustrates a real case human-robot collaborative workstation with all components. The workcell has a supporting table that is dedicated to the metal sheets with dimensions 500 × 500 mm.

Fig. 7. Real case workcell with the automated detaching application.

4 Framework of Automated Detaching System for Laser Cut Sheet Metal Parts

The development of the automated detaching workstation starts with the creation of 3D models for workcell components and their implementation in a simulation environment based on RoboDK software (POLITO has a RoboDK educational license). The simulator gives the possibility to program robots in online and offline modes. The simulation of removal processes requires the identification of the grasping point of each laser cut part available in the sheet metal. Such operation is performed in a CAD environment where the appropriate evaluation of 2D geometry of laser cut parts (mainly center of mass and inertia properties of features in the CAD file) identifies the coordinates of the grasping points. Such coordinates are imported to the RoboDK environment and re-evaluated in order to align the reference frame in the CAD file. The resulting reference frame is located with respect to the UR3 base, thus allowing the identification of the grasping points of the detaching parts according to the reference frame.

The availability of grasping points in the RoboDK simulated environment allows for programming the detaching process of the laser cut sheet metal parts. The simulated detaching process, free of collision and critical situation, can be executed in the real workstation by connecting RoboDK to the UR3 robot using TCP/IP protocol. Such operation compares the simulated process and the real case activity.

The simulation environment manages detaching and removal processes for two different cases: the metal sheet with micro joints and without micro joints.

In both cases, UR3 with electromagnetic gripper moves to the grasping coordinates with respect to the reference frame. Once UR3 reaches the target positions, an electromagnet is activated using digital output (DO[0]) and the gripper attaches the workpiece to the surface of the electromagnet gripper. After detaching the workpiece from the initial positions UR3 with electromagnet gripper places detached workpieces to the indicated boxes according to the size of the boxes and workpieces. The robot detaches the components from the metal sheet until it removes all the reachable components in the metal sheet.

Figure 8 demonstrates the steps for the development of an automated detaching system for laser cut sheet metal parts.

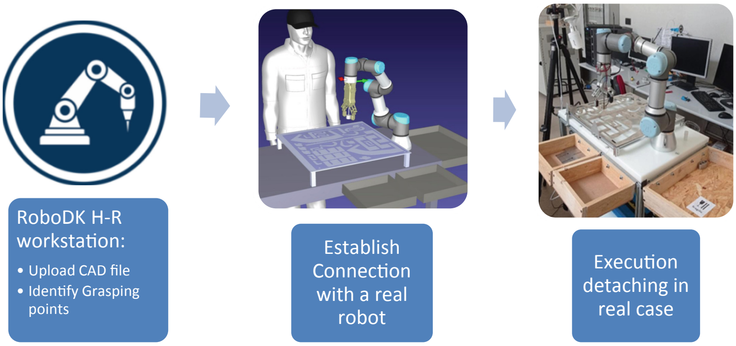

Fig. 8. Proposed framework of automated detaching system for laser cutting sheet metal parts

The default simulation speed is five times faster than in real-time but the ratio can be changed in the simulation environment. When the laser cut sheet metal parts do not have micro-joints, the identification of the grasping point allows for the programming of automated removal and storing process. The UR robot moves the electromagnet to the grasping point, activates the magnetic field, removes the part from the blank, and moves it to the specified box.

Viceversa, parts with micro-joints require a detachment process that separates the part from the blank. The detachment process applies force and torque that cause a fatigue failure of the micro-junction. All three cases are described and analyzed in the next chapter.

5 Case Studies

In this chapter three detaching approaches have been analyzed within the three case studies: Case A: cobot only detaching without micro joints; Case B: cobot and human operator detaching with micro-joints; Case C: cobot only detaching with micro-joints. After each detaching operation, according to the size of the elements, sorting and placing into the stocking boxes have been performed as follows: small piece elements have been programmed to be sorted and placed into the box with dimensions 250 × 250 × 10 mm; medium piece elements into the box with dimensions 250 × 250 × 10 mm and large pieces into the box with dimensions 350 × 490 × 10 mm.

Case A. This case study involves the cobot that picks, detaches and places workpieces attached to the metal sheet with no micro-joints. The main challenge is to evaluate the best grasping point for complex shape pieces since their centre of gravity is outside the cut shape. Normally, for convex shapes, the grasping point coincides with the centre of mass. Contrariwise, the grasping point for the concave shapes is different from the centre of mass (CoM) and it is outside from the cut shape. Figure 9 depicts a convex shape workpiece that has CoM outside the cut shape. For such convex shapes, the methodology is to recompute grasping points by moving alongside the principal axis of inertia, to minimize the torque generated due to the mass of the component itself.

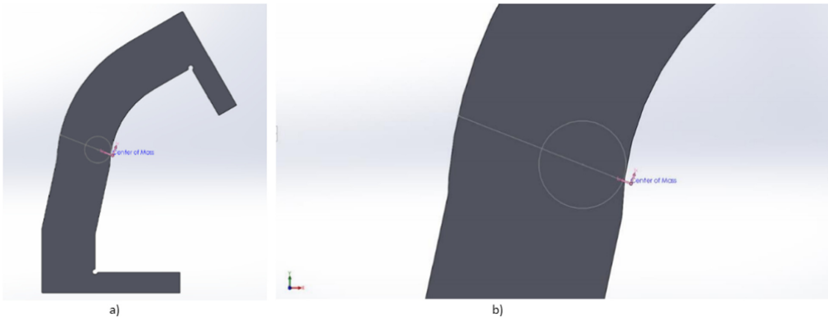

Fig. 9. Convex shape workpiece: a) Center of mass outside the cut shape b) enlarged view

Figure 10 shows CoM (indicated with red "x" sign) and recomputed grasping points (indicated with the circular shape) of the workpieces on the meal sheet. Thus, in this case, cobot receives all grasping points computed on the RoboDK and executes pick and place, detaching and sorting tasks.

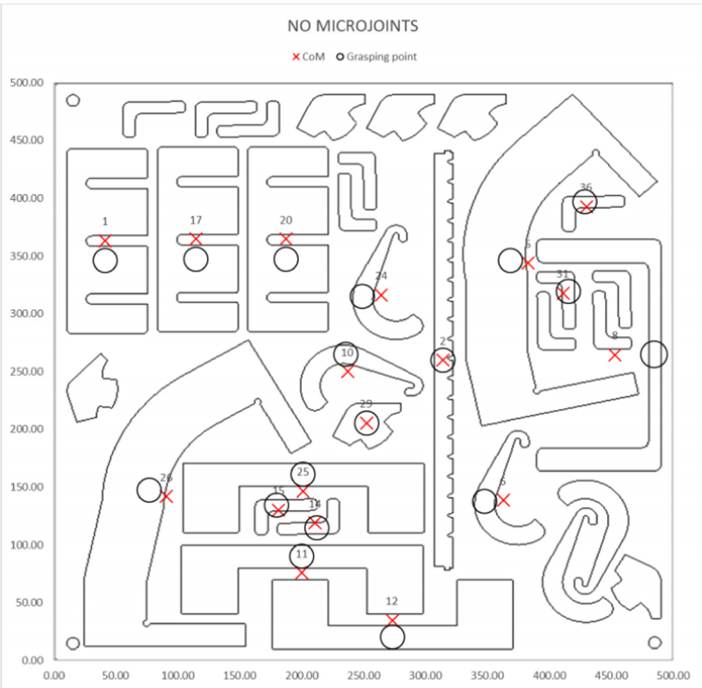

Fig. 10. Grasping points respect to the CoM (Color figure online)

Case B. In the case of B, workpieces have micro-joints, detaching process of the workpieces involves a human operator who collaborates with a robot. In this process, the new grasping points have been calculated with the aim to allow enough space for the operator to push with the finger, thus generating a torque that is used to detach the components. Once the pieces have been detached by the operator, the cobot using a magnetic gripper has to move detached workpieces to the boxes. Figure 11 demonstrates CoM, micro-joints positions and, recalculated grasping points of the cobot and, proposed finger positions for the operator to apply a force.

Fig. 11. Grasping points of the cobot, finger positions of the operator when there are micro-joints on the workpieces.

Case C. Case study C does not involve the operator and the cobot must detach autonomously the pieces attached to the metal sheet by means of the micro-joints. The new set of grasping points has been computed with the aim to maximize the lever arm of the force applied by the electromagnetic gripper with respect to the micro-joint. An oscillatory force is then applied to develop the necessary momentum to break the micro-joint. Figure 12 shows recalculated cobot grasping positions of the workpieces when there are micro-joints. The grasping points have been moved to increase the lever arm and thus the ability to generate a larger torque.

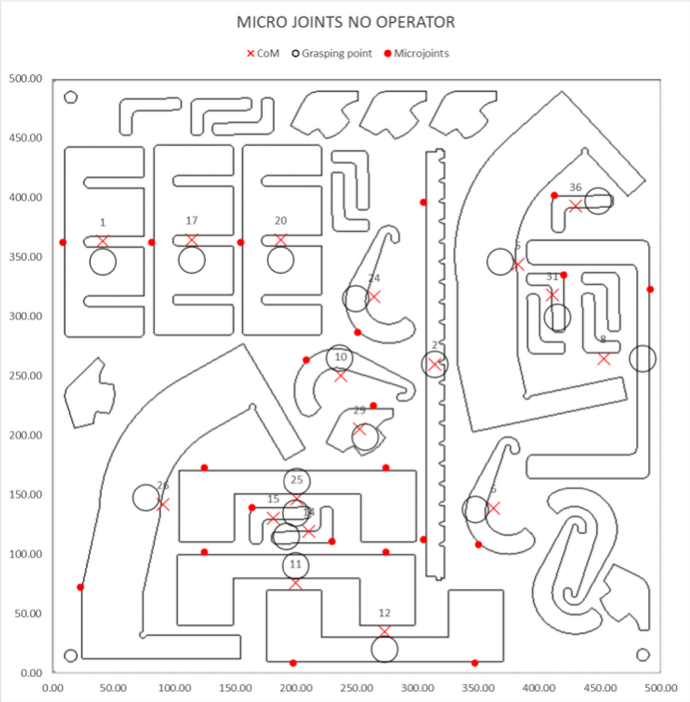

Fig. 12. Grasping points with micro-joints without human collaboration.

6 Results and Discussion

This chapter discusses the results of the three cases of detaching workpieces from the metal sheet after a laser cut. The detaching process was tested in simulation and real case environment that gave the possibility to simulate a workstation and to evaluate the system in real-time through online programming using a collaborative robot and human operator. First, a simulation environment of the workstation has been created and after that, we used online programming from the simulator to the real case application.

In the simulation, grasping points were extracted from the CAD file of the metal sheet and grasping positions sent to the real cobot using online programming. In the simulation and in a real case situation, the reference frame of the metal sheet was placed using a user-defined reference frame that was with respect to the base of the UR3 that helped to find workpiece coordinates on the metal sheet.

In Fig. 13, the simulation results of the three case studies are demonstrated: A) Case A simulation of the workstation where cobot is detaching workpieces without micro-joints; B) Case B where cobot and human operator arm detaching workpiece with micro-joints, human is applying force and electromagnet gripper is holding the workpiece; C) Case C simulation where cobot is detaching a workpiece with a micro-joint is depicted.

In a real case of detaching processes, all the tools and methodologies are combined. As the tool, we used UR3, electromagnet gripper mounted on the end effector of the UR3, human-robot workcell, aluminum support for metal sheet, boxes to place detached

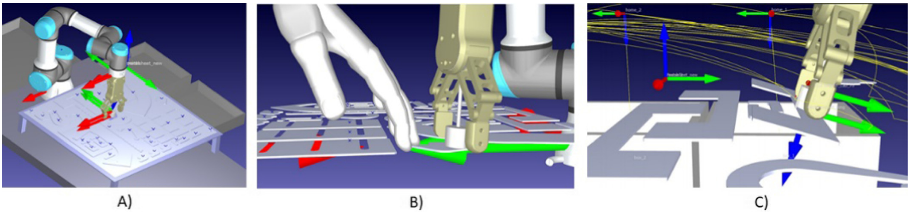

Fig. 13. Three case studies simulation results.

workpieces, and automatic identification of grasping points from CAD file. Figure 14 shows the real-time detaching process of laser cut parts from metal sheet. In Fig. 14a electromagnet gripper is picking the laser cut piece without micro-joint from metal sheet. Figure 14b, 14c, and 14d show the electromagnetic gripper detaching process after laser cut sheet metal parts with micro-joints.

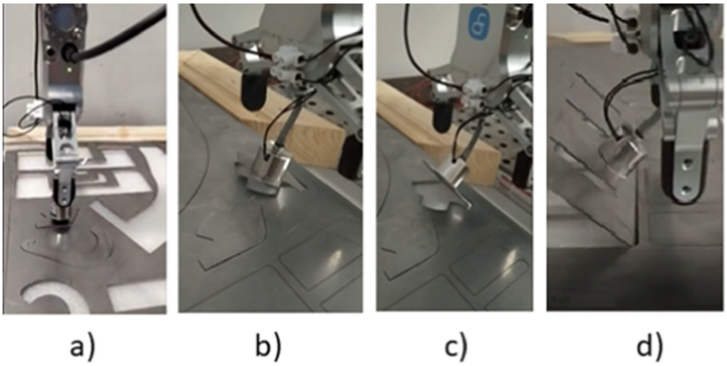

Fig. 14. Real case detaching process

In Fig. 15, the real-time and simulation process time differences of three case studies are presented. The processing time of case A, where cobot detached workpieces without micro joints required only 775.4 s in simulation and 790 s in a real case. For detaching process in case B where cobot and human operator arm detached workpieces with micro-joints required 783.7 and 798 s respectively in simulation and in real cases. Finally, case C required more time to detach the workpieces from sheet metal where simulation process time resulted in 879.2 s and real case processing time was 894 s. Case C time consumption was due to oscillatory force applied to develop the necessary momentum to break the micro-joint.

This study has several limitations, which must be improved in the future:

- A designed workcell area is considered for the metal sheets with dimensions 500 × 500 mm. The working area must be increased for large metal sheets.
- The case study has been tested with one type of metal sheet. It should be tested with different shape parts and different dimensioned metal sheets.

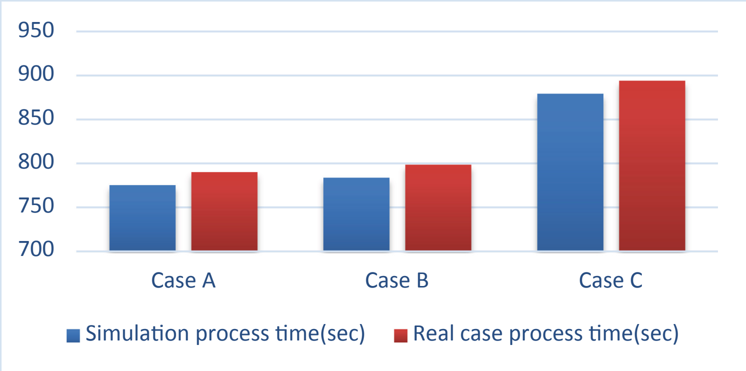

Fig. 15. Simulation and real case process time comparison.

- The study design has been developed in the laboratory level and lacks integration in the real SME production process.
- Custom electromagnetic gripper is used for detaching process. Other grippers such as air suction or other solutions must be tested.

7 Conclusions

This paper demonstrates the applicability of cobot to manage laser cut sheet metal parts within the simulation and real case environment. The developed human-robot collaborative environment is tested in three cases: cobot detaches laser cut metal sheet parts when there are no micro-joints; cobot with a human operator detaching with micro-joint/s; detaching workpieces with micro-joint/s but without cooperation of a human operator and after each task, cobot sorts removed workpieces into the different sized boxes according to their dimensions. The proposed human-robot workcell within the implemented enabling I4.0 technologies can improve the ergonomics of the human operator working station and increase the productivity of the SME. Moreover, such workcell can save the operators time from monotonous tasks. Integrated cobots can handle tasks that require more precision and repeatability and the task distribution between human and robot can reduce stressful activities that affect the wellness of the workers.

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Financial Assistance in a Capital-Constrained Cellphone Supply Chain

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Abstract. In the cellphone industry, some manufacturers may face the problem of insufficient funds in the production process and some retailers can return unsold phones to the manufacturer at a repurchase price. Hence, in this article, we aim to investigate the supply chain operation and financing strategy under a buyback policy in the product lifecycle management of the cellphone. In this supply chain, the manufacturer can obtain money from two sources, one is the downstream retailer's advance payments, the other is the loans from a third-party financial institution. Through modeling, the optimal strategy of the supply chain is determined, and the influence of the deviation between repurchase price and residual value on the optimal strategy of the supply chain is analyzed. The results show that the deviation between the repurchase price and the residual value of the unsold cellphone has an impact on the manufacturer's decisions, and the repurchase price has an impact on the financing equilibrium. Finally, the numerical analysis verifies the results.

Keywords: Supply Chain Management · Capital constraints · Supply chain financing · Residual value · Buyback policy

1 Introduction

Many cellphone enterprises are faced with capital constraints when they make decisions such as purchasing or production and cannot make optimal decisions because of the lack of money. Therefore, they choose financing to meet the needs of business development and enhance the profitability of enterprises. Some enterprises, especially small and medium-sized enterprises (SMEs), often fail to apply for bank loans due to their mortgage assets and the lack of guarantees, which not only affects their development but also affects other enterprises in the supply chain [1, 2]. In the supply chain, if upstream manufacturers face a shortage of money, it will lead to supply disruptions or shortages for downstream enterprises. To address this problem, supply chain finance (SCF) has emerged, which uses the high-quality credit resources of the core enterprises in the supply chain to help SMEs obtain money [3]. In the past few years, SCF services have been widely adopted worldwide. How to use effective financing strategies and solve the problem of capital constraints of manufacturers is important in cellphone research.

Further, cellphone manufacturers introduce new products quickly, resulting in a short product life cycle. Due to the rapid change of client tastes and the existence of many

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unobservable factors, demand is random. If the retailer orders more than the actual market demand, at the end of the selling season there will be unsold stock with residual value, and the retailers can clear excess via the residual value [4]. In this article, we investigate cases where residual values are handled by the manufacturer. We consider a buyback contract, also known as a return contract, which is an agreement at the end of the sale period for the manufacturer to repurchase any unsold inventory from the retailer at a certain price. This contract is common in perishable goods supply chains, which was first proposed by Pasternack [5]. Under the return contract, the risk of uncertain market demand can be shared by the manufacturer and the retailer.

Therefore, this paper studies two kinds of financing instruments, one is an external financing instrument: return support buyer-backed purchase order financing (RSBPOF), and the other is an internal financing instrument: return support advance payment discount (RSAPD) to ease the financial constraints of the manufacturer. RSAPD is a form of cash in advance, to alleviate the financial stress before product delivery. If the retailer is willing to pay in advance, the manufacturer will offer a unit discount on the wholesale price. By paying for products in advance, the downstream enterprise can help the manufacturer produce smoothly or motivate the manufacturer to prepare more inventory to cope with the uncertain market demand in the future. On the other hand, by providing financing loans, downstream buyers can build closer partnerships with key manufacturers. RSBPOF means that a financial institution provides loans according to a reliable buyer purchase order before product delivery. There is no literature on how to solve the problem of supply chain working capital constraints through RSAPD and RSBPOF. Hence, with these two financing ways, our research objective is to investigate the optimal decisions in the cellphone supply chain under some conditions, and our main results are in three aspects: 1) the manufacturer's capacity level and expected profit are affected by the deviation between repurchase price and residual value. The smaller the gap, the higher the capacity level, and the higher the manufacturer's profit. 2) in RSAPD, with a higher deviation, the manufacturer should offer a lower discount rate to the buyer, thus reducing the financing cost and risk.

The rest of this research begins with the literature review in Sect. 2. Two models with RSAPD and RSBPOF are built in Sect. 3. Section 4 analyzes the financing equilibrium. Numerical experiments are carried out in Sect. 5 and Sect. 6 summarizes and concludes the paper.

2 Literature Review

Two literature streams are relevant to the research: SCF and the study on the buyback contract.

Firstly, the closest thing to our work is SCF research. For a long time, operating management and corporate finance research respectively in different directions. The studies of operating management have tended to ignore the corporate usability problem, and the corporate finance research often neglects the operational problems of the enterprise. Few scholars take operations management and financing at the same time into consideration. Joint operational and financial strategies could be used to deal with the enterprise's budget constraints. Recently, there has been a growing emphasis on various financing ways. According to Petersen and Rajan [6], trade credit is the most popular short-term financing for American companies. Trade credit is also widely used in economies with underdeveloped financial markets or weak bank-enterprise relationships [7]. Cai, Chen [8] investigated the relationship between trade credit and bank financing when a retailer faces both budget constraint and demand uncertainty. Zhong, Shu [9] proposed a supply chain network design model with trade credit to optimize system-wise location, transportation, inventory, and financing costs. Yang and Birge [10] theoretically and empirically showed that even when bank and supplier financing can be jointly used, supplier financing is still preferred to bank financing. Alan and Gaur [11] explored the role of inventory in bank financing and trade credit. Tanrisever, Cetinay [12] studied how reverse factoring creates value for each party in the supply chain. Lekkakos, Serrano [13] examined how the adoptions of reverse factoring and traditional factoring affect the inventory policy in a stochastic multi-period setting. Khan, Shaikh [14] presented the impact of early-payment financing on supply decisions for perishable goods and showed the demand depended on price and inventory. Qin, Han [15] investigated the importance of advance payment financing on carbon emission problems. Most SCF studies focus on retailers' capital constraints, with little discussion of upstream enterprises' capital constraints (e.g., [16–18]).

Further, a buyback contract, also known as a return contract, is an agreement at the end of the sale period for the manufacturer to repurchase any unsold product from the retailer at a certain price. The purpose of the return contract provided by the manufacturer is to stimulate the retailer to increase the order quantity and ultimately improve the revenue of himself and the supply chain. Under the return contract, the risk of uncertain market demand can be shared by the manufacturer and the retailer. This contract focuses on adjusting the return price, which is common in perishable goods supply chains, which was first proposed by Pasternack [5] to study sales pricing. The individual rational buyback contract was designed by Devangan, Amit [19] that can coordinate the supply chain when the retailer was faced with the demand related to inventory level. He and Zhao [20] found that the commonly used classic coordination contracts could not coordinate the supply chain, and showed that combining production cost subsidy, an advance-purchase discount contract, and a revenue-sharing contract can effectively coordinate the supply chain. Xue, Hu [21] studied the value of buyback contract by analyzing the supply chain of one manufacturer and two competing retailers and present the effects of uncertainty of demand, level of competition, and processing cost of the contract on the profits of the manufacturers, retailers and the supply chain. This paper is related to the studies on the return contract, however, different from the previous studies, the presence of the residual value is considered, and the effect of buyer return on the two financing ways when using return policy is studied.

3 Models

This study considers a newsvendor framework that a buyer places an order with a manufacturer before the sales period starts. The manufacturer then produces the finished product to meet the retailer's need, and the retailer receives these finished products from manufacturers, sells them to clients, and charges retail prices for each item. The buyer faces a stochastic market demand, and purchases from the manufacturer to meet the demand. The manufacturer provides a return policy for repurchasing unsold goods at the end of the sale period. This in turn stimulates the retailer to order more. In the model, the manufacturer is strapped for cash, and the retailer may run into financial difficulties in financing manufacturers. Without sufficient working capital, the retailer uses RSAPD or RSBPOF to obtain money.

Furthermore, D, $F(D)$, $f(D)$, $\overline{F}(D)$ and $h(D)$ are the uncertain demand, the cumulative distribution function, the probability density function, the complementary cumulative distribution function, and the hazard rate, respectively. Here, $\overline{F}(D) = 1 - F(D)$ and $h(D) = f(D)/\overline{F}(D)$. Let $H(D) = Dh(D)$ represents the generalized failure rate, and the generalized failure rate is shown as $h(D) = Df(D)/(1 - F(D))$. Figure 1 shows the sequence of RSAPD and RSBPOF. The notations are presented in Table 1.

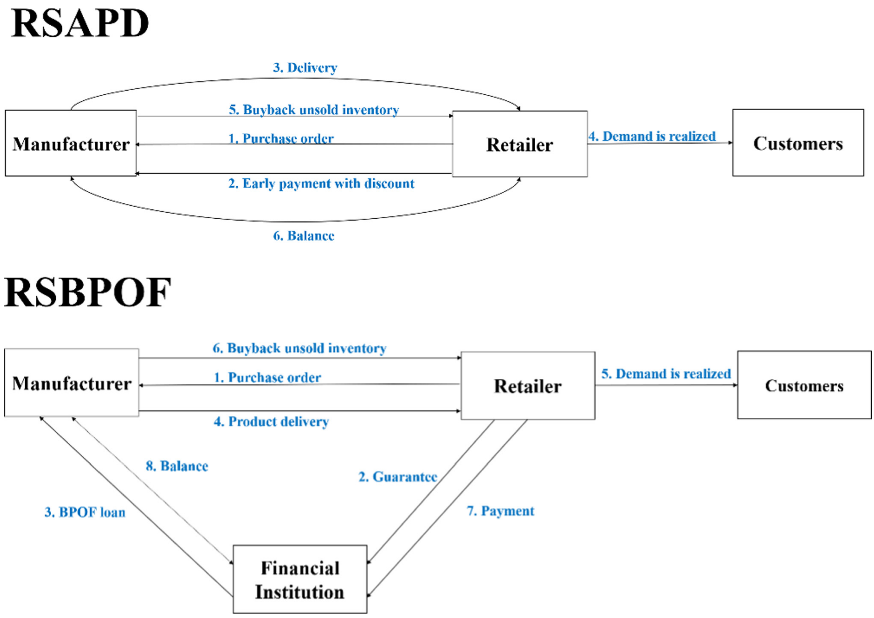

Fig. 1. The sequence of events in RSAPD and RSBPOF.

Table 1. Summary of notations.

Notation	Definition
Π_i	Expected profit
L_i	Short-term debt

(*continued*)

Table 1. (*continued*)

Notation	Definition
A_i	Asset level
p	Selling price
α	Proportional distress cost
γ	Proportional liquidation cost
δ	A portion of financial institution's loss
c_p	Production cost
c_k	Capacity cost
i	Interest rate
s	Residual value
r	Repurchase price
Q	Order quantity
K	Capacity level
W	Wholesale price
D	Discount rate
λ	A portion of purchase order value

3.1 RSAPD Model

In this case, only RSAPD is applied. It is important to notice that there exist unsold inventories, and the upstream manufacturer has the responsibility to repurchase the unsold goods at the repurchase price. In our study, the capital market is imperfect. That is, when the manufacturer fails to pay debts, the manufacturer can either be liquidated or be in an expensive restructuring process. In the case of liquidation, the cost of financial default is a proportion $1 - \gamma$ $(0 < \gamma < 1)$ of firm value. In the case of reorganization, the cost of financial distress is a proportion $1 - \alpha$ $(0 < \alpha < 1)$ of raised capital.

Therefore, the manufacturer's expected profit is

$$\begin{aligned}\pi_m^{bsapd} &= [w(1-d) - c_p]N^{bsapd} - c_k K - (r-s)[N^{bsapd} - D]^+ \\ &-(1-\alpha)[L_s - A_s + c_k K - w(1-d)q]^+\end{aligned} \tag{1}$$

Here $N^{bsapd} = \min(q^{bsapd}, K^{bsapd})$. For liquidation, the optimal capacity $K^{bsapd*} = 0.K^{bsapd*}$ under continuation (C), and K^{bsapd*} under reorganization (R) satisfy $[p - (p-r)F(K^{bsapd*})][1 - h(K^{bsapd*})] = [c_p + c_k + (r-s)F(K^{bsapd*})]/(1-d)$, and $[p-(p-r)F(K^{bsapd*})][1-h(K^{bsapd*})] = [c_p+(2-\alpha)c_k+(r-s)F(K^{bsapd*})]/(1-d)$, respectively:

Under RSAPD, the retailer's expected profit is

$$\pi_r^{bsapd} = p\mathrm{E}\min[D, N] - w(1-d)N + r[N-D]^+ \tag{2}$$

If RSAPD is enough to support the manufacturer's financial needs, the retailer's optimal order quantity q^{bsapd*} meets $(p-r)F\left(q^{bsapd*}\right)=p-(1-d)w$ in continuation and $(p-r)F\left(q^{bsapd*}\right)=p-(2-\alpha)(1-d)w$ in reorganization.

Proposition 1. In RSAPD financing, the deviation between r and s harms the profit of the manufacturer and the capacity level; Moreover,π_r^{bsapd} and q^{bsapd*} are increasing with the repurchase price.

Proposition 1 first proves that the manufacturer's expected profit and production capacity are affected by the deviation between the repurchase price and the residual value when the quantity transported exceeds the customer's demand. Under the return policy, the manufacturer is more inclined to pack fewer goods with high *r-s* to reduce losses. Besides, the retailer's expected profit and optimal order quantity are not related to the residual value of the unsold cellphones, but since the retailer returns the products and the residual value is not processed by the retailer, the retailer's expected profit and optimal order quantity are positively affected by the repurchase price.

Proposition 2. The discount rate d is decreasing with the deviation between r and s.

Proposition 2 indicates that in RSAPD, the larger the deviation between r and s, the smaller the discount rate provided by the manufacturer. In other words, the greater the deviation between the repurchase price and the residual value of the remaining cellphones, the higher the adverse degree to the manufacturer and the greater the risk that the manufacturer takes. Therefore, when return costs are high, the manufacturer should offer lower discount rates and thus lower financing costs.

3.2 RSAPD Model

In RSBPOF financing, the financial institution provides the manufacturer with a loan that is guaranteed from the downstream retailer. We can get the manufacturer's profit:

$$\begin{aligned}\pi_m^{bsbpof} &= (w-c_p)N^{bsbpof}-c_kK-(r-s)[N^{bsbpof}-D]^+ \\ &-\lambda wqi-(1-\alpha)[L_s-A_s+c_kK-w(1-d)q]^+\end{aligned} \tag{3}$$

Here $N^{bsbpof}=\min(q^{bsbpof},K^{bsbpof})$. For liquidation, the manufacturer's optimal capacity $K^{bsbpof*}=0$. Otherwise $K^{bsbpof*}$ satisfies:

$$\begin{aligned}&[p-(p-r)F(K^{bsbpof*})]=[c_p+c_k+(r-s)F(K^{bsbpof*})]/[1-h(K^{bsbpof*})] \quad (C)\\ &[p-(p-r)F(K^{bsbpof*})]=[c_p+(2-\alpha)c_k+(r-s)F(K^{bsbpof*})]/[1-h(K^{bsbpof*})] \quad (R)\end{aligned} \tag{4}$$

Further, the retailer's profit is:

$$\begin{aligned}\pi_r^{bsbpof} &= p\mathrm{E}\min[D,N]-wN+r[N-D]^+- \\ &\int_{\underline{A}_S}^{\tilde{A}_S}\delta\left\{\lambda wq-\gamma\begin{bmatrix}(w-c_p)N-c_kK-(r-s)[N-D]^+\\ -\lambda wqi+A_s-L_s\end{bmatrix}\right\}\phi(A_s)dA_s\end{aligned} \tag{5}$$

The retailer's profit function is concave, and the optimal order quantity is $q^{bsbpof*}=F^{-1}(\frac{p-w}{p-r})$.

Proposition 3. In RSAPD financing, both the profit of the manufacturer and the capacity level decrease with the deviation between the repurchase price and the residual value. The retailer's profit and order quantity are positively related to r.

Proposition 3 holds that the manufacturer's profit and capacity are affected by the repurchase price and residual value. If there is surplus inventory, a higher *r-s* would give the manufacturer an incentive to install less capacity, reducing expected profits. Therefore, the implementation of the return strategy will bring greater risk to the manufacturer. For the retailer, his order quantity and expected profit will be affected by the repurchase price, the higher the repurchase price will encourage the retailer to place more orders, to maximize his profit. It is worth noting that the retailer's order number and profit are not related to the residual value, but only positively related to the repurchase price because all unsold items are bought back by the manufacturer.

4 Financing Equilibrium

After analyzing the two financing methods separately, we will study the financing equilibrium problem under the single financing condition. We assume that if the retailer is unfamiliar with both types of financing, the retailer will prefer RSAPD.

Theorem 3. Under single financing, if the manufacturer's repurchase price is over a threshold μ_r such that RSBPOF is preferred. Here,

$$\mu_r \triangleq \frac{\begin{array}{l} p[\mathrm{E}N^{bsapd*} - \mathrm{E}N^{bsbpof*}] + w[q^{bsbpof*} - (1-d)q^{bsapd*}] \\ + \displaystyle\int_{\underline{A}_S}^{\tilde{A}_S} \delta\left\{\lambda w q^{bsbpof*} - \gamma\left[\begin{array}{l}(w-c_p)q^{bsbpof*} - c_k K^{bsbpof*} \\ -(r-s)M^{bsbpof} - \lambda w q^{bsbpof*} i + A_s - L_s\end{array}\right]\right\}\phi(A_s)dA_s \end{array}}{M^{bsbpof} - M^{bsapd}},$$

where $N^{bsbpof} = \min(q^{bsbpof}, K^{bsbpof})$, $N^{bsapd} = \min(q^{bsapd}, K^{bsapd})$, $M^{bsbpof} = (q^{bsbpof*} - D)^+$, $M^{bsapd} = (q^{bsapd*} - D)^+$. Otherwise, RSAPD is preferred when $r \le \mu_r$ since $\pi_r^{bsapd*} \ge \pi_r^{bsbpof*}$.

Theorem 3 reveals that whether the manufacturer's repurchase price exceeds a certain threshold can determine the retailer's financing decision. The retailer is more likely to use RSBPOF than RSAPD when the manufacturer's repurchase price is extremely high and there is no financial difficulty. This is because high repurchase prices reduce the losses of the retailer and release the financing risks. Therefore, when the unique threshold is lower, the retailer has more incentive to fund the manufacturer with its money (RSAPD financing).

5 Numerical Analysis

In this section, the deviation between the repurchase price and the residual value is investigated on the decisions of the cellphone manufacturer through a numerical study. The benchmark parameter values include $p = \$600$, $\alpha = 0.85$, and $ck = cp = \$100$. Demand is normally distributed, N (1000,100). We allow *r-s* to vary between 0 and 150.

We first investigate how the deviation between the repurchase price and the residual value affects the manufacturer's capacity level and discount rate under RSAPD and RSBPOF conditions. We show these effects in Fig. 2 and Fig. 3. Figure 2 first shows that the manufacturer's capability level is affected by *r*-*s*. Under the return policy, the manufacturer is more inclined to pack fewer goods with high *r*-*s* to reduce losses. When *r*-*s* is relatively small, the manufacturer's capacity level is larger. With the increase of *r*-*s*, the manufacturer's capacity level in RSBPOF decreases, which also makes the manufacturer's profit at a lower level. We can also see from Fig. 2 that the deviation between the repurchase price and the residual value has a greater impact on RSBPOF, and the decline is more obvious, because the wholesale price of RSAPD is lower, and the manufacturer tends to prepare less capacity before shipment. Therefore, to maximize profits, the manufacturer prefers to borrow money by adopting RSBPOF.

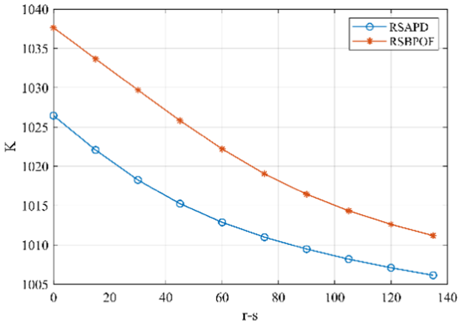

Fig. 2. Impact of *r*-*s* on manufacturer's capacity level.

Figure 3 shows that in RSAPD, the discount rate provided by the manufacturer decreases with the increase of the deviation between the repurchase price and the residual value. When *r*-*s* is relatively small, the discount rate offered is high. And when *r*-*s* goes up, the discount rate goes down. The higher the price deviation between *r* and *s* is, the more unfavorable it will be to the manufacturer. Therefore, in the face of higher return costs, the manufacturer should offer a lower discount rate.

6 Conclusion and Future Research

This study considers a capital-constrained supply chain with a cash-strapped manufacturer selling to an established retailer considering the existence of the residual value under the return policy. To address the financial distress in the product lifecycle management of the cellphone, the manufacturer can use financial institution loans (RSBPOF) and/or the retailer's early payment (RSAPD). In the study, the following research questions can be addressed: In the presence of the residual value, whether the deviation between the repurchase price and the residual value affect the participants' decisions in the supply chain? What is the financing equilibrium of RSAPD and RSBPOF? It is shown that the deviation between the repurchase price and residual value of unsold cellphones affects the manufacturer's capacity level under both RSAPD and RSBPOF and the discount rate

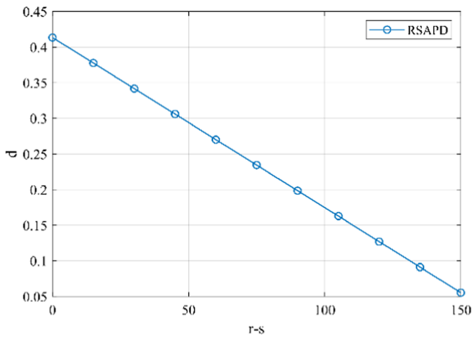

Fig. 3. Impact of *r*-*s* on the discount rate.

under RSAPD. Furthermore, when the repurchase price is above a certain threshold, the only financing equilibrium is RSBPOF. Otherwise, RSAPD should be selected.

In the future, the research work can be divided into two parts, that is investigating other post-shipment financing instruments and exploring a variable residual value on the financing equilibrium in the supply chain.

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Analysis and Modeling the Intersection of Design for X Techniques, Business Strategies and Product Life-Cycle Management

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Abstract. In today's dynamic digitalization environment, companies must continually seek to make improvements while still retaining their current position. This requires the use of new sustainable models that will ensure design efforts, addresses customer and societal needs during the entire product lifecycle phases (PLC). To succeed in improvements Design for X (DFX) requires addressing these issues across multiple factors X's that generates value for each stakeholder in the value chain. However, a variety of DFX techniques have been developed which makes the practitioners and researchers facing great difficulty to decide which techniques to use in which PLC phase to ensure which business strategy. In this respect, the aim of this paper is first to present a review of the most used and applicable DFX techniques to the sustainability dimension and PLC phases. Then, to define the hierarchical structure of the relationships among the identified DFX techniques and to analyze the characteristics power of each one, "interpretive structural modeling" (ISM) and MICMAC are implemented. The proposed framework would be useful for academics and practitioners because it demonstrates the interrelationships of DFX techniques and also offers an additional viewpoint for handling these techniques using the integrated ISM-MICMAC approach. The major implications and limitations are discussed.

Keywords: Sustainability · Design for X · Product Lifecycle Management · Business strategy · ISM · MICMAC

1 Introduction

Globalization and digitalization have been causing a major shift in the global economy in recent years [1–3]. Many companies have sought to improve sustainable product design practices by focusing on not only economic targets but also environmental and social issues [4]. In fact, during the early stages of a project, improvements can be interpreted as opportunities for incremental product development, which can lead to innovation [5]. In this regard, Design For X (DFX) plays a critical role in promoting sustainable product

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design from upstream to downstream operations, among various sustainable product design practices [6, 7]. The DFX techniques are used to enhance product design as well as the design process from the X perspective [8]. Across the year, more than 50 DFX techniques have been evolved beyond manufacture and assembly (DFMA) to the global supply chain (DFSC) with the updated implementation for various domains, taking into account the effect of the environment (DFE), serviceability (DFSv), quality (DFQ), and safety (DFS) in the product lifecycle (PLC) phases [7].

To deal with such issue and motivated by the fact that the PLC phases have a significant effect on the decision on which DFX techniques to use, Arnette et al. (2014) have developed a design for sustainability framework to incorporate the relationship between DFX techniques and PLC phases as well as product differentiation and cost leadership strategies [6]. After that, Benabdellah et al. (2020) provided a relationship between different DFX techniques and PLC phases as well as a classification of them according to common benefits such as the reduction of cost production and variation and defects strategies. The authors have also used the Analytical Hierarchy process to connect DFX techniques with IATF quality attributes to satisfy customers' requirements [3] in automotive industry.

Among the research developed, no paper has been focusing on the relationship between DFX techniques using a multi-criteria decision-making strategy. To fill this gap, this study aims is to look into the contextual relationships between various DFX techniques and prioritize them using the Interpretive Structural Modeling (ISM) methodology. One of the key advantages of using ISM is that it converts the conceptual model into a measurable and organized model that can be used to place and prioritize DFX techniques [9]. Parallel to the use of ISM, other methodologies such as ANP (Analytic Network Process), TOPSIS, and AHP (Analytic Hierarchy process) were considered [10]. Since they are quantitative methodologies that would make the proposed framework more complicated and difficult to reproduce, they were omitted. However, as ISM produces a hierarchical graph, it's necessary to decide which of the DFX techniques have a higher or secondary impact [9]. To do so, MICMAC analysis is used.

The article is organized as follows: Sect. 2 presents basic terminologies needed to prepare the groundwork of this study. Section 3 shows the methodology used in this paper. Section 4 studied the relationships between DFX techniques, PLC phases, and strategies undertaken by companies. Section 5 provided the ISM-MICMAC for DFX techniques. Section 6 illustrates the implications for both practitioners and researchers. Conclusion and future works are drawn in the final section.

2 Research Background

2.1 Product Development Process

In the literature, there is not a unified definition of the product development process (PDP). Thus, an analysis of the different definitions found in the literature shown that "PDP allows making decisions at the right time, to avoid design and manufacturing problems. It can also save time as it avoids backtracking, helps to minimize financial risks through a goal validation system, and increases the chances of getting to market at the right time by controlling development time" [5]. Thus, PDP emphasizes the multi-disciplinary aspect to meet customer requirements. Besides, the implementation of this process is conditioned by the commitment, integration and collaboration of all the different areas of expertise throughout the whole life cycle of a product. In this regard, outside of the Product Lifecycle Management (PLM) approach, PDP cannot be considered [11].

"PLM is about how to organize product development, manufacturing and support in the way that will make your product a first-class citizen" [3]. Several researchers and practitioners have suggested categorizing the product lifecycle into three major categories to follow a clear model of use: the beginning of life (BOL), the middle of life (MOL) and the end of life (End of Life) (EOL) [3, 12, 13]. In this paper, the product lifecycle is categorized into five value chain to BOL, MOL, and EOL (Fig. 1): (1) BOL includes Feasibility, Design, and logistics value chain; (2) MOL includes Service value chain; and (3) EOL includes Reverse logistics value chain.

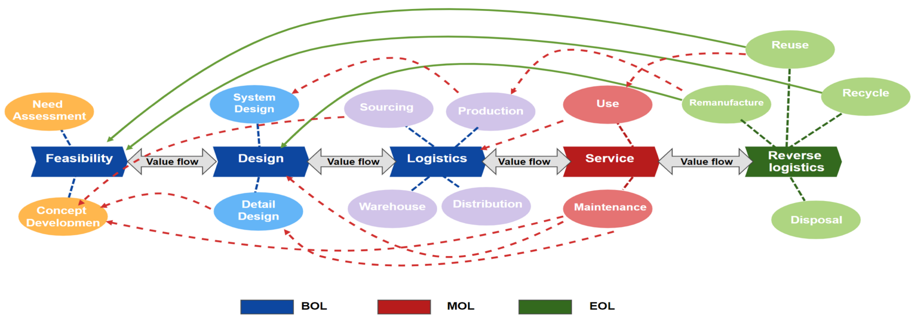

Fig. 1. Value chain of product lifecycle.

In general, the complexity of products is increasing, while the development time and the lifespan of products are decreasing. The design phase, at the start of the product life cycle, appears eminently strategic, and in particular, it's very upstream phases as it involves many experts with different skills [14]. Indeed, it is during this phase, which generally only consumes around 5 to 10% of the product cost, that the vast majority of the characteristics and behaviors of the future product, as well as its production process, are determined and decided. Thus 80% to 95% of the life cycle is practically defined at the end of the design phase, any modification subsequently made to the product to reduce certain costs is particularly expensive or ineffective, or even both [5].

2.2 Design for X

Technological and computing advances have led to a rapidly changing environment in recent decades. In this respect, diverging markets, product and process complexity, digital demand, and cost pressure are the new challenges that companies have to face to compete effectively [7]. However, the reality of the new PDP requires a much more realistic approach by using methodologies to meet the changing of the customer, manufacturers and government regulatory requirements [3, 6]. To deal with these issues, several design techniques have been developed leading to the Design for X (DFX) umbrella term. The specific perspective represented by X refers to a specific virtue or life-cycle phases [3, 7, 8]. Furthermore, the DFX approach is employed to improve product design as well as the design process from the specific perspective represented by X.

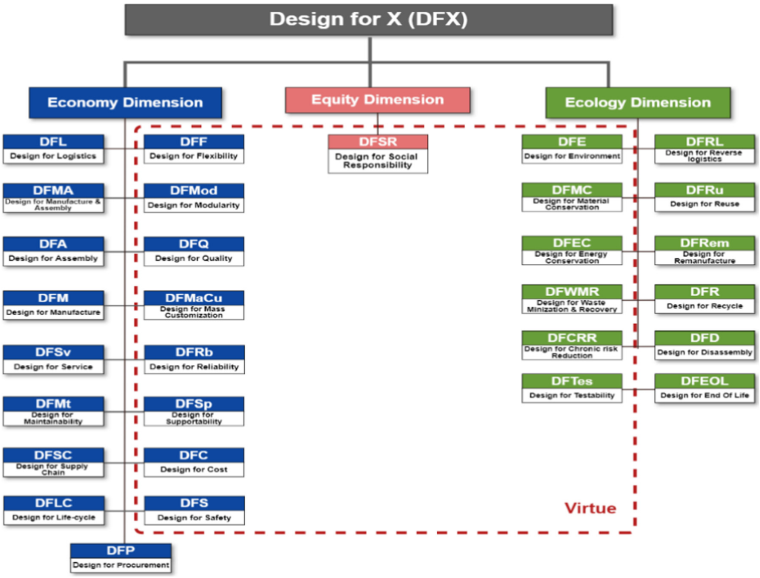

Fig. 2. Design for X taxonomy according to sustainable dimension

The initial "Design for" methods were designed to make the organizational and manufacturing aspects of product development more effective and to minimize costs, time, and mistakes. To proactively handle these production problems, DFX techniques such as "Design for Manufacture "(DFMA), "Design for Supply chain" (DFSC), and "Design for Quality" (DFQ), were developed [7]. After that, Managers, researchers, and engineers recognized that through enhanced product design, many environmental challenges could be reduced, leading to new DFX approaches such as "Design for Recyclability" (DFR), "Design for remanufacture" (DFRem), and "Design for environment" (DFE) [4]. More recently, concerning the equity dimension, other DFX techniques, namely "Design for Social Responsibility" (DFSR) appear to provide opportunities for society [6]. By considering all these integrated DFX techniques, we implement the ideas of the Triple Bottom line and evaluated the sustainability while developing a product. Figure 2 illustrates the main DFX techniques found in the literature from 1980 to 2019 according to the three sustainable dimensions that are economy, ecology, and equity [7]. In terms of the perspectives of the X, which can be a virtue or a lifecycle, the techniques were also classified.

3 Research Methodology

This study aims to establish which DFX techniques are most useful during the design process, as well as the relationships and trade-offs that occur between design decisions made during the different stages of the product lifecycle. Mixed investigative methods are used to answer the research questions (Fig. 3).

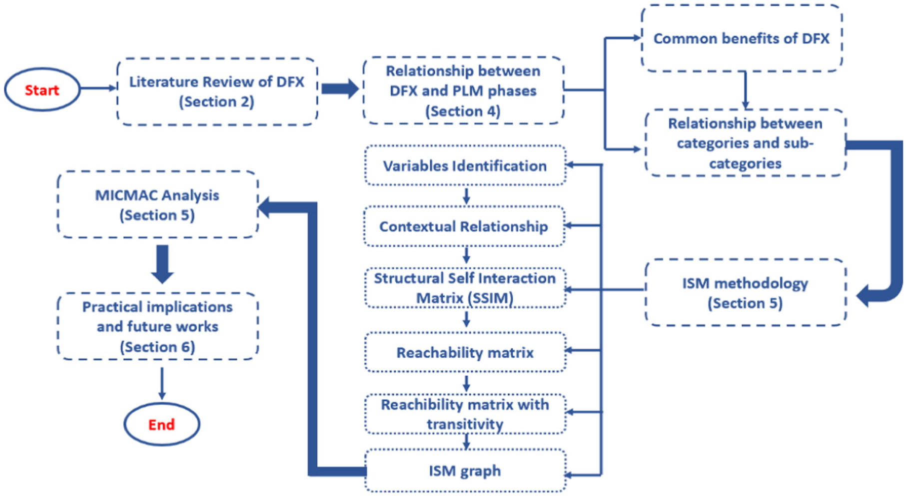

Fig. 3. The methodological process followed in the study

According to the conceptual map, we give first an overview of the main DFX techniques used in the literature from various databases such as Emerald, IEEE, Scopus, Taylor & Francis and Google Scholar (Benabellah et al. 2019). As shown in Sect. 2, we have a plethora of DFX techniques that have been established and proposed over time. Therefore, the questions such as which one to implement in which lifecycle phase need to be answered. To do so, in the second step, the relationship between the DFX techniques and the product lifecycle phases is shown. Third, according to the typical benefits ("Cost leadership" or "product differentiation"), we identify the needed DFX and for the chosen ones, we analyze the potential relationships and trade-offs and determine the principal ones. Through the ISM and MICMAC analysis, the established techniques are deeply evaluated. The goal of using such multi-criteria decision methods is to look at how DFX interact with each other and describe and summarize their contextual relationship in a hierarchical manner. In this regards, five steps are involved:

- Contextual relationships are formed between attributes for which pairs of attributes are examined.
- Structural Self Interaction Matrix (SSIM) is formed, which indicates pair-wise relationships between the DFX techniques under consideration.
- Binary Matrix is obtained first converting the SSIM matrix and a reachability matrix is formed by considering transitivity properties that state that if an attribute A is associated with B and B is associated with C, then A is related to C.

- The reachability matrix is partitioned into different levels and transitive links are removed allowing to obtain a digraph.
- The resulted digraph is converted into an ISM by replacing attribute nodes with statements and it is then checked for conceptual inconsistency.

Once the ISM hierarchical model is obtained, we then use the MICMAC analysis to evaluate the DFX techniques' driver and dependency strength.

4 Classification of DFX Techniques with Product Lifecycle Phases

Research studies have strengthened our understanding of different design problems for more than 30 years and enhanced decision-making processes [3]. For this purpose, several DFX techniques across many disciplines have been developed. In this respect, the decision about which DFX method to apply is directly affected by the phases of the product life-cycle as well as the strategies considered by companies [3, 6]. Concerning the PLM process, some DFX techniques are used in the wrong phase while other ones are not properly implemented [15].

Several researchers have tried to relate DFX techniques with only the design process rather than the entire lifecycle [16, 17]. Other ones have considered DFX techniques that were insufficient and did not recognize the entire lifecycle [6]. Recently, Benabdellah et al. (2020) have categorized more than 37 DFX techniques into product lifecycle phases [3]. Following the same reasoning, Fig. 4 presents a categorization of the most applicable DFX techniques while considering the lifecycle categorization presented in Sect. 2. In addition, to connect DFX techniques to lifecycle phases, there is a need to relate them with adequate business strategies. In general, "a strategy is defined as the business-level decision mechanism that should guide competitive decisions to one product or a family of products" [18]. In this respect, there are two key strategies considered in the literature: (1) "Cost leadership" that aims to minimize cost in the whole PDP; and (2) "Product differentiation" that aims to satisfy consumer needs based on features or service [18]. According to Benabdellah et al. (2020), the strategies are breaking into many sub-categories to better understand them and improve their performance. For the "cost leadership", the business strategy has been decomposed into three sub-strategies that aim at reducing the cost of supply chain, production and ownership [7]. For the "product differentiation", the business strategy has been decomposed into two sub-strategies that aim at reducing environmental effect and variation and defects [7]. By considering the two categories and subcategories and following the same methods as considered by [7], we added three other subcategories such as reduction of barriers to innovation, reduction of failure and lifecycle rate.

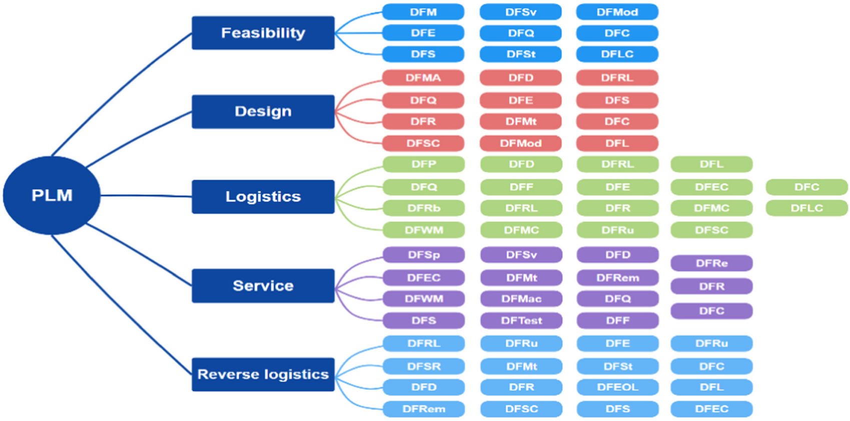

Fig. 4. DFX techniques in product lifecycle phases

For "Cost leadership strategy", as presented in Fig. 5, to decrease the cost of ownership several researchers have adopted DFSv and DFMt [19]. To reduce life-cycle cost, we can adopt DFLC or DFC [20]. To decrease production cost, DFMA and DFP are implemented [21]. Finally, to decrease supply chain costs, researchers and practitioners have adopted DFSC and DFRL [22]. In contrast, for the "product differentiation" strategy, as presented in Fig. 6 to reduce barriers to innovation, we can adopt DFRu [21]. To reduce Failure mode or rates, we need DFTest and DFRel [23]. Besides, to reduce variation and defects, DFQ and DFS can be implemented [24]. Finally, to reduce environmental impact, we can consider DFE, DFR and DFEOL [25].

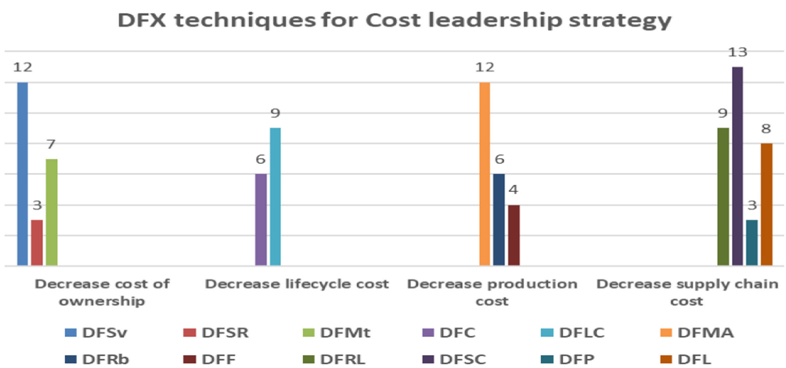

Fig. 5. DFX classification according to cost leadership strategy

However, after classifying DFX according to the PLC phase and then categorizing them in terms of strategy considered by companies, we may argue that the publications vary depending on the methodology and strategy used. In this respect, managing more than 30 DFX is difficult especially when they have different techniques that have the same issues with different names. To facilitate the consideration of these techniques while developing a product, we use a graphic adapted from [3] to understand the relationship between DFX techniques. The broader techniques are depicted as squares while subcategories are represented as circles [3].

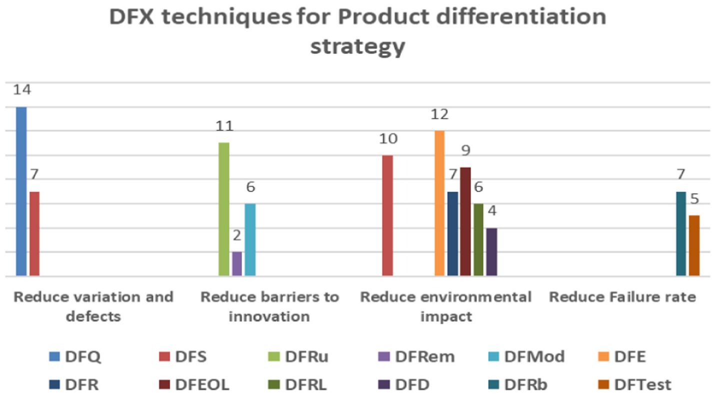

Fig. 6. DFX classification according to product differentiation strategy

Figure 7 illustrated the relationship between the 30 studied DFX techniques. DFSC and DFE, for example, influence each other, so DFMA and DFL are influenced by and have an effect on DFE goals. Based on this analysis, we can argue that instead of considering 30 DFX, we can simply consider the wider categories that are DFMA, DFLC, DFC, DFQ, DFSv, DFSC, DFL, DFS, DFE, DFRL and DFEOL. Design for life-cycle (DFLC) was excluded from the table as many of the other DFX are related to life-cycle phases, making it redundant and design for cost (DFC) was not included as most, if not all other DFX, take cost into account.

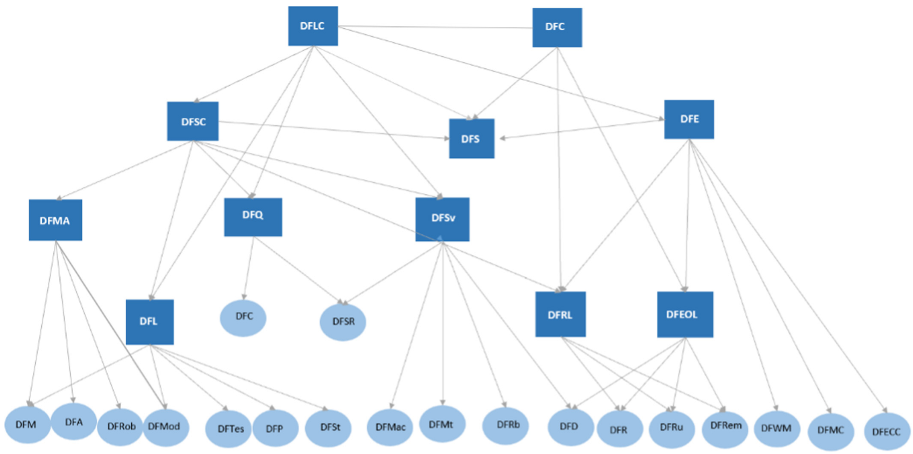

Fig. 7. DFX classification according to product differentiation strategy

In the next section, we are going to present a well-established methodology for the identification of the relationships between the considered DFX techniques using ISM and MICMAC method.

5 ISM-MICMAC Approach for DFX Techniques

ISM was proposed for the first time by J. N. Warfield [26]. It creates interrelationships of unstructured variables based on expert judgment making it a useful technique for defining and summarizing relationships among specific factors [9]. Besides, the basic concept behind ISM is to decompose a structure that is complicated into many subsystems, called elements, using experts' practical experience and expertise to create a multi-level structural model [27]. In this respect, as a common method for evaluating and approaching interrelationship attributes, techniques like AHP, DEMATEL, TOPSIS and DEA can also be used to evaluate multi-criteria decision [10]. However, by considering what makes a strong management operations theory, we can conclude that ISM is a methodology that is parsimonious and generalizable [10]. However, to decide which of the DFX techniques have a higher or secondary impact [9]. To do so, MICMAC analysis is used.

5.1 Data Collection

The ISM approach involves a series of repeated interrogations of a group of experts whose opinions or decisions are of concern. Three experts (Design for Manufacture and Assembly specialist, Project Manager, and consultant and trainer in Quality Management) from various industries have validated all of these measures to create the contextual relationship between the 9 established DFX techniques. In other words, the experts were charged with deciding whether one technique led to another one. They examine and validate also the finding after defining the contextual relationship between the DFX techniques. Once the criteria (DFX techniques) for evaluating the interactions have been listed, the contextual relationship between them must be identified to create the "structural self-interaction matrix (SSIM)".

5.2 Structural Self-Interaction Matrix (SSIM) and First Reachability Matrix

In the development of SSIM and the first reachability matrix, four symbols were used to denote the direction of relationship between the attributes (i and j) [27]. If the technique i affects/reaches/alleviates j, then we note V. In contrast, we note A, if the technique j affects/reaches/alleviates i. If the techniques are not related, then we note O. Whereas when the technique i and j affect/reach/alleviate each other, then we note X. Therefore, once the SSIM is obtained, we transform it into a binary matrix (first reachability matrix) by replacing V, X, A and O with the binary variables (1 or 0). More clearly, the initial reachability matrix (Table 1) is obtained by following these rules. "If the (i, j) entry in the SSIM is V, then the (i, j) entry in the reachability matrix becomes 1 and the (j, i) entry becomes 0". "If the (i, j) entry in the SSIM is A, then the (i, j) entry in the reachability matrix becomes 0 and the (j, i) entry becomes 1". "If the (i, j) entry in the SSIM is X, then both the (i, j) and (j, i) entries of the reachability matrix become 1". "If the (i, j) entry of the SSIM is O, then both the (i, j) and (j, i) entries of the reachability matrix become 0".

Table 1. Initial reachability matrix

No	DFX techniques	1	2	3	4	5	6	7	8	9
1	DFMA	1	1	1	1	0	1	0	1	1
2	DFL	0	1	1	0	1	1	1	1	1
3	DFE	0	0	1	1	0	1	0	1	1
4	DFQ	0	1	0	1	0	1	0	1	1
5	DFSC	1	0	1	1	1	1	1	1	1
6	DFEoL	0	0	0	0	0	1	0	0	1
7	DFS	1	0	1	1	0	1	1	1	1
8	DFSv	0	0	0	0	0	1	0	1	1
9	DFRL	0	0	0	0	0	0	0	0	1

5.3 Final Reachability Matrix and Level Partitions

In the final reachability matrix, the fundamental assumption which is transitivity is used (denoted by 1*). This last state that if attribute A is related to B and B to C then, A is necessarily related to C [9]. Table 2 presents the final reachability matrix for DFX techniques that define the driven and dependence power of each technique. More clearly, the sum of interactions of the technique in the line, is its driving force, while the sum of interactions in the columns, is the dependence power.

Once the final reachability matrix is obtained, to classify the DFX techniques into levels, we organize the elements according to their levels based on their antecedent and reachability index, the reachability matrix is transformed into a canonical matrix format. By doing so, the first level has the max number of the antecedent, once it is established it is removed from the matrix and the process is repeated until the last level is reached. Table 3 presents the final level classification of DFX techniques.

5.4 ISM-MICMAC Proposed Model for DFX Techniques

The structural model is developed using the final reachability matrix. Each element in its level, as well as relations between them, are represented in the digraph [10]. Following that, we removed transitiveness from the model and replaced each ID node with the definition that corresponded to it. Finally, we tested the model for any conceptual inconsistency. Figure 8 shows the hierarchical proposed model for DFX techniques.

Table 2. Final reachability matrix

No	DFX techniques	1	2	3	4	5	6	7	8	9	**Drive power**
1	DFMA	1	1	1	1	1*	1	1*	1	1	**9**
2	DFL	1*	1	1	1*	1	1	1	1	1	**9**
3	DFE	0	1*	1	1	0	1	0	1	1	**5**
4	DFQ	0	1	0	1	1*	1	1*	1	1	**7**
5	DFSC	1	1*	1	1	1	1	1	1	1	**8**
6	DFEoL	0	0	0	0	0	1	0	0	1	**2**
7	DFS	1	1*	1	1	0	1	1	1	1	**8**
8	DFSv	0	0	0	0	0	1	0	1	1	**3**
9	DFRL	0	0	0	0	0	0	0	0	1	**1**
	Dependency power	**4**	**6**	**5**	**5**	**4**	**8**	**5**	**7**	**9**	

Table 3. Level partitions of DFX techniques.

Level partition	DFX techniques	No
I	Design for Reverse logistics (DFRL)	9
II	Design for End of Life (DFEOL)	6
III	Design for Service (DFSv)	8
IV	Design for manufacture & assembly (DFMA)	1
	Design for logistics (DFL)	2
	Design for Supply Chain (DFSC)	5
V	Design for Safety (DFS)	7
	Design for Quality (DFQ)	4
VI	Design for Environment (DFE)	3

According to the proposed hierarchical-based model of the ISM, we can remark that Design for Environment (3) is one of the most important techniques that influence the sustainable PDP. The second is Design for quality (4) and Design for safety (7). The third ones are Design for Manufacture (1), Design for Logistics (2) and Design for Supply Chain (5) which have the same importance and influence. The fourth is Design for Service (8) and the less influential technique to drive design process activity is Design for Reverse logistics (9) followed by Design for End of Life (6). With respect to the obtained results, the effectiveness of PDP should start with the consideration of virtues such as environment, quality and safety because it can affect other techniques such as manufacture, assembly, logistics, supply chain, service and end of life. In addition to that, the relationship between these techniques encompasses the basic principle of the product lifecycle phases, which start with product development and end with product

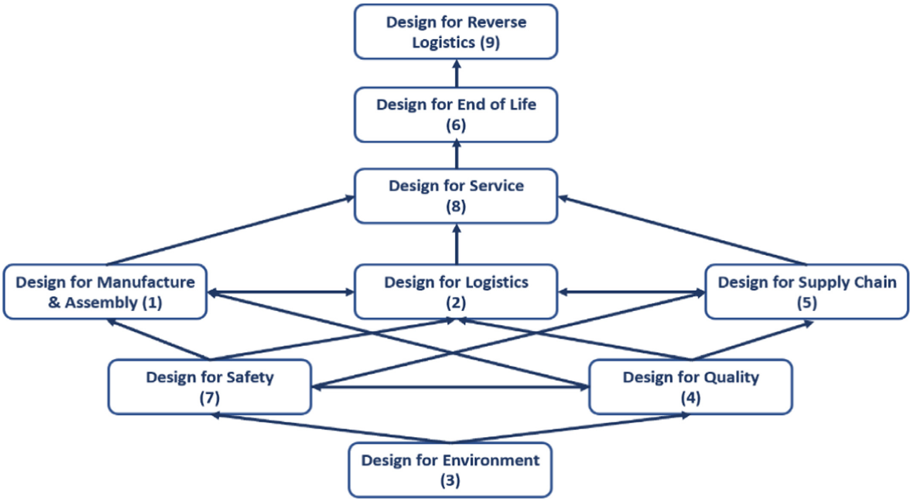

Fig. 8. ISM hierarchical based model for DFX techniques

disposal. Furthermore, to specifically implement DFL or DFMA or DFSC it is essential to drive such technique coupling with both DFS, DFQ and DFE where their outputs affect each other. Similarly, to have a good DFSv, techniques including DFMA, DFL and DFSC should be integrated as their performance is related. Finally, the consideration of the seventh DFX (DFMA, DFL, DFSv, DFE, DFQ, DFS, DFSC) techniques can lead to a sustainable product with the end of life and reverse logistics cost, energy and time-saving. However, in addition to the obtained bigraph, it is important to provide details about the relative importance and interdependence of the various DFX techniques to find a wealth of knowledge. To do so, based on driver and dependency power, MICMAC evaluates each technique using an indirect classification scheme [9].

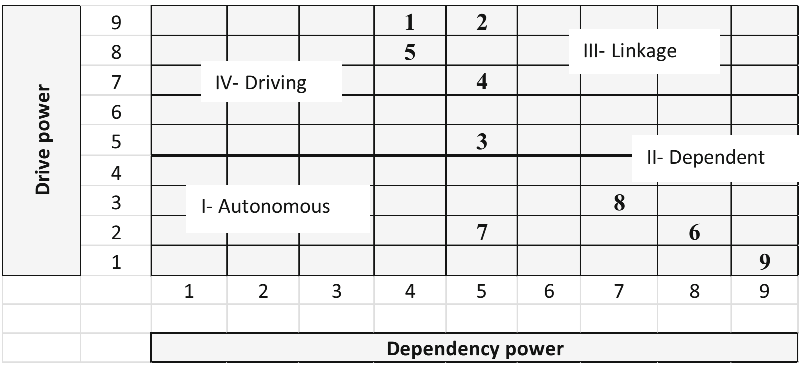

Fig. 9. MICMAC analysis for DFX techniques

Figure 9 shows that there are no autonomous techniques that indicate the importance of the selected DFX techniques for this study. We notice that, as presented in Sect. 4, to choose the prominent DFX techniques, we have categorized more than 30 DFX techniques according to the sustainability dimension. After that, we have presented the relationships between them and the PLC phases. The considered DFX techniques from this step have been also categorized according to strategies undertaken by companies. To more simplify and reduce the number of DFX techniques, we have studied the relation between them and show the categories and subcategories. Among the ninth DFX technique, two techniques (DFMA and DFSC) are falling in the driving quadrant as they are techniques that have a high driving power and low dependency. This means that these techniques need to be controlled and managers and engineers must work hard to deal with them as they are the pillar of the PDP performance. Further, four techniques (DFS, DFSv, DFEoL and DFRL) consist of low driver power and strong dependency power. This means that these risks should be regarded as important techniques because their strong dependence can affect the whole PDP. While the others (DFL, DFQ and DFE) consist of high driving and dependency power. This means that these techniques are unstable and change with regard to different disruptions.

These findings complement the work of Benabdellah et al. (2020) by evaluating not only the most prominent DFX techniques but which technique are more important than other one and which one influence the others [3]. Besides, we indicate the cruciality of each DFX technique to the fourth category of MICMAC analysis. By doing so, the proposed ISM-MICMAC hierarchical model would assist companies' decision-makers in efficiently planning their operations through the PDP. In the next section, key implications for both practitioners and researchers are presented.

6 Practical and Theoretical Implications

In this article, the ISM-MICMAC methodology has been made to expose DFX techniques interdependencies. Managers may use the approach to create a map of the dynamic between different factors in a decision-making process. The pairwise technique analysis in a community of experts from various areas invites input from those who are familiar with the issues being addressed but may not be familiar with all of the relevant issues to the overall PDP. From a theoretical point of view, the proposed model will first decompose complex structures into a multi-level hierarchical model and provide such a fundamental understanding of DFX techniques interrelation and influence. Second, this research offers a thorough overview of the most important DFX techniques for achieving long-term sustainability. Third, it serves as a reference for researchers who are new to DFX techniques to discuss this study and focus on the potential issues. Fourth, this paper contributes to sustainability design by investigating crucial DFX techniques and gaining better insights into economic, environmental, and social studies issues. From a practitioner's standpoint, the current model first will assist decision-makers in understanding the mutual impact among different DFX techniques and their implications for design strategy decisions towards organizational efficiency. Second, by effectively implementing the identified DFX techniques, it can assist managers and designers in focusing their efforts toward achieving high organizational efficiency. Third, it will also assist in achieving sustainability operations and improving the PDP's economic efficiency. Finally, this research represents a major step forward in design research at the intersection of service, safety, quality, assembly, supply chain, reverse logistics and environmental considerations, as well as a wider method of combining these factors.

7 Conclusion and Future Works

Designing a product with various X factors is a complex task that requires a holistic approach. Structural, economic, human, social, and environmental factors must all be addressed. The use of DFX techniques will help a company's competitiveness while lowering environmental and economic risks for a successful, sustainable process in the PLC phases. Several important contributions to the existing body of knowledge to link manufacturing products to sustainable outcomes have been made as a result of this research.

First, this paper contributes in this regard by providing practitioners with a structure for determining which DFX techniques are appropriate for a given product design based on strategy and life-cycle process. Second, it shows the relation between DFX techniques in terms of categories and sub-categories. In this respect, instead of considering all these techniques to achieve sustainability outcomes, we can simply consider the wider categories that are DFMA, DFLC, DFC, DFQ, DFSv, DFSC, DFL, DFS, DFE, DFRL and DFEOL (Fig. 7).

Third, this article uses an ISM-MICMAC approach to examine the interdependencies among DFX techniques to better understand their mutual influences and thus better manage the PDP. This approach aids in understanding the interactions among techniques by using a hierarchical graphical model. Figure 8 shows that Design for Environment (3) is one of the most important techniques that influences the sustainable product development process. The second is Design for quality (4) and Design for safety (7). The third ones are Design for Manufacture (1), Design for Logistics (2) and Design for Supply Chain (5) which have the same importance and influence. The fourth is Design for Service (8) and the less influential technique to drive design process activity is Design for Reverse logistics (9) followed by Design for End of Life (6).

Fourth, combining ISM and MICMAC analysis allows DFX techniques to be classified into four categories: autonomous, linkage, dependent, and independent. As a result, the criticality rating of DFX can be determined based on their direct and indirect dependencies on one another. It has been presented in Fig. 9 that there are no autonomous techniques, while DFMA and DFSC are driving techniques that need to be controlled as they are the pillar of the PDP performance. In contrast, DFS, DFSv, DFEoL and DFRL are dependent techniques that can affect the whole PDP. Finally, the DFL, DFQ and DFE are unstable techniques to different disruptions that affect the PDP.

There are some drawbacks to this paper that provide opportunities for future research. First, the ISM model can be also used in a fuzzy manner to improve binary ISM. Second, the indices are based on expert judgment, the metaheuristic method can be used for data collection to reduce the mistakes of decision-makers and experts. Third, the proposed ISM-based hierarchical model could be verified using Structural Equation Modeling

(SEM). Finally, multi-criteria methods such as fuzzy-AHP, TOPSIS, ANP, and fuzzy-DEMATEL can be used or combined to test the defined techniques, and the results can be compared.

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Methodology to Enhance the Lifetime of Mechanical System by Utilizing Parametric Accelerated Life Testing

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Abstract. To enhance the design of mechanical systems, parametric Accelerated Life Testing (ALT) as a systematic reliability method is proposed as a way to evaluate the design of mechanical systems subjected to repeated impact stresses. It requires: (1) a parametric ALT scheme shaped on system BX lifetime, (2) a load inspection, (3) parametric ALTs with the associated design modifications, and (4) an assessment of whether the revised product design(s) reach the targeted BX lifetime. We propose using a general life-stress model and sample size equation. A test example using both market data and parametric ALT was the redesign of a hinge kit system (HKS) in a refrigerator. To conduct parametric ALTs, a force and moment balance analysis was utilized. The mechanical impact loadings of the HKS were evaluated for an working refrigerator door. For the first ALT, the HKS failure happened in the crack/fracture of the kit housing and oil spilled from the damper when the HKS was disassembled. The failure modes and mechanisms constructed in the 1st ALT were similar to those of the unsuccessful samples found from the marketplace. The missing design parameters of the HKS included stress raisers such as corner roundings and the rib of the housing in HKS, the seal in the oil damper, and the material of the cover housing. In the second ALT, the cover housing fractured. The design defect of the cover housing in the HKS was the plastic material. As a corrective action plan, the cover housing was modified from plastic to aluminum. After the second ALT, the lifetime of the modified HKS was reassured to be B1 life 10 years with a yearly failure rate of 0.1%.

Keywords: Lifetime design · Hinge kit system · Fracture · Parametric ALT · Design defects

1 Introduction

Mechanical products such as automobiles, airplanes, and refrigerators convert some form of power into a mechanical advantages utilizing various mechanisms. Most mechanical products are multi-module structures. If the modules are assembled, the mechanical

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product can satisfactorily function and perform its own planned purposes. For instance, a refrigerator is designed to provide chilled air from the evaporator to the freezer (or refrigerator). It includes various modules – cabinet, door, internal fixture (shelves and drawers), generating parts (motor or compressor), controls and instruments, heat exchanger, water supply device, and other various parts. A refrigerator may have as many as 2,000 parts.

The reliability of a mechanical product might be described as the multiplication of its lifetime, L_B, and failure rate, λ. The entire failure rate of mechanical product such as refrigerator over its lifetime is the grand total of the failure rate of each module. If there were no premature failures in a product, the product lifetime could be decided by problematic designed module #3 in Fig. 2 such as a newly designed HKS examined in case-study in this paper. The refrigerator lifetime is anticipated to beat a B20 life 10 years, That is, the time period that accumulated failure rate becomes 20% is ten years. If a refrigerator consists of 20 units and each unit has 100 components, the lifetime of each unit is targeted to be a B1 life 10 years. In other word, the time period that accumulated failure rate becomes 1% is ten years. We can conduct a parametric ALT for the newly designed mechanical system to potentially identify the design issues (Figs. 1 and 2).

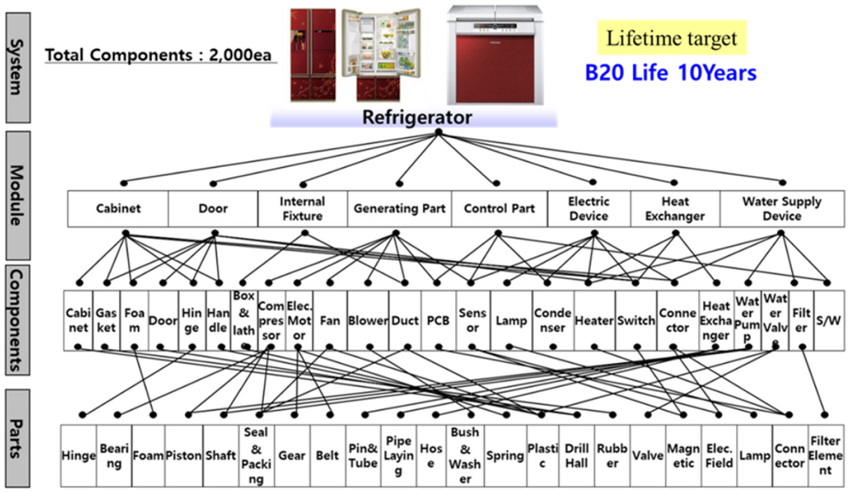


Fig. 1. Classification of refrigerator with multi-modules.

To reduce the failure rate of a mechanical system in the marketplace, it should be designed to robustly endure the working conditions for the consumers who purchase and use it. Any design defects should be identified and altered through statistical methodology or reliability testing [1] before a product is released. However, this approach demands enormous computations for an optimum answer but may not identify the most likely failure. If there are design faults that create an insufficiency of strength (or stiffness) when a product is subjected to repeated loads, the product will fail before its anticipated lifetime due to fatigue.

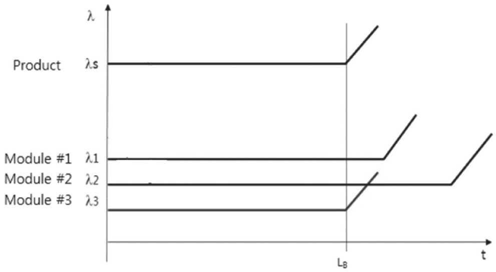


Fig. 2. Lifetime L_B and failure rate λ_S of multi-modules product.

The typical methodologies for identifying failures in a product are stress–strength interference analysis, failure modes, effects, and criticality analysis (FMEA/FMECA), and fault tree analysis (FTA). In the product development process, these analyses are executed and documented by a company's technical specialists. Because the crucial designs of a new product is often missed in reviewing designs, the product can undergo field failures and then have to be recalled. Stress/strength interference models predict why mechanical products fail during a gradual wearout process. It also explains product failure if the stress is larger than the strength. However, because product failure may occur rapidly from fragile parts of a product, it necessitates using complementing design concepts such as fracture mechanics and life-stress model [2].

To execute the optimal design of a mechanical structure, engineers have investigated conventional design perspectives such as strength of materials. A new fracture mechanics study on the crucial components should be include fracture toughness instead of strength as a relevant material attribute. With quantum mechanics advances applied in electronic technology, engineers have identified system failures from micro-void coalescence (MVC), that may appear in metallic alloys or numerous engineered plastics. To determine the failure phenomena of a mechanical product, a better life-stress model might be combined with the traditional design approaches and applicable to electronic parts indentifying a small crack or pre-existing defect that is impractical to model using FEM.

To understand why systems failure in the field, some engineers try to use the finite element method (FEM) to model the components in a system. Many engineers believe that infrequent product failures can be appraised by: (1) mathematical modeling utilizing Newtonian or Lagrangian methods, (2) after getting the system response for (dynamic) loads, the product stress/strain from it obtains, (3) employing the rain-flow counting method for von Mises stress, and (4) approximating thr system damage by the Palmgren–Miner's law. However, employing a systematic method that can produce a closed-form, specific answers would entail making countless assumptions that cannot identify multi-module product failures due to micro-void, contacts, design defects, etc. when subjected to loads.

This work presents a parametric ALT as a systematic reliability method that might be relevant to mechanical systems. It contains: (1) a parametric ALT scheme shaped on product BX lifetime, (2) a load inspection for ALT, (3) a parametric ALTs with the design changes, and (4) an assessment of whether the latest design(s) of the product gets the objective BX lifetime. As an case-study, we will examine the design of a HKS in a domestic refrigerator.

2 Parametric ALT for Mechanical System

2.1 Placing an Comprehensive Testing Plan

Reliability can be manifested as the system potential to run under stated conditions for a specified period of time. Product reliability can be illustrated by a diagram called the "bathtub curve" that is composed of three areas. At the beginning, there is a lessening failure rate in the early life of the product (β < 1). Then, there is a nearly constant failure rate (β = 1). Utimately, there is a growing failure rate at the end of the system's life (β > 1). If a product follows the bathtub curve, it may have difficulties being successful in the field because of the large failure rates and short lifetimes due to design defects. A manufacturer can update the product design by targeting reliability for new products to (1) minimizing premature failures, (2) reduce random failures during the product working period, and (3) enlarge product lifetime. As the design of a mechanical product improves, the failure rate of the product in the market decreases and its lifetime lengthens. For such states, the failure rate can become nearly a straight line (Fig. 3).

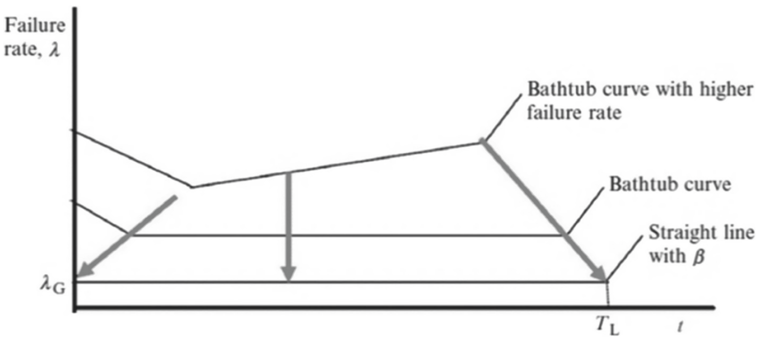


Fig. 3. Bathtub curve and straight line with slope β to the ending of the life of the product

For a constant failure rate, the cumulative failure function of a mechanical product might be evaluated from the product lifetime L_B and failure rate λ as follows:

$$F(L_B) = 1 - \mathrm{R}(\mathrm{L_B}) = 1 - \mathrm{e}^{-\lambda \mathrm{L_B}} \cong \lambda \mathrm{L_B} \quad (1)$$

where R(·) is reliability function, F(·) is unreliability function.

Equation (1) is relevant to ≤20% of cumulative failures, F(·). After targeting the product lifetime L_B, designer should recognize any design defects and alter them through parametric ALT (Fig. 4 and Table 1).

In targetting the BX lifetime of a mechanical system for a parametric ALT, there is (1) a newly designed module, (2) an revised module, and (3) identical module where there is no change to the preceding design. A HKS can be considered as a new module

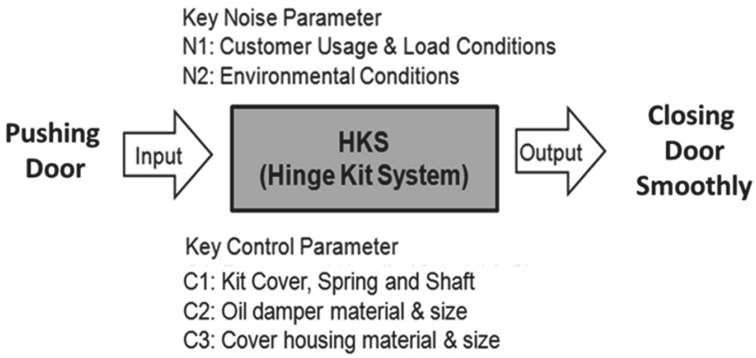


Fig. 4. Robust design schematic of a mechanical system such as HKS

Table 1. Whole parametric ALT plan for a mechanical system – refrigerator (example).

No	Module Name	Market Data, F (BX=1.8)		Design	Conversion	Expected, F (BX=1.8)		Targeted, F (BX=1.0)	
		Yearly Failure Rate, %/year	L_{BX} Life year			Yearly Failure Rate, %/year	L_{BX} Life year	Yearly Failure Rate, λ_G, %/year	L_{BX} Life year
1	Module A	0.34	5.3	New	x5	1.70	1.1	0.10	10
2	Module B	0.35	5.1	Given	x1	0.35	5.1	0.10	10
3	Module C	0.25	7.2	Modified	x2	0.50	3.6	0.10	10
4	Module D	0.20	9.0	Modified	x2	0.40	4.5	0.10	10
5	Module E	0.15	12.0	Given	x1	0.15	12.0	0.15	10 (BX=1.5)
6	Others	0.50	12.0	Given	x1	0.50	12.0	0.45	10 (BX=4.5)
Total	Product (R-Set)	1.79	5.1	-	-	3.60	3.6	1.00	10 (BX=10)

for the refrigerator because consumers desire to close the door softly. Like module A analysed in Table 1, HKSs from the marketplace had yearly failure rates of 0.34% per year and a lifetime of B1.8 life 5.3 years. To respond to customer complaints, a lifetime for the HKS was targeted to be B1 life 10 years.

2.2 Failure Mechanism and Accelerating Testing

Mechanical systems move (generated) power from one place to another by adapting its mechanisms. A HKS is a mechanical system that allows the refrigerator door to be gently closed by using a proper mechanism. A HKS is subjected to repeated stress due to impact loads. If there is a design defect in the structure that creates an inadequate strength (or stiffness) when the loads are applied, the HKS may quickly fail before its anticipated lifetime. After identifying the product failure by a parametric ALT, an engineer can redesign the HKS configuration with a proper material. The HKS can then endure repeated loads over its lifetime so that it can reach the targeted reliability (Fig. 5).

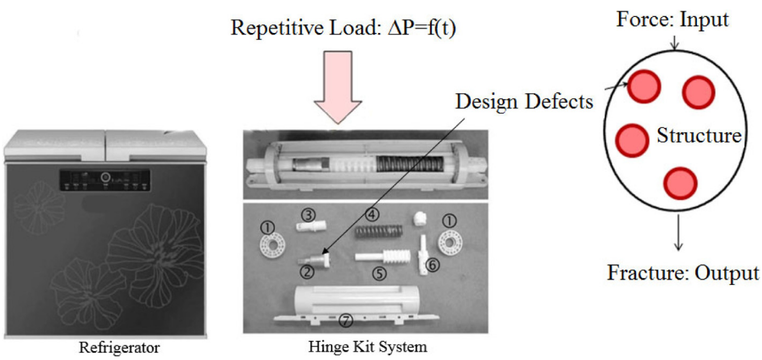


Fig. 5. Failure mechanics on the structure generated by repeated load and design flaws

The most important matter for a reliability test is how a potential premature failure mode can be identified. A life-stress (LS) model of the HKS can be developed which involve stresses and reaction parameters. This model can describe some failures such as fatigue in the mechanical system. Fatigue failure appears, not due to conceptual stresses in a flawless part, but rather due to the existing of a tiny crack or a defect on the exterior of a part that can become plastic by the implied stress. It is important to understand how a small crack or pre-existing material defects may be generated. Because system failures start from the existence of a material defect shaped on a microscopic level, we might eavaluate the life-stress model from such a standpoint. For example, we could adopt processes utilized for solid-state diffusion of impurities in silicon that is widely used as semi-conduct material: 1) electro-migration-induced voiding; 2) build-up of chloride ions; and 3) trapping of electrons or holes.

When electric magneto-motive force, ξ, is exerted, we know that the impurities such as void in a material shaped by electronic movement is effortlessly migrated because the barrier of junction energy is lowered and distorted/phase-shifted. For solid-state diffusion of impurities in silicon, the junction equation J can be expressed as (Fig. 6) [3]:

$$J = B\sinh(a\xi)\exp\left(-\frac{Q}{kT}\right) \tag{2}$$

where B is constant, a is the interval between (silicon) atoms, ξ is the exerted field, k is Boltzmann's constant, Q is energy, and T is absolute temperature.

In contrast, a reaction process that is relied on speed could be stated as [4]:

$$\begin{aligned} K = K^{+} - K^{-} &= a\frac{kT}{h}e^{-\frac{\Delta E - \alpha S}{kT}} - a\frac{kT}{h}e^{-\frac{\Delta E + \alpha S}{kT}} \\ &= 2\frac{kT}{h}e^{-\frac{\Delta E}{kT}} \cdot \sinh\frac{\alpha S}{kT} \end{aligned} \tag{3}$$

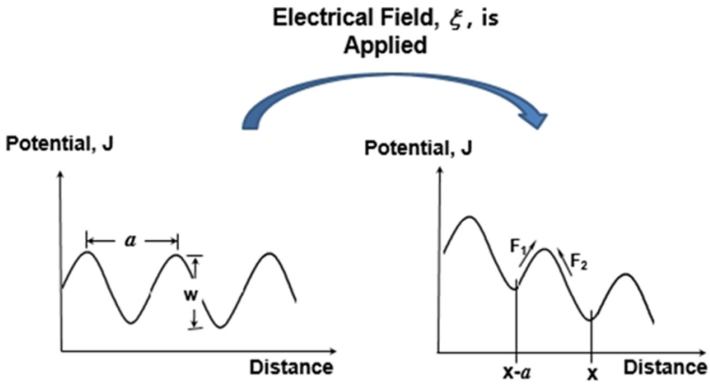


Fig. 6. A potential (barrier) change in material for electron/void migration after electric magneto-motive force is applied.

So the reaction rate, K, from Eqs. (2) and (3) can be simplified as:

$$K = B\sinh(aS)\exp\left(\frac{E_a}{kT}\right) \tag{4}$$

If Eq. (4) takes an inverse function, the generalized life-stress model might be stated as

$$TF = A[\sinh(aS)]^{-1}\exp\left(\frac{E_a}{kT}\right) \tag{5}$$

The hyperbolic sine stress term grows the stress as follows: (1) initially $(S)^{-1}$ in low stress effect, (2) $(S)^{-n}$ in medium stress effect, and (3) $\left(e^{aS}\right)^{-1}$ in high stress effect. Because ALT will be executed in the medium stress range, Eq. (5) is stated as follows (Fig. 7):

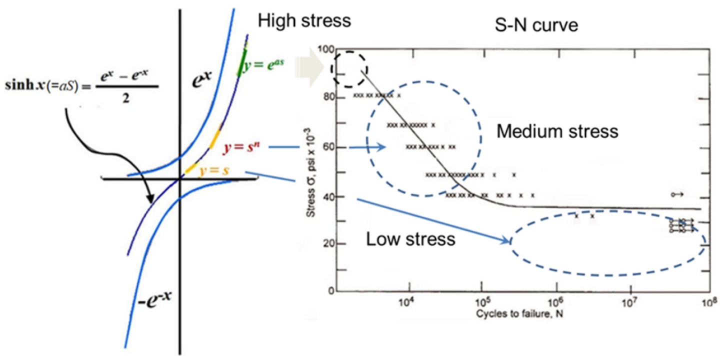


Fig. 7. Hyperbolic sine stress term versus S-N curve.

$$TF = A(S)^{-n} \exp\left(\frac{E_a}{kT}\right) \tag{6}$$

Because the stress of a mechanical system is hard to measure in testing, we need to redefine Eq. (6). When the power is expressed as the multiplication of effort and flows, stresses may come from effort in a multi-port system. Equation (6) can then be ststed as the more general form:

$$TF = A(S)^{-n} \exp\left(\frac{E_a}{kT}\right) = A(e)^{-\lambda} \exp\left(\frac{E_a}{kT}\right) \tag{7}$$

Design defects in products can be attained by exerting larger forces under elevated conditions. From the time-to-failure in Eq. (7), an acceleration factor (AF) can be stated as the proportion between the proper elevated condition levels and common condition levels. AF can be stated to integrate the effort ideas:

$$AF = \left(\frac{S_1}{S_0}\right)^n \left[\frac{E_a}{k}\left(\frac{1}{T_0} - \frac{1}{T_1}\right)\right] = \left(\frac{e_1}{e_0}\right)^\lambda \left[\frac{E_a}{k}\left(\frac{1}{T_0} - \frac{1}{T_1}\right)\right] \tag{8}$$

2.3 Parametric ALT for Mechanical Systems

Sample size equation with the AF in Eq. (8) would be stated as [5]:

$$n \geq (r+1) \cdot \frac{1}{x} \cdot \left(\frac{L_{BX}^*}{AF \cdot h_a}\right)^\beta + r \tag{9}$$

The lifetime of the new HKS was targeted to be B1 life 10 years. Based on the customer usage conditions, the mission cycles of the product were studied. Under the worst case, the number of required test cycles could be estimated from Eq. (9) for the assigned samples. ALT equipment could then be performed on the basis of the observed loads on the product. In parametric ALTs, the missing design defects of HKS could be identified to attain the lifetime target – B1 life 10 years.

2.4 Case Study: Improving the Lifetime of the HKS

When a consumer uses the door in commercially produced refrigerator, they usually want the door to close comfortably. For this (intended) function, the HKS should be designed to endure the working conditions subjected to it by the consumers who purchase and use the refrigerator. The principal parts in a HKS consists of a kit cover, shaft, spring, and oil damper, etc. (Fig. 8).

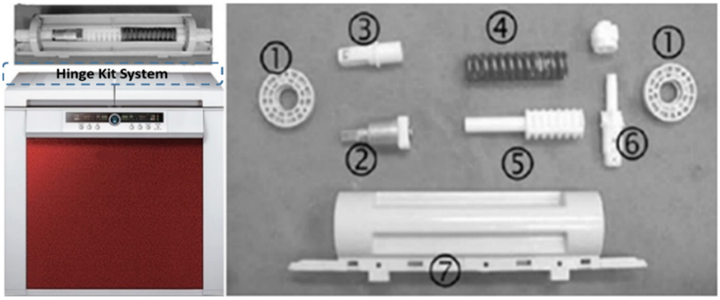


Fig. 8. Domestic refrigerator and HKS parts: kit cover ①, oil damper ②, fixed cam ③, spring ④, cam ⑤, shaft ⑥, and HKS housing ⑦

In the marketplace, the HKS parts in refrigerators were failing due to repeated loading under unidentified consumer operation conditions. When data from the marketplace were examined, it appeared that the HKS in the refrigerators had structural design defects, including sharp corner angles and not enough enforced ribs resulting in high stress concentrations. These design flaws, integrated with the repeated impact loads on the HKS, could create a crack in the part and produce a failure in the system (Fig. 9).

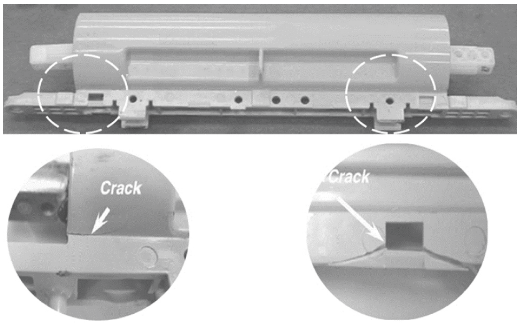


Fig. 9. Products damaged from the marketplace

The closing function of the HKS included several mechanical structural parts. The HKS was often subjected to repeated mechanical impact loads when the consumer closed the door. Door closings required straightforward mechanical procedures: (1) the customers opened the door to take out or store food, and (2) they then closed the door by force.

Thus, the HKS were subjected to various loads during the functioning of the refrigerator door. To identify the required AF, it was crucial to determine the forces on the HKS during the operation of the door. Because the HKS was a comparatively simple mechanical structure, the forces impacting the HKS could be modeled with a force-moment equation. As the customer opened or closed the refrigerator door, the stress due to the door weight was concentrated on the HKS (Fig. 10).

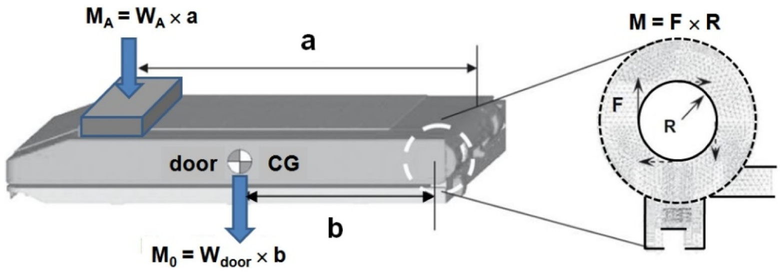


Fig. 10. Design concept of HKS

The moment balance around the HKS can be defined as

$$M_0 = W_{door} \times b = T_0 = F_0 \times R \tag{10}$$

The moment balance around the HKS under ALT condition can be defined as

$$\begin{aligned} M_1 &= M_0 + M_A = W_{door} \times b + M_1 \times a \\ &= T_1 = F_1 \times R \end{aligned} \tag{11}$$

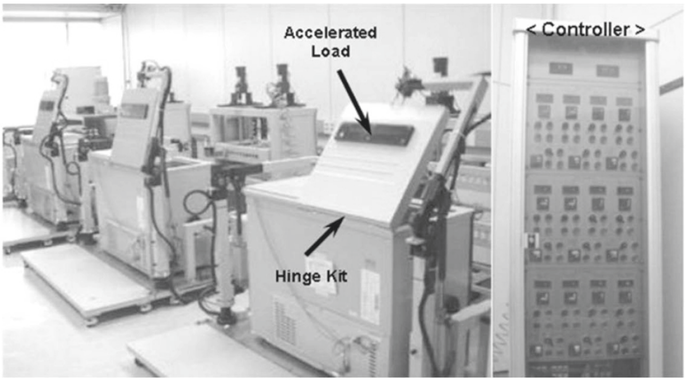
F_0 is the impact force in usual conditions and F_1 is the impact force in the ALT. The stress on the HKS relied on the applied impact due to the elevated weight. The life-stress model (LS model) in Eq. (8) can be restated as

$$TF = A(S)^{-n} = AT^{-\lambda} = A(F \times R)^{-\lambda} \tag{12}$$

The AF can be stated as

$$AF = \left(\frac{S_1}{S_0}\right)^n = \left(\frac{T_1}{T_0}\right)^\lambda = \left(\frac{F_1 \times R}{F_0 \times R}\right)^\lambda = \left(\frac{F_1}{F_0}\right)^\lambda \tag{13}$$

The working conditions for the HKS in a refrigerator were a temperature between 0 °C and 43 °C, relative humidity varying from 0% to 95%, and 0.2–0.24 g's of acceleration. The opening and closing of the door ocurred approximately 3 to 10 times per day. With a life design cycle for 10 years, the lifetime of HKS was about 36,500 usage cycles for the worst case.



(a) ALT Equipment (b) Controller

Fig. 11. Design concept of HKS

For this scenario, the impact force around the HKS was 1.10 kN which was the anticipated greatest force exerted on the HKS by a user. For the ALT with an accelerated weight, the impact force on the HKS was 2.76 kN. Using a cumulative damage exponent, λ, of 2.0, the AF was established to be roughly 6.3 in Eq. (13).

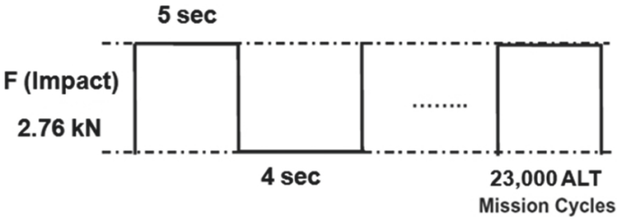
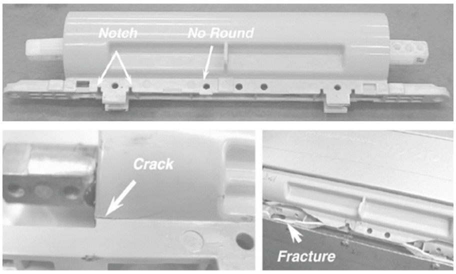


Fig. 12. Duty cycles of the repeated impact load F on the HKS.

For the lifetime target – B1 life 10 years, the test cycles for sample six pieces using Eq. (9) were 23,000 cycles for a shape parameter of 2.0. This parametric ALT was designed to ensure a B1 life 10 years with a 60% confidence level it would fail less than once during 23,000 cycles. Figure 11 shows the test facility of the ALT with equipment for evaluating the durability of the design of the HKS. As seen in Fig. 12, repeated stress caused by the on/off duty cycles allow for the evaluation of the impact on the HKS life. The control console was used to operate the testing apparatus. It ran the number of tests, the testing time, and the starting/stopping of the equipment. As the start button on the controller keypad was pressed, the simple hand-shaped arms could grasp and lift the refrigerator door. As the door was closing, it could apply to the greatest mechanical impact force necessary to reproduce the accelerated load in the HKS (2.76 kN).

3 Results and Discussion

Figure 13a and 13b show the failed product from the marketplace and the failed from the 1st ALT, respectively. In the 1st ALT, the housing of the HKS fractured at 3,000 cycles



(a) Failed products from the marketplace (b) Fracture after first ALT

Fig. 13. Failed products from the marketplace and fracture after 1st ALT.

and 15,000 cycles. As shown in the picture, the tests affirmed that the HKS housing had a fragile structure near the notch because there were high stresses produced at the sharp edges where it failed. The defective shape of the 1st ALT was very similar to that of the returned product from the marketplace. Figure 14 shows a graphical representation of the ALT consequences and market data on a Weibull plot. With similar repetitive stresses, the failure patterns manifested in 1st ALT and field were similar. When the shape parameter was originally approximated at 2.0, it was affirmed to be 2.1 from the Weibull plot of the first ALT.

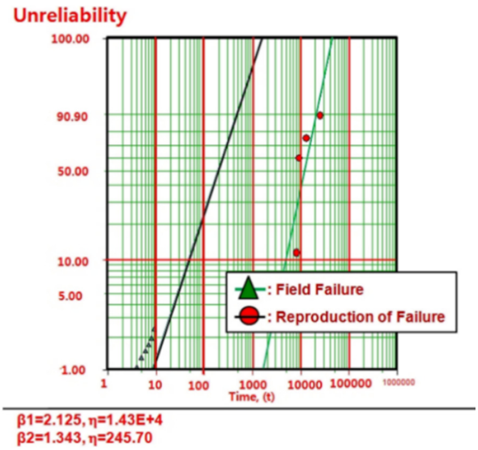


Fig. 14. Field data and results of ALT on Weibull chart.

Based on the test results and Weibull plot, the parametric ALT was justified because it identified the design defects that accounted for the failures in the marketplace. This systematic method helped in identifying the problematic designs found in failures from the marketplace. These failures determined the lifetime of the product.

When taking apart the HKS for examination, the oil damper in the HKS was found to leak at 15,000 cycles (Fig. 15). With the repeated impacts of the HKS in combination with its structural design defects, the HKS housing fractured and the oil damper leaked. Based on a finite element analysis, the concentrated stresses of the housing HKS was

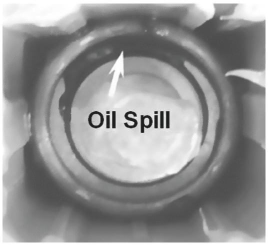


Fig. 15. Spilled products after 1st ALT.

about 21.2 MPa. The stress raisers in the high stress areas originated from design defects such as sharp corners/angles, poorly enforced ribs, and housing notches.

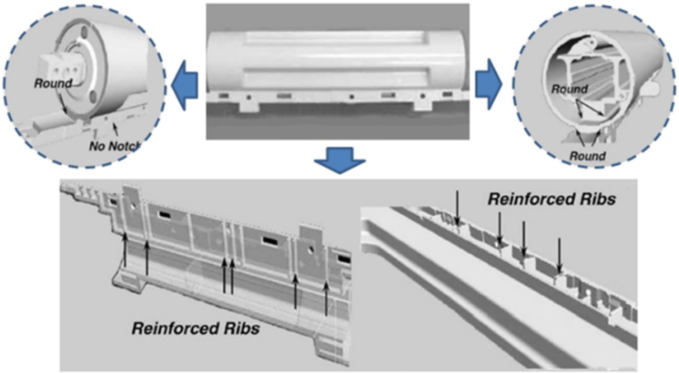


Fig. 16. Redesigned HKS housing structure.

The corrective action plans for the fragile HKS housing included making fillets, adding enforced ribs, and rounding the notches on the housing of HKS (Fig. 16). Upon executing the new designs, the stress concentrations in the housing of HKS were reduced from 20.0 MPa to 10.5 MPa. Thus, a corrective action plan had to be prepared at the design phase before manufacture.

When the spilled oil damper was investigated, the sealing structure in the oil damper had a 0.5 mm gap in the O-ring/Teflon/O-ring assembly. Due to the impact of the door closings, this sealing structure with the gap leaked for first ALT. With the corrective action plan, the sealing structure of the reformed oil damper was modified to have no gap between the Teflon/O-ring/Teflon (Fig. 17).

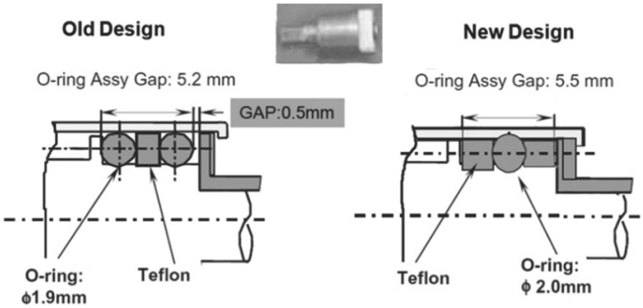


Fig. 17. Reshaped oil damper.

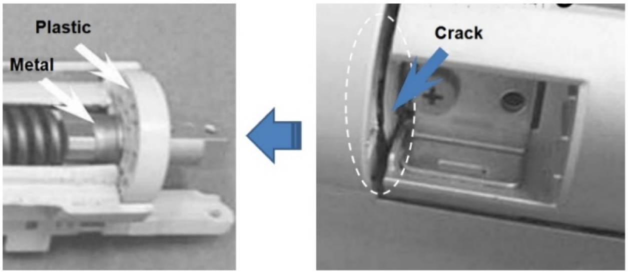


Fig. 18. Structure of problematic products at 2nd ALT.

The altered HKS produced more than the lifetime target – B1 life 10 years. The affirmed values of AF and β in Fig. 14 were 6.3 and 2.1, individually. The recomputed test cycles in Eq. (9) were 24,000 for sample six pieces. To evaluate the design flaws of the HKS, second ALTs were performed. In the second ALTs the fracture of the hinge kit cover ocurred at 8,000, 9,000, and 14,000 cycles (Fig. 18). The root cause of these fractures originated from striking the cover housing (plastic) by the support of oil damper (aluminum). As a corrective action plan, the material of the cover housing were changed from plastic to an Al die-casting. The final design of the HKS could endure the high impact load during operation of the door.

4 Conclusions

To enhance the lifetime of a newly designed mechanical system such as HKS, we have proposed a parametric ALT as a systematic reliability method that incorporates: 1) a parametric ALT plan, 2) a load examination, 3) a parametric ALTs with design alterations, and 4) an assessment of the last design needs of the HKS to assure they were fulfilled. A HKS in a refrigerator was investigated as a case study.

(1) Based on the products that failed both from the marketplace and in 1st ALT, the failure of HKS happened in the fractured HKS housing and oil damper spilling. The design defects of the HKS were the oil sealing structure and the HKS housing

that was caused from the concentrated stress due to inappropriate fillets, ribs, and notching. The corrective action plans were the alterations of the HKS housing and the redesigned sealing structure in oil damper.

(2) Based on the 2^{nd} ALT, the fracturing of HKS happened in the cover housing. The design flaw of the HKS was the material of cover housing. As a corrective action plans, the cover housing from plastic to aluminum was altered. After ALTs, HKS with the correct values for the design parameters were decided to ensure the lifetime target – B1 life 10 years.

(3) As systematic reliability design method, we recognized that check of the returned product, load examination, and ALTs with design alternatives was much improved for the newly designed HKS in refrigerator. It also might be relevant to other mechanical systems such as airplane, automobiles, washing machines, and construction equipment. To employ this systematic method, engineers should understand why products fail. In other words, if there are design defects in mechanical product that creats inadequacy of strength (or stiffness) when subjected to repeated loads, the mechanical product will fail over its lifetime.

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Sustainable Software Engineering: An Empirical Study of the Brazilian Financial Sector

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Abstract. Sustainability concerns have been noticed as the most critical asset worldwide to allow the next generations to survive in a world better than the one we live in today. Many initiatives are determined to monitor, enhance technology, and avoid environmental degradation. The financial sector is one of these players who have social responsibility at the strategic level of the organizations. In past years digital transformation of the banks and fintech helped to achieve the sustainability aspects. Therefore, this research aims to discover the practices of sustainability applied during the software development process and software product management of the financial sector through multiple case studies. Five organizations were interviewed, 80 practices were extracted and grouped into six categories related to social, environmental, and economic sustainability aspects.

Keywords: Sustainability · Software engineering · Green IT · Software product management · Social responsibility

1 Introduction

The financial sector is responsible for 14% of investments in technology in the world, according to [1]. Only in Brazil, the investments increased 24% in 2019 when comparing to the last four years. Since 2015 the financial sector is developing its own software and investing in mobile banking, representing over 89,9 billion digital transactions such as payments and electronic money transfer [1].

Sustainability is one of the aspects that the financial sector should be aware of and practice. They play a significant role as an enabler of social, environmental, and economic responsibility; therefore, they must comply with the Brazilian Central Bank policies [2]. Since April 25th of 2014, banks must comply with the Social and Environmental Responsibility Policy article 6º, resolution Nº 4.327. One of the initiatives is to control greenhouse emissions by improving business processes, systems, and controls.

A pathway to sustainability is to develop software product using sustainable software engineering practices. The definition of Sustainable Software Engineering [3] is the software code being sustainable and agnostic of purpose. In [4] the software purpose is to support the achievement of sustainability goals, for instance to improve the sustainability

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of humankind on our planet. We can take this definition forward by defining Sustainable Software Engineering in the way of developing software with these approaches: minimizing the environmental impacts on natural resources [5–8]; maximizing the social aspects in the local community [9–11]; and, changing software economics perspective from expenses to investment, and return on it as valuable and tangible benefits regarding sustainability [12]. In the context of product life cycle management, software is a product when it includes activities like portfolio management, strategy definition, product marketing, product development, development engineering process, sales distribution, and support [13]. From the perspective of Sustainable Software Engineering, the practices can be applied in all phases of software product management.

The primary motivator of this research is the possibility to identify Sustainable Software Engineering practices in a financial company since they are pioneers on the usage of ICT to run their business, they seek for opportunities of reducing costs, investing on social initiatives and technology. According to the scenario and the definitions of Sustainable Software Engineering stated before, the general objective of this work is: to understand how Sustainable Software Engineering practices are applied in Information Technology in the financial sector. Therefore, to investigate how these practices were applied, a case study was conducted in five financial sector organizations. The multiple case studies were composed of field data collection through semi-structured interviews and individual case description, in the light of the analysis, data analysis in aggregate form, outlining the panorama of the sector and extracting the generalizations and conclusions.

The results have shown that these organizations apply practices of sustainability during their software development process and thus in software product management. Using Grounded Theory methods, these practices were categorized to analyze the answers and identify systematic practices also found in the literature. In the end, a set of 80 practices were obtained by this exploratory research and classified into seven categories related to sustainability dimensions, energy consumption, energy efficiency, business process, social responsibility, and sustainability awareness which can be used as a reference of how the organization can implement these practices to manage the software life cycle development as a product.

This paper is structured as follows. Section 1 presented here aims to provide the reader an overview of this research's objective and motivation. Section 2 describes the literature review available about the topic. In Sect. 3, we report the case studies structure and steps conducted. The case studies results are reported in Sect. 4, and Sect. 5 concludes this work with contributions and future works.

2 Literature Review

Information Communication Technology (ICT) has positives and negatives impacts on the sustainability regarding carbon dioxide gigatons (GtCO2) emissions as reported by SMARTer 2030 Projections [14]. The projection shows that adverse effects are increasing each year; in contrast, the reduction in global emission percentage is perceived as a positive impact. The SMARTer justifies this decrease in footprint due to high investments in the sector [14].

In the book ICT for sustainability [15], it is clearly described and synthesized the dimensions of ICT impacts, order of impacts, and technology activities that lead ICT to be the part of solution, as enabler of sustainability as part of the problem too. In the matrix proposed by [15], the first-order impact considers the "direct environmental effects of the production and use of ICTs", such as hardware or software life cycle assessment. The second-order impact is described as "indirect environmental impacts through the change of production processes, products, and distribution systems". The third-order impact is stated as "indirect environmental impacts through impacts on lifestyles and value systems".

Social, economic, environmental, technical sustainability aspects related to software requirements was proposed by [16] in the form of a survey to identify the contribution of sustainable software requirements to develop software product which is: a) social: data privacy, data access, data integrity, and safety; b) economic: user satisfaction, testability, and freedom from risk; c) environmental: energy consumption, maintainability, and environmental risk mitigation; d) technical: functional correctness, functional appropriateness, availability, interoperability, and reliability.

Many practices applied during software development can be used to determine the sustainability achievements of the software developed [17]. The set of practices related to Software Engineering can be found in the Software Engineering Body of Knowledge [18] and the standard of software development life cycle ISO/IEC/IEEE [19]. Regarding life cycle assessment (LCA), the proposed life cycle sustainability assessment of a product can be adopted during the sustainable software engineering process while developing a software [20], which means that the product life cycle management for a software development is similar in terms of ideation, initial assessment, business case, construction or development, test, release, and business review [21, 22]. Studies related to Sustainable Software Engineering suggest adding or refactoring the best practices and standards proposed and commonly used nowadays to consider sustainability practices during software development, as presented in the systematic mapping of Penzenstadler et al. (2014) [23].

3 Case Study

Due to the research characteristics, the case study method was chosen once it is a research method that investigates contemporary phenomena in any form of data collection [24]. It is possible to develop a theory from multiple case studies by defining research strategies, propositions, or theoretical constructs from empirical evidence [25].

The following steps were carried out: i) definition of research roadmap and protocol; ii) unit of analysis description; iii) propositions review; iv) case study execution in the companies; v) transcriptions of individual's case; grounded theory; vi) proposition analysis; vii) propositions analysis aggregation; viii) reflection about the scenarios; and ix) generalization and final considerations.

Step i) definition of research roadmap and protocol is composed of research presentation, non-disclosure terms, operational procedures, propositions with the corresponding analysis points, and interview analysis points sent to the organizations. The next stage is the ii) unit of analysis description. According to [26], a unit of analysis is formed by an organization, a person, an event, or any entity as decisions, programs, and processes to implement organizational change as presented in Fig. 1. It describes the object to be studied to identify or describe a phenomenon. We defined the criteria described: a) an organization from the financial sector classified by Banco Central do Brasil as a financial institution taking demand deposits, foreign exchanges banking, and insurance companies [27]; b) have one or more Information Technology areas present in Brazil regardless of being a national or international bank; and c) in this IT area, have people working with software development directly or indirectly hired by the organization.

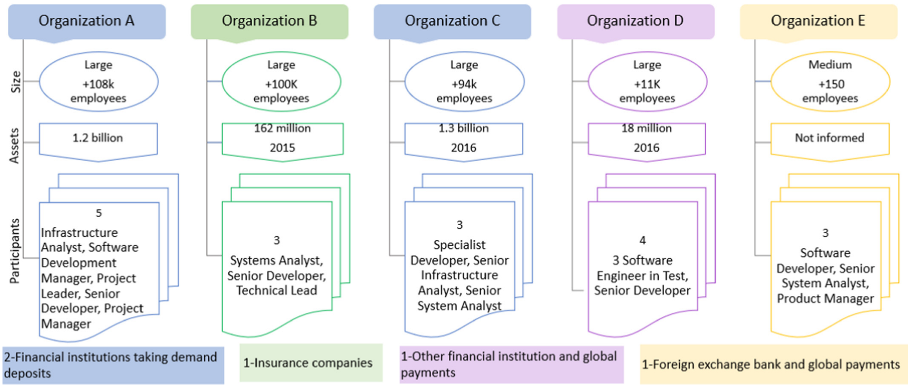

Fig. 1. Organizations profile

Individually each of the organizations is in accordance with the criteria presented and is part of the Brazilian Financial System. All of them have an information technology area in Brazil that is responsible for its software development.

Regarding the steps of iii) proposition review, to identify how the organizations follow the PRSA in the Information Technology area during the software development, three propositions and thirteen analysis points (AP) were defined and reviewed based on previous systematic literature reviewed [17] results as below:

- Proposition P1 – Organizational policies driven to sustainability are systematically applied in software development in the financial sector.
  - This proposition was created thinking about the practices found in the literature that could be systematically applied in the organization – following organizational policies or guidelines.
- Proposition P2 - Sustainable Software Engineering practices are applied in a non-systematic way during software development.
  - In this proposition, we analyze whether there are practices not related to any policies or guidelines defined or determined by the organization. It means a practice adopted because of individuals' past experiences, seniority, or observation.

- Proposition P3 - Tools that automatically measure or change the energy consumption of developed software are used.
  - This proposition was created thinking about tools, techniques, or implementation in the source code of an application that automatically change its state when an energy consumption peak is identified.

Once the propositions and analysis points were created based on the systematic literature review results, step iv - case study execution in the companies was executed by scheduling an interview with the selected participants. An authorization to record this interview was signed off. After finishing the interviews, step v - transcription of individual cases - was performed. During this step, the Grounded Theory (GT) research method was applied for each transcript as a mechanism of qualitative data analysis [28]. The first step to be conducted in GT analysis is the open code analysis. The second step is the axial code to identify each code as systematic or non-systematic, helping to answer our propositions. One network for systematic and another for non-systematic was created for each organization. The networks help the researcher identify the relationships and helps to bring to the surface new categories or relate the existing ones.

The third step was part two of axial code, to refine even more the findings, allowing the abstraction of the theoretical concepts found. In this step, practices were classified as new practices when new data not yet listed in the literature was found in the interviews. On the other hand, we named it as existent practices when we found practices from the literature. Moreover, to the networks be understandable for the reader, we preferred to represent the codes with colors and relationship names "is new practices of" and "is a".

The fourth step is the last part of the analysis and is about finding the connections between new practices and existing practices with analysis points and their concepts. This was done by looking at each network created and marking the findings in a table. This result is detailed in each Organizations' section about Analysis Points descriptions. The networks are also shown on each Organization section about Network analysis.

For each unit of analyses the step vi - proposition analysis regarding the units of analysis - was conducted, and the data was a) neither non-systematic nor systematic, meaning that nothing was found or referred to this question during the interview and GT analysis; b) non-systematic, meaning that the result found is applied or defined by the employee and is not something that is found in organization policy or guidelines; and c) the result is systematic, meaning that the organization has policies or guidelines about sustainability in any level of organizational planning and software life cycle.

Step vi - proposition analysis aggregation - aimed to analyze the results of all organizations together and report it clearly stating the findings between the organizations.

Regarding steps vii - reflection about the scenarios - and ix - generalization and final considerations – they are presented in the discussion section along with each organization results presentation.

4 Discussion

Table 1 presents the Analysis Points (AP-01 to AP-13) and the related Propositions (P1 to P3) that the AP helps to analyze. For example, AP-01 helps to analyze propositions P1 and P2.

Table 1. Description of analysis point

AP	Description of analysis point
AP-01	Initiatives that promote awareness about organizational social responsibility within the IT sector (P1, P2)
AP-02	Practices of Sustainability Dimensions are considered during the software development. (P2, P3)
AP-03	Practices of Energy Consumption are considered during software development. (P2, P3)
AP-04	Guidelines about sustainability requirements. (P1, P2)
AP-05	Sustainable Software Engineering practices are identified at some levels of organization planning within the IT area. (P1)
AP-06	Strategic alignment of the organization regarding the adoption of sustainability practices. (P1)
AP-07	A preference is given to hiring IT vendors who apply sustainability to their business. (P1)
AP-08	Concern to inform the customer that sustainability practices were adopted during the software development. (P1, P2, P3)
AP-09	It is possible to identify Sustainable Software Engineering practices at each phase of the software life cycle. (P1, P2, P3)
AP-10	When abnormally energy consumption is detected, the software developed adjusts itself to reduce its energy consumption. (P3)
AP-11	It is possible to measure the energy efficiency of the developed software. (P3)
AP-12	The criteria for evaluating software quality include sustainability practices. (P1, P2)
AP-13	Concern about the organization's reputation for adopting sustainability practices (P1)

The networks presented in the next sections were created based on Grounded Theory (GT) open and axial coding steps performed after interview transcription to AtlasTI software tool. For each network, we classified systematic practices (institutionalized), and non-systematic practices (not institutionalized) in the Organizations. The third classification was about the existent practices (from the literature) marked in purple and new practices (discovered in the organizations) marked in green. Due to the quantity of practices discovered in Organization C and E the networks figures were removed from this article and the results were summarized containing the most relevant practices.

4.1 Organization A - Analysis Points Description

In Fig. 2 it is possible to identify four practices discovered in Organization A that are applied in a systematic way. Organization A has guidelines about these practices, noted as purple, categorized into Practices of Sustainability Dimensions which are Internal Communication about Organizational Sustainability (organization raises awareness of individuals about environment protection); and Use of Less Paper (it is possible to identify initiatives of sustainability in the company level). Regarding the new practices, we discovered two practices. One was categorized into Practices of Business Process, and another into Practices of Energy Consumption.

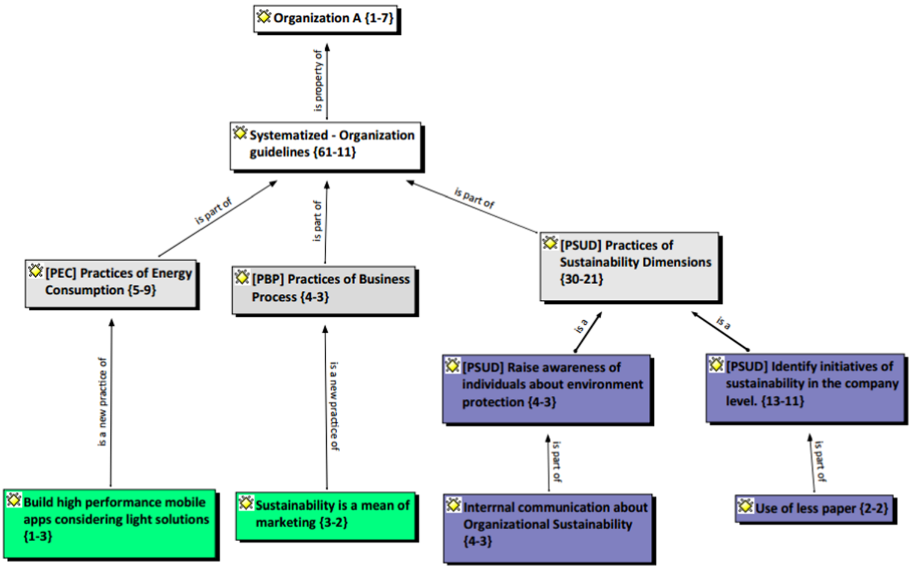

Fig. 2. Organization A network

Even though Organization A has a concern to raise awareness about sustainability to the employees and the customer, confirmed in AP-01, it is not related to the Information Technology area. This is related to the organizational level, and it does not mean that the employee in the IT area check these communications frequently and are aware of this. The concern to inform the customer about adopting sustainability practices is confirmed in a non-systematic way by AP-08. It means that the employees care about its adoption. However, there is no evidence or documents regarding the application, measurement, or quality control by the organization. The same reason to be classified as non-systematic occurs for AP-09.

The AP-13 was confirmed by the new practices found in Organization A about Sustainability as a mean of marketing. In this case, Organization A promotes marketing campaigns regarding using mobile banking without internet connection. Therefore, when we analyzed the practices adopted in IT area that impact software development, we concluded that P1 has non-systematic practices invalidating our assumptions that organization policies are applied systematically in the software development area.

Regarding P2, we concluded that this proposition was valid once non-systematic practices were found (AP-02, AP-03, AP-08, and AP-09). We can also see these practices in the network presented before. It is essential to observe that the interviewee reported two new practices related to end-user energy consumption. They applied it without guidance from the organization and without knowing about Sustainable Software Engineering. Since propositions P1 and P2 complement each other, it is possible to observe the same results of AP-01 and AP-13 reported in proposition P1 previously.

Proposition P3 is about using algorithms, measures of power consumption, and methods that automatically change the application state when there is high energy usage. It was not possible to identify practices related to P3. We concluded that it was not possible to validate Proposition 3 in Organization A.

4.2 Organization B – Analysis Points Description

In Organization B, it was possible to identify five practices applied systematically, as presented in Fig. 3. In this case, we found five existent practices from SLR present in Organization B categorized into Practices of Sustainability Dimension. Two new practices identified in the interview was discovered in Organization B and are categorized into Practices of Sustainability Dimension.

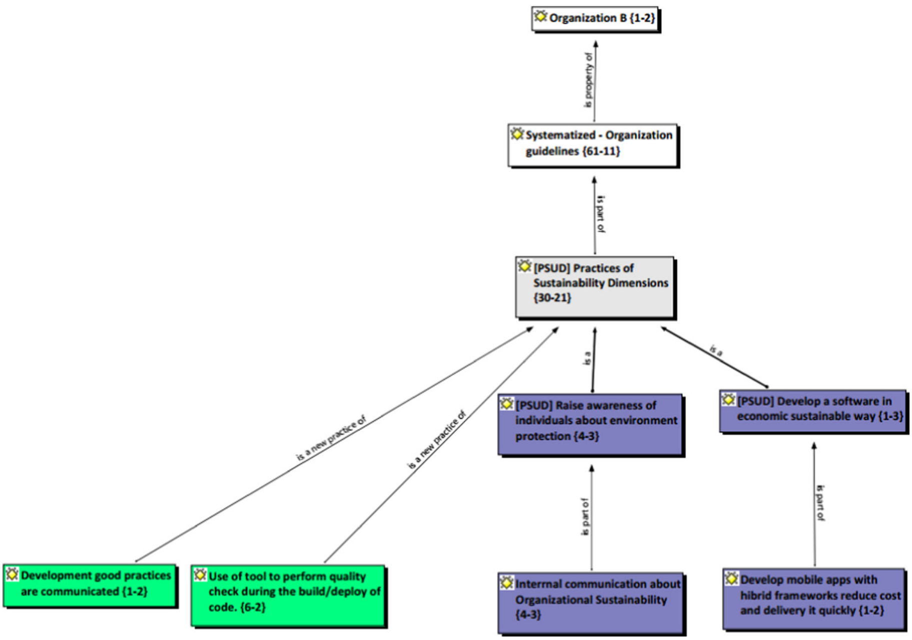

Fig. 3. Organization B network

It was possible to confirm systematic practices in AP-01, AP-05, AP-06, and AP-07 as detailed in the previous section. Organization B presents the sustainability aspects at the organizational strategy level since they raise awareness about sustainability initiatives by emails to the employees and choose a green data center.

If we look at the IT area, the sustainability aspects are adopted as the organization is changing its architecture model to use hybrid mobile development technologies. This decision was based on project costs, short timelines, and available resources that know about the technology used. Therefore, when we analyzed the practices adopted in the IT area that impact software development, we concluded that the organization has systematic practices validating our assumptions that organization policies are applied systematically during software development (P1).

Proposition 2 is related to P1 but tries to find non-systematic practices during the software development. When we looked at the AP's, we found non-systematic practices in AP-03, AP-08, and AP-09. The critical finding of this P2 is about the new practices, and new category emerged from the interviews. The new category is Practices of Code Improvement, which means implementations to turn the software code more supportable and easier to understand. None of the selected papers from SLR [17] nor the literature review references mentioned those practices discovered in Organization B. It seems evident for everyone working as a programmer that code maintenance, refactoring, and best practices should be applied. However, from the interviewee's perspectives, even the more experienced one, code improvements are considered a Sustainable Software Engineering practice, and it is crucial for their daily work routine.

The result of P2 is positive since we could find many new practices and existing practices in a non-systematic way and could identify a new category and the understanding from the interviewee who developed the software of Organization B.

Regarding P3, we concluded that Organization B has no measures or tools to identify this information in the application. Even though avoiding building solutions that use too much mobile battery is considered, it does not mean that these solutions are applied automatically without human intervention.

4.3 Organization C - Analysis Points Description

Organization C is the second bank in Brazil in assets, and it has noticeable concerns about social responsibility and sustainability. Since 2008 the bank has created Digital channels like the internet and mobile services. These channels are used by 73% of the customers in contrast with standard channels like ATMs or physical branches (27%). Consequently, the organization has invested millions of dollars in technology and its infrastructure; a new data center was built with many green implementations that had saved tons of water, representing an economy of 300 million dollars. Compared with other sustainability initiatives, the initiative regarding IT is where the most savings happen.

There are twenty-five existent practices discovered in Organization C. From this network, two practices are categorized into Practices of Energy Consumption, an example is "Use of software power metrics like disk hits transaction per second". Sixteen practices are organized into Practices of Sustainability Dimension one of them is "Communications about green data center and hardware energy efficiency". The last category is Practices of Evaluating Energy Efficiency with seven practices, for instance the "Use of development best practices to reduce the application size and perform better".

The systematic new practices are composed of eight new practices. Two of them were categorized into Practices of Sustainability Dimensions one of them is "Sustainability indicators are communicated to employees"; one into Practices of Code Improvement for instance "Code refactoring to enhance application performance"; one into Practices of Energy Consumption which is "Applications automatically change its performance when high CPU process are being used"; two into Practices of Business Process one of them is "Practices of performance are not communicate openly due to market strategy", and two into Practices of Evaluating Energy Efficiency one of them is "Develop a mobile app that do not require a lot memory our too much hardware processing".

Analyzing the Organization C profile, we identified that sustainability gains are recognized and are part of its business strategy. The evidence regarding these analysis points is found in Organization C's annual reports available online to the public and freely confirmed by its employees.

AP-04 was not possible to confirm in its totality since it was not possible to find evidence regarding a survey, model, or guide to identify sustainable software requirements. This is probably because the organization does not know the term "Sustainable Software Engineering" and has never used a model or guideline to apply such an approach. However, isolated evidence of systematic practices was found related to other software development phases, as an example "Sustainability as means of marketing" when the software is released which also contributes positively to confirm P1 from the AP-13 point of view.

Regarding P2 non-systematic practices, the AP-04 was neither non-systematic nor systematic. Therefore, it was not possible to identify guidelines about sustainability requirements. Regarding the remaining analysis points it was possible to find systematic practices mostly. This happens because there is only one new practice related to non-systematic related to Develop a code that is easier for everyone to understand and support.

Regarding the validation of Proposition 3, it is possible to identify systematic practices applied that are variables to support software energy consumption measurements responding to AP-11.

4.4 Organization D - Analysis Points Description

The Central Bank of Brazil identifies organization D as global payments type. The main business stream is credit card processing and services used by other banks and companies worldwide. In Brazil, the IT area has around 200 employees. All the employees working to Organization D are hired through an international company that provides IT services.

In Fig. 4, it is possible to observe the new practices and existing practices applied systematically. In the network, there are two new practices not found in SLR, which were categorized as Practices of Code Improvement. Regarding the existent practices there are six practices. Three of them are categorized into Practices of Sustainability Dimensions and three into Practices of Evaluating Energy Efficiency.

Only three APs were confirmed in Organization D for Proposition 1. It is possible to find some systematic practices at Strategic and Operational levels. Specifically on strategic level, the practices found are related to organizational aspects and not to the IT area.

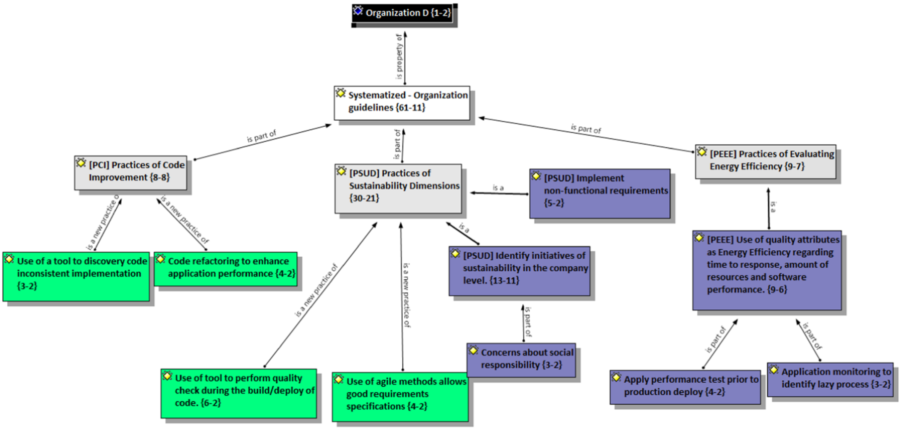

Fig. 4. Organization D network

However, at the operational level, we found practices used during software development. Those practices were discovered at software testing and maintenance phases supporting AP-09. About the software testing, practices discovered were related to quality criteria and software performance evaluation.

For Organization D the software performance is crucial for its business since millions of credit card transactions are made by second. If one fails, it means money and reputational losses. This justifies why the testing area dedicates time and resources to performance testing. However, it is crucial to notice that energy consumption is not monitored nor measured.

Regarding software maintenance, it is possible to see a list of tools used to improve code performance, understanding, and supportability, allowing the programmers to adjust the code immediately. From interviews, it was possible to find the mention of best practices as sustainable software practices. Although there are some analysis points with systematic findings, it is not enough to conclude that P1 was confirmed.

Regarding P2 - Non-systematic Sustainable Software Engineering practices - it is possible to see that we found only systematic practices related to software development (AP-03 and AP-09). Organization D has non-systematic practices; however, it did not support this proposition since we had it only on maintenance phase of software development. The same analysis was made for AP-09, which has non-systematic only on software design. In this case we concluded that P2 was not confirmed.

It was possible to find practices that support software testing and software maintenance; however, they do not perform it automatically. No evidence of energy consumption measure was found on developed software or during the software development. Therefore, P3 was not confirmed in Organization D.

4.5 Organization E - Analysis Points Description

Organization E is identified in the Central Bank of Brazil as a global payment operator and a Fintech offering payment methods services to international companies. A Fintech is an organization that provides parts of bank services. In this case, payment methods. Founded in 2012 to democratize the bank drafts for many international companies, this Fintech has been growing and providing digital services with impressive expansion.

In this Organization six new practices were discovered. Five of them are categorized into Practices of Sustainability Dimensions, one of them is “Use of agile methods allows good requirements specifications”. One is categorized as Practices of Business Process which is “Communication to external client about digital services”; and one is categorized as Practices of Code Improvement which is “Code refactoring to enhance application performance”.

It was possible to find eight existent practices applied in the Organization E in systematic away. Two Practices of Evaluating Energy Efficiency one of them is “Apply performance test prior to production deploy”. Four Practices of Sustainability Dimensions, for instance “Implement non-functional requirements”. Two Practices of Energy Consumption, one of them is “Use of server services to automatically adjust memory and CPU when the application requires”.

The P1 analysis points can be confirmed since practices related to Sustainability are applied in the Organization systematically (AP-05, AP-06, AP-07, AP-09, AP-12, and AP-13).

Some observations around the practices found in this Organization are about the way sustainability is conducted. They know about sustainability, and the employees demonstrate good behavior towards sustainability without the organization asking for it. Therefore, it is something that occurs naturally.

A robust practice related to Sustainability as a means of marketing emerged by the insight of an employee. He sent the information to the customers about the new functionality of scanning the screen rather than printing a paper. This was initially seen as a concern regarding user experience, but they later noticed its sustainability aspect. Therefore, it was possible to conclude that P1 is confirmed in Organization E.

Regarding P2, it is possible to observe only systemized practices related to software development. This is good from the perspective of P1. However, for P2, it means it did not reach the assumption of non-systematic practices been adopted. Therefore, we concluded that P2 was not confirmed.

Proposition 3 seems to be confirmed in Organization E, but it is not fully guaranteed since it did not meet the primordial analysis points AP-10 and AP-11.

4.6 Reflection About the Results

What we concluded about P1, is that some Organizations are more ahead of this time than others. For example, Organization C keeps the IT area informed about all the changes. From interviews, everyone knows about the same topics. Another positive point of Organization C is the sustainability report, which details the actions, CO2 emissions in its operations, and more. Organization B is the second place on this P1 list and mainly because the company’s architecture is working with sustainability practices.

Regarding AP-02, the concepts related to Practices of Sustainability Dimensions considered during software development applied in a non-systematic way were only identified in Organization A, which has many practices not defined by the organization.

An example is the "Technical solutions for use less battery and less 3G/4G" that an employee raised.

AP-03 (Practices of Energy Consumption), the second category with more than 70 practices found from the literature [17] returned with one organization as non-systematic and another as neither systematic nor non-systematic.

In Organization C, it was possible to confirm P3 due to the new practice related to AP-11 (application monitoring to identify lazy processes). The interviewee reported that all the applications are monitored regarding performance like CPU usage and memory performance. However, when the application is too slow, they report this to the development team, who investigates the problem presented.

The indicator presented on AP-11 - use of MIPS indicator to identify transaction slowness - applied by Organization C, is commonly used in mainframe servers provided by IBM. In the end, it is only possible to confirm the use and application of this proposition by this Organization only. Although we have confirmed all the propositions on Organization C, the main contribution of this study is to provide a list of sustainability practices that are applied in the industry and/or are proposed in other studies. In addition, some of the practices can be used to identify, implement, and promote the environmental and social responsibility of organizations worldwide.

The intention of AP-13 was to investigate whether the organizations informed your customer about sustainability or received a recognition for developing sustainable software. In this case, it was possible to confirm this finding in Organizations A, C and E. Although none of them has received recognition for it, they shared their initiatives about sustainability to the customer as a means of marketing for their product and organization, therefore it confirms P1.

Regarding the limitation of this study, it is not possible to confirm that all the 80 practices can be applied in any organization since there are some specific practices regarding the software development process. As future work, we intend to measure and check efficiency in terms of the positive and negative impacts of applying these practices during the software life cycle.

5 Conclusion

We reflect on the results returning to the general objective of this work: to understand how Sustainable Software Engineering practices are applied in Information Technology areas of the financial sector. Observing the results presented on each analysis point and proposition, we discovered new practices and existing practices used at all levels of the organizations, not only during the software development. For instance, when we have initiatives of sustainability communicated throughout the organization and naturally adopted by the employees, we recognize the organization is not greenwashing the terms but strongly applying sustainability on a daily basis. Therefore, the results suggest that a smart organization can adopt these practices to support, as an attempt to accomplish, the corporate social responsibility terms during its software development process or software life cycle management.

During the interviews, it was asked what the interviewee knew about sustainability and Sustainable Software Engineering. To our surprise, all interviewees replied what they know about sustainability in general, and all answers were correct. However, about Sustainable Software Engineering, nobody answered as expected. As we progressed through the interview, the employees started understating what Sustainable Software Engineering is, and they could make associations and remember facts from the organization they represented.

Moreover, the financial sector applies some of the Software Engineering practices proposed by this study systematically. The systematic practices are in summary related to organizational process, and just a few of these practices could be applied during the software development. On one hand, we concluded that this observation is typical due to a lack of knowledge about Sustainable Software Engineering that is present even nowadays. On the other hand, Sustainable Software Engineering practices related to business process, sustainability dimensions and energy consumption can support the organizations on their corporate social responsibility agreements and facilitate the adoption of these practices either at the tactical, operational, and strategic level of any product life cycle management.

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Green and Blue Technologies

Digital Management of Large Building Stocks: BIM and GIS Integration-Based Systems

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Abstract. Organizations involved in the management of large building stocks require high quality data in order to properly manage their assets. Due to more restricted environmental requirements, funding and intervention times, these organizations need to solve inefficiencies and uplift tasks adopting improved digital systems for the management of their assets and related data. Currently, each stakeholder involved adopts its software for specific tasks, with limited data interoperability and standards for data exchange. A comprehensive system which can handle large scale and heterogeneous data is required, but it must be designed to precisely fit the needs of the organization and to overcome current technical limitations. Since BIM and GIS are two IT-based methodologies which can provide data about built assets and related environment, the BIM/GIS integration is investigated through the analysis of over 100 journal and conference papers published in the 2015–2020 period. This analysis reveals categories and sub-categories explored in the current state of art, features that have been satisfied by future BIM-GIS integrated systems and a roadmap for its implementation. The results of the study can support scientists and practitioners in addressing their research interests and implementation activities for leading a digitization of data and information in large building stocks management.

Keywords: BIM · GIS · Large building stocks · Integration

1 Introduction

The concept of large building stocks is not a fixed term, since it can include whole city centers or a fragmented collection of punctual buildings. Organizations involved in this field and in the more general AECO/FM sector (Architecture, Engineering, Construction, Operation and Facility Management) require consistent and non-redundant datasets about their assets, with GIS providing georeferenced information and BIM for detailed components. In this perspective, BIM can be seen as a digital synthesizer of several unlinked and non-semantic data, such as paper documentation or CAD files. The BIM model, therefore, constitutes a centralized, 3D, and semantic database of the building, but it lacks geo-referencing at the geographic scale and query potential. The integration

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with GIS, by means of ontologies or scripts for IFC to CityGML conversion, allows performing at lower scales tasks, which are usually done with territorial data and larger contexts. However, usually the system design and its implementation require intensive manual work, and they depend on the quality of existing data for the BIM modeling of the assets and their integration within GIS databases.

The heterogeneity of data is addressed in literature by means of ontologies and graph databases, which are generally preferred to complex interventions on BIM and GIS data model, since data loss is hardly evitable, since it typically involves to the fitting of the more detailed IFC into CityGML, which requires specific extensions. Instead, the conversion of BIM and GIS files into RDF/OWL with semantic web technologies allow a smoother approach and the availability to link with other sources such as IoT sensors. Depending on the organizations involved, the BIM/GIS integration system can cover one or more kind of the managed assets data: for example, social housing organizations would like to cover both the energy performance, user comfort and loans regularity, and a BIM/GIS database can support the management of the asset providing visualization, centralization of data and analysis tool. The management of the assets therefore can require multi-level data, in which for example the technical, energetic, economic and social levels intertwine.

Even if there are already feasible methods for multi-scale systems, the technical limitations of BIM/GIS integration are still addressed to achieve a smooth, bidirectional, and automated conversion. Commercial software already provide some of these features, but an omni-comprehensive and open-source approach is still an open topic, especially for uncovered semantic fields by the two technologies (e.g., HBIM) or to interact with new data sources (e.g. technical databases, IoT sensors). Besides this, the required systems should take into account that high-detailed BIM models require cost and time, and they can be quite heavy files at the data level. Depending on the size of the assets portfolio, BIM models should be more or less detailed, depending on which data are required by the agencies in order to properly manage their assets. If a component-level is not required by the agency, then BIM models can be at a lower detail regarding material and other details, focusing instead on other data and bigger granularity, such as space usage or maintenance cost at story or whole building level, rather than single room details.

Based on the described context, the BIM/GIS integration becomes relevant for enabling the centralization, geo-location, and digitalization of assets information. This paper aims to analyze the literature about the integration of BIM/GIS for more efficient management of large building stock, which can be adopted by several stakeholders such as asset and facility managers, maintenance personnel, and technicians. Based on the review of more than 100 papers, the results allow to provide a structured classification of the current studies in categories and sub-categories, to provide an overview of the main features to be satisfied by a system based on a BIM/GIS integration and on the proposal of a roadmap of steps for leading such integration.

In the next section, the systematic literature review method will be detailed. In Sect. 3, the papers classification in categories and sub-categories and the main features to be satisfied in a BIM/GIS integration will be described. Section 4 proposes a roadmap of steps for BIM/GIS integration based on the analyzed literature. Finally, Sect. 5 concludes the paper.

2 Systematic Literature Method

This paper follows the Systematic Literature Review (SLR) approach as the research methodology. The SLR is a type of review that is defined as the identification, evaluation, and interpretation of a field of research that can be reproduced by other researchers [1]. The research is focused on a qualitative analysis, although it also provides schematic classification and highlights found in the literature. The paper selection process must be clearly explained and circumscribed to be replicable.

The SLR treated in this paper, took place on the online database Scopus for retrieving academic papers, both from journals and conferences, and it included works published between January 2015 and February 2021. Given the wide scope of the analysis, the search process was based only on the use of the keywords BIM and GIS and their combination. References to the type of building were avoided in order to collect a wider set of studies and insights for leading future research. Therefore, the following query was performed on the database: ("BIM" or "Building information model*") and ("GIS" or "Geographic information system*") and "integration". BIM and GIS were also expressed in their extended form in order to avoid missing papers.

The query retrieved a total of 196 papers in the chosen period. After that, a selection was performed in order to remove non-English, not available or out of topic papers. This required a manual check of title and abstract, and finally, 163 out of 196 articles were kept. Table 1 shows the number of papers published by year, highlighting a positive trend and thus an increasing interest of the subject in literature (Table 1).

Table 1. Numbers of papers published by year

Year	2015	2016	2017	2018	2019	2020
Number of papers	13	13	28	24	28	50

3 Fields of Application

The review unveiled that the BIM/GIS integration was employed in several AECO/FM applications and with several methods. In fact, the term "BIM/GIS integration" referred to different strategies and objectives and thus it can be considered an umbrella term [2]. Moreover, among the 163 papers investigated, over one-third (63 out of 163) were addressing how to implement a BIM/GIS integration, discussing it at a high-skill technical level or in other cases discussing it at a general level, without applying it to a specific context.

Based on these premises, the first classification of the papers found delimited the scale of intervention, which were subdivided as:

- ***City and Urban***: BIM/GIS integration is discussed in relation to subjects which interest urban areas or whole cities;
- ***Infrastructure***: infrastructures which are both inside or outside cities, (e.g., underground utilities and roads) are treated in this category;
- ***Building***: applications on a single building, or a small set of them are described;
- ***Technical***: They are not focused on a specific AECO/FM context, and rather discussed the BIM/GIS integration on a technical level or general purposes.

This high-level classification was needed to evaluate a preliminary distribution of the BIM/GIS integration. As it can be seen, the first three referred to physical entities, like buildings, infrastructures and cities or urban areas, intended as a collection of constructions. These three categories will be referred as "thematic contexts". Instead, the "technical" category refers to papers in which the BIM/GIS integration is investigated at the information and technical level. This last category treats technological issues that are out-of-scope of this study, therefore, it is not considered in the remaining part of the analysis (Table 2).

Table 2. Classification of papers by category

Category	References	Total number	% on the total
City and Urban	[3–35]	33	20%
Infrastructure	[36–66]	31	19%
Building	[67–102]	36	22%
Technical	For consultation the reference list is available here: https://cpdm.unisalento.it/icplm/annex2.html	63	39%

Below this classification, a vast collection of sub-categories can be defined, as reported in Table 2. The granularity of the classification was evaluated in order to identify trend topics and insights related to each category and to assign a paper to only one category (Table 3).

At the technical level, the BIM/GIS integration is divided into two main issues, namely the geometric and semantic conversion of data. During the years, researchers achieved one or both of them, but as can be found from recent papers, the matter still suffers several problems, such as intensive manual work or scarce generalization capability [103]. The BIM/GIS integration workflow, on a practical level, is mainly intended as an IFC to CityGML uni- or bi-directional conversion [104, 105], or in the alternative as the employment of Semantic Web Technologies and Linked Data approach (e.g. ontologies, [106, 107]). This brief insight about the technical aspects of the matter is necessary because it is a transversal theme that interests every classified article in this review.

Table 3. BIM and GIS fields of application classification

Category	Sub-category	N. papers	References
City and Urban	Analysis	6	[4, 5, 9, 13, 28, 35]
	Application	3	[8, 20, 29]
	Cadastre	2	[3, 15]
	e-permit	2	[16, 21]
	HBIM	2	[18, 32]
	Modelling	3	[22, 30, 31]
	Planning	3	[10, 11, 25]
	Safety	2	[14, 17]
	Sustainability	7	[7, 19, 24–26, 33, 34]
	Visualization	3	[6, 12, 23]
Infrastructure	Roads	6	[37, 43, 49, 55, 57, 62]
	General	4	[39, 41, 48, 58]
	Utility	4	[47, 50, 56, 59]
	Railway	8	[38, 42, 44, 54, 61, 63, 65]
	Electrical systems	2	[40, 66]
	Subway	2	[45, 51]
	Tunnel	1	[46]
	Bridge	2	[52, 60]
	Hydraulic	2	[36, 53]
Building	Analysis	7	[67, 68, 73, 80, 86, 93, 95]
	HBIM	11	[71, 76, 77, 81, 83, 89, 91, 96, 97, 101]
	Management	10	[69, 72, 75, 78, 85, 87, 88, 92, 94, 100]
	Safety	4	[79, 84, 90, 98]
	Sustainability	4	[7, 74, 99, 102]

3.1 City and Urban

Since GIS relates to territorial and environmental data, it is a natural deduction that the integration with BIM can be applied to large collections of buildings, such as urban areas or whole cities. The sub-category distribution shows a trend, with the "Sustainability" topic as the most frequent one (22%, 7 papers out of 33). Following this, a series of general activities are recognized, such as Analysis (16%), Visualization (10%), Planning (10%), Modelling (9%). The Sustainability sub-category also refers to work related to energy management [19], planning [7, 34], and assessment [27]. Moreover, a dedicated literature review of the sustainable built environment and BIM/GIS integration was found [24]. The other sub-categories cover a heterogeneous plethora of topics. For instance, the BIM/GIS integration was involved in noise analysis [5], comfort and quality of public spaces [35], and smart city appraisal [4]. City and urban contexts involve not only buildings, but also every element that offers services and well-being to citizens. Data and their management play a crucial role in delivering these services to stakeholders and end-users, and since this means that several data sources need to be handled together, a BIM/GIS integrated environment can constitute the core of solutions for several purposes. For example, thanks to a Linked Data approach, McGlinn et al. [10] integrated the spatial data storage Prime2 of Ireland's national mapping agency, namely Ordnance Survey Ireland (OSi)m with IFC and Dbpedia data. This interlinking led to a richer data hub integrated with BIM data. Since BIM models were not originally intended to handle geospatial data, they are expressed in a local reference system that needs to be transposed in GIS environments with the required coordinate reference system (e.g., coordinates in WGS84). Some commercial software allows to easily import and locate BIM models, [30], and almost open-source solutions can be found [6]. BIM can support the development of virtual 3D City models, which are nowadays mainly based on the CityGML data model and format, and they could be employed for several applications such as 3D cadastre, utility management, emergency response etc. [20]. The BIM/GIS integration can also provide support to automate permitting, shifting from paper-based permits to automated and BIM/GIS permitting systems [21].

3.2 Infrastructure

Built infrastructure is the second main category that can benefit from the BIM/GIS integration, since it merges detailed modelling of the assets from the BIM side and the geospatial analysis that can be performed in a GIS environment. Infrastructures are built both in and between cities. For instance, the "Railway" sub-category considers high-speed railway [42] and urban rail [63, 64]. "Railway" was the most frequent sub-category found (27%), followed by "Roads" (20%), "Utility" (13%), "General" (13%), "Bridge" (7%), and other minorities. Infrastructures included in cities can be embedded in the smart city management, such as utilities [40, 47, 50, 56, 59] and subways [45, 51]. BIM/GIS infrastructure models can be used for full lifecycle digital control [63], and can be integrated with technologies such as computer vision and machine learning [41]. Moreover, the idea of a BIM/GIS digital twin was proposed for highway maintenance and monitoring [49, 57]. It is worth noting that on the BIM side, infrastructures are still not fully developed and implemented in the data model. However, works are in progress to deliver these kinds of constructions in the IFC format, thanks to buildingSMART initiatives such as IFC bridge, IFC road and IFC airport [108].

3.3 Building

The "Building" category includes papers in which the focus of the BIM/GIS integration is on applications at the building scale. The most frequent sub-category is "HBIM", namely "Historic BIM". HBIM refers to existing buildings whose geometry is obtained by survey, for instance by point-cloud technology, from which the BIM model is consequently generated [109]. HBIM can benefit from the BIM/GIS integration because it can provide semantically rich models, and it can help to document and analyse cultural heritage sites [97]. An 8 years research, named Chimera, led to a BIM/GIS system which allows managing transversal information on different levels, from object to building to the environment [81, 101]. As in other studies, a common workflow for the BIM/GIS integration in HBIM adopted FME software [77, 91, 102]. The work of Cecchini et al. declines the HBIM both on a city and single building, with a focus on the energy management of the heritage [102]. Similarly to the City/Urban, the integration of BIM/GIS can be supported by other data sources such as IoT sensors [73, 99]. In the "Building" category are also included studies focused on facility and asset management, [75, 78, 87, 88, 92, 94] in which GIS aid BIM models to be queried, georeferenced and located. GIS also allows relating BIM models with their surroundings, in order to analyse and assess external factors which can impact on the buildings, such as a flood [67, 68], fire emergencies [90, 98] or to link indoor and outdoor routes for planning [86].

3.4 BIM/GIS Features for Integration

Public agencies and organizations which have to manage large building stocks require detailed and authoritative data about their assets [91]. Depending on the scale of intervention, the BIM/GIS integration can aid at both large territorial environment and detailed in-building components scale. Between the three main scales, namely territorial, building and component, there are a series of intermediate level which can be identified. For instance, the BIM/GIS integration effort performed by Li et al. [74] is based on a case study on the University of New South Wales (UNSW) campus. Another intermediate level between the building scale and the city scale can be the neighborhood level [70]. In these two cases, the distribution of the buildings is concentrated in a single area, but this is not always the case. For instance, agencies dealing with social housing management commonly have large building stocks which can be spread through one or more cities [80]. Regarding this point, Vacca et al. [110] converted IFC models of social housing buildings and their components into geodatabase.gdb format to store them in Arcgis, using FME software a single georeferenced environment. While these last examples are relatable to the main subject of this paper, the literature review was extended to the general BIM/GIS integration topic in order to find insights for the management of large building stocks, even from less related contexts such as infrastructures. In fact, in this perspective, large building stocks can be placed in a fluctuating context which is the function of the managed assets and their area of intervention. Being a hybrid context, several features taken by the classified categories can suit a system for managing this kind of assets and related data. Table 4 collects a list of key features observed in the literature, organized by categories.

The supply chain management feature, for instance, was commonly found in relation to the construction phase [9, 69, 93] and it can be extended to the whole lifecycle of one or more buildings through its operation and maintenance.

It is worth noting that the relation between BIM and GIS is of mutual benefit. In fact, while BIM can be expanded by GIS, on the other hand, GIS can be supported by BIM models which provide digitalized data in order to populate the geospatial database. Due to the wide number of applications for GIS, data sources can be heterogeneous, and without standards, they can suffer technical and cooperation limitations. BIM can therefore provide standardized and detailed data at building and even smaller scale, such as facility

Table 4. Key features suitable for BIM/GIS integrated system for large building stock

Category	Features
City and Urban	City planning, georeferenced visualization, buildings metadata management, socio-economic and political analysis, environmental context definition, aggregated performance and data monitoring and analysis, city operation and management, policy development
Infrastructure	Intra-building utility, in-cities utilities and in cities infrastructures
Building	Component inventory definition, facility management, single building simulation, performance management and monitoring, life-cycle management
Transversal features	
Supply chain management, data monitoring, digital twin features, environmental analysis, cost and time management	

management. Regarding this, the literature review of Wong et al. [94] investigated BIM, GIS, and IoT sensors for facility management, highlighting the need for interoperability data and BIM/GIS integrated database for assets. Agencies and organizations involved in the maintenance and management of large building stocks are in an in-between situation in which they need data that range from the component to the territorial level. Moreover, multidisciplinary data are involved, since technical, social and economic management of the assets can be required. Thus, the BIM/GIS integration can be seen as a common core in which other sources can be integrated based on the specific case. The linkage between this core and other data sources can be achieved by geospatial databases [8, 74, 77, 102, 111]. To this point, the work of Cecchini et al. [102] addresses the BIM/GIS integration with a multi-scalar approach using a relational database on PostgreSQL with PostGIS extension, allowing to perform tasks at both urban and building scale. On the former scale, the GIS component is prevalent, with geolocation of EPC (Energy Performance Certificates) in the city center of Pavia. The latter scale is focused on the building stock of the University of Pavia, with the visualization of the thermal and electrical demand of building stock and a detailed energy assessment on a single building. To build this system, several data sources were needed, which on the GIS level are commonly provided by territorial information systems and surveys, while building-specific data need to be provided by owners (e.g., plans, sections and elevations).

4 A Roadmap for BIM/GIS Integrated Systems

Based on the analyzed literature, a roadmap is defined (**Erro! Fonte de referência não encontrada.**), showing the conceptualization of the main modules that could be implemented in a BIM/GIS integrated system. The roadmap tries to overcome the gaps in the current literature on BIM/GIS integration, proposing a path to better address the management of the large building stocks, taking into account that the solution can be composed in a modular way, according to the specific needs of the stakeholders. In detail, it tries to cover and organize currently missing, in development and existing modules addressing the the hybrid dimension of "large building stocks", which lies between the city and building scale; the generalizability of the solution depends on the complexity of the asset portfolio, the context of application, and the stakeholders involved in the processes. Due to these factors, an important underlying premise for the effective implementation of this roadmap is to develop vendor-neutral solution. The adoption of commercial software was found in literature, although BIM promotes open interoperability by means of IFC files. In complex contexts like large building stocks, with assets that can be spread on a large territory with different stakeholders, the lack of open standards could hinder or compromise the overall implementation of the solution.

The modules are disposed in a 2D space, whose dimensions are the heaviness of the system and the importance of semantic in data for the given module. Oriented lines mean that the previous module can provide data for the following module (Fig. 1).

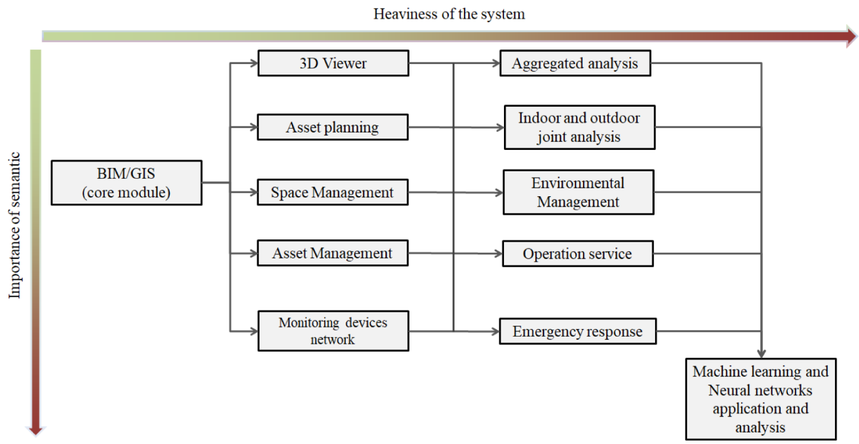

Fig. 1. 2D axis conceptualization of modules for systems for large building stocks

Starting from the BIM/GIS module, the core of the system can be of several types (e.g., PostgreSQL DBMS, graph database), and the complexity of the purposes which need to be achieved and the importance of semantic must be taken into account. If users need a BIM/GIS ground mainly focused on visualization and overall asset planning, then 3D viewers, which merge GIS maps and BIM models, are available on commercial software. On this application, the semantic importance of data is relatively low and the overall level of detail of BIM models can be focused on external features of the assets. When indoor features data are required, BIM models become more detailed, with the definition of spaces and components. Here, thanks to GIS power of analysis, indoor and outdoor context can be jointed and applications like network analysis and indoor/outdoor routing can be achieved. Managers for large building stocks, in order to shift to a BIM/GIS integrated system, need to preserve data on existing asset management and CAFM (computer-aided facility management) software. On this kind of system, a data model is required to map and link BIM objects with existing data. The complexity of the system rises when data are not simply collected, but also analyzed and processed. In these cases, the semantic preservation of data becomes more important, because data are commonly exchanged between stakeholders and software. For example, the environmental management of the assets implies life-cycles assessment (LCA) studies, and at the current state of the art the BIM and LCA integration is another open topic.

To allow the convergence of heterogeneous and redundant data, semantic web technologies can provide support to develop a system in which a link between information is provided, rather than converting and attempt to fit a data model into another. Semantic web technologies also provide a lean way to a more complex system, in which dataset are also processed by machine learning and neural networks, which could automate tasks in every stage of the buildings. However, semantic web technologies imply information technology expertise and costly and time-consuming processes, and these types of system may be of interest for experimental studies or long-period projects with governments and public agencies. The BIM/GIS integrated system can be developed for several purposes, and most of them can be satisfied by recent technological achievement, but the lack of standardized procedures and limited generalizability could require intense manual tasks and expensive tailored solutions.

5 Conclusions

Considering the relevance and the contribution provided by an integrated environment for managing BIM models with GIS information for large building stocks, the literature review suggests a categorization of the current studies in four main categories “City and Urban”, “Building”, “Infrastructure” and “Technical”. The first three categories are explored in the paper to suggest current fields of applications and guide practitioners and scientists in a structured overview of the existing studies, and to discover insights for extracting useful features for the discussed BIM/GIS systems. Starting from this contribution, papers under a specific sub-category can be selected based on the needs of further specific research.

Furthermore, the paper provides a summary of the main features that a system integrating BIM and GIS has to satisfy. This finding is based on the analysis of the literature and aggregates the features successfully implemented in other studies. Practitioners can consider this summary for defining the functionalities of a new BIM/GIS integrated system.

Finally, the last contribution of the paper is a roadmap of steps to follow to guide an appropriate integration for concrete digital management of information assets of large building stocks. Practitioners and scientists can benefit from this contribution. It can be used as a guideline for future implementations or single steps that can be integrated into an own roadmap.

Therefore, future studies should continue to investigate in order to provide a standardized, open and intuitive solution for effective, flexible and scalable BIM/GIS integrated systems, providing a tool that can support the management of assets throughout their whole lifecycle. This topic is strategic for the digitization of the AECO/FM sector and it is the subject of research for BIM and GIS-based leading communities such as buildingSMART and ESRI.

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Requirements and Barriers in the Process of Food Export from Brazil to Europe

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Abstract. Export has been a good way to leverage the agroindustry. However, the small Brazilian companies have been facing difficulties with the European Union, considering the requirements for the import of food. This work aims to clarify the requirements and barriers to food exportation from Brazil to Europe. The study presents a review of the internationalization, regulatory, normative requirements, and difficulties in this process. Aiming to understand the industry's difficulties, four small companies from Brazil were interviewed. In addition, the study also interviewed some professionals in the exportation area. Finally, the study followed the export process of a small food industry that was beginning an export to Europe, to understand all the requirements and procedures involved. The results show the requirements to export food from Brazil to Europe and note the consistency between the theoretical and practical data on the barriers and difficulties found in this process.

Keywords: Export process · Food industry · Support for export

1 Introduction

Many studies highlight the importance of exports in the growth of world trade and one of the sectors that stands out most is the agribusiness [1, 2].

The agribusiness exports are divided into basic and industrialized products. The basic products are known as commodities (raw materials) and the industrialized products are processed foods, whose have higher added value and contributing to the Brazilian economy [1].

The exporting companies have considerable growth, which means, they have financial gains, the company improves competitiveness in the internal market, increases sales, profits, and market share. In addition, the company reduces its dependency on the internal market, decreases its idle capacity, dilutes fixed production costs, and benefits from seasonality and new technologies. Other export benefits highlighted by [3], and [4] are the partnerships, benefiting from government incentives, the trade of surplus production, and the process improvement to adjust to external demands. Consequently, the enterprises search for improvements, transforming their process, reach a high level of quality, maturity, efficiency, and becoming more sustainable [5, 6].

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However, it important to highlight, that firms exhibiting higher productivity tend to export a higher percentage, then, it is important that firms and governments need to direct their policies towards increased productivity in order to improve competitiveness in foreign markets. Furthermore, once industry export orientation is positively associated with a firm s export intensity, export promotion policies should be directed towards the industries with greater export orientation [3]. However, all stages of the export process present certain difficulties [7–10].

Some barriers vary depending on the importing country [11–13]. The studies show some export difficulties related to the company s marketing and communication aspects, national export administration, production technology, and position in the market [8, 14].

According to [15], large-sized companies can export with greater ease because they are already export and have the infrastructure to support all the procedures involved. The micro, small and medium-sized enterprises (MSMEs) demand support because they have difficulties in obtaining credit to support the high cost of exports, besides the lack of knowledge about the exporting process and the requirements of the buying countries [4]. They have no knowledge of business opportunities abroad [4, 9, 16], nor know to deal with the bureaucracy involved. In addition, there are language differences, difficulty in defining export prices, the best trading channels, taxes, rates, exchange and customs procedures [7] and [8].

Considering that European countries are among the largest importers of food products from Brazil and that they have many import requirements [1, 2, 17, 18], this research addresses, in particular, the European Union (EU) requirements and barriers.

There are studies that address export requirements for specific food products and studies about the requirements of the product export process. Also, there are agencies that provide support to exporting companies such as: "*Aprendendo a Exportar*" (Learning to Export), Invest Export Brazil and the website of the National Institute of Metrology, Quality, and Technology (INMETRO). INMETRO supports Brazilian exporters, especially the MSMEs. Among the international agencies that assist in the export process, there are the Small Business Administration (SBA) –UNZCO, Canada Border Services Agency, the Canadian Trade Commissioner, GOV-UK, Export Start Guide, Australian Government, MATRADE - Malaysia External Trade Development Corporation, Trade and Enterprise New Zealand, and others.

However, it was not found studies about "the industrialized food export process", including "the necessary requirements, documents, and legislations of the Brazil-Europe export process focusing on MSMEs". Considering the lack of centralized and complete information addressing the various levels of requirement, this study aims to clarify the requirements and barriers in the process of food exports from Brazil to Europe. To this end, the work presents a literature review on internationalization of companies, regulatory and normative requirements and the difficulties in the Brazil-Europe export process. In order to complement the literature review, the study conducted a survey with four Brazilian food industries (MSMEs), aiming to "identify the operational difficulties of companies in the export process". The work also carried out interviews with seven export specialists from five sectors of activity. Finally, the study followed the export process of a small food industry that was beginning to export to Europe, aiming to understand better all the requirements and procedures involved during a complete export process.

2 Material and Methods

In order to complete the general objective, the study conducted a bibliographic search, aiming to understand the general scenario of exports of food products from Brazil to the European Union. The work also carried out a survey of the fundamental requirements for food entry into the European Union, including standards, documentation, regulations and agreements, focusing on MSMEs.

Subsequently, the research sought to identify the main difficulties faced by companies, found during the export process. In addition to a bibliographic survey, the study also sought information in the field through a survey. The research selected 227 MSMEs, which were food-exporting industries from the Register of Industries of the State of Paraná - Brazil/2015 - FIEP. From this selection, only 192 industries had an email registered, enabling to send a questionnaire. This questionnaire contained six open-ended questions, in order to identify the difficulties of these companies during the export process. Among the 192 emails sent, 67 presented registration errors and, among the remaining 125 industries, only four delivered the questionnaire answered. The questionnaire was also available on social networks such as Facebook and LinkedIn, through the Google Form tool (elaboration of online form), but there were no answers. Therefore, only the four companies' answers were analyzed.

In order to widen the scope of the difficulties faced by MSMEs food industries, the study also conducted interviews with seven export specialists, located in five different sectors. They are: Innovation Manager and Business Analyst at the FIEP Internationalization Department, Commercial Representative from a food industry, two customs brokers, an international business consultant and a consulting company in the area of foreign trade. The work conducted face-to-face semi-structured interviews, lasting approximately one and a half hours, in order to take advantage of each interviewee's level of knowledge. Thus, the interviews had variations regarding the focus on the "export" theme, as shown below:

(1) Manager of the Innovation Sector, FIEP Internationalization Department - the objective was to identify the situation of MSMEs regarding exports, research on the growth of exports of higher value-added (industrialized) products and identify trends in food exports;
(2) Business Analyst, FIEP Internationalization Department - the objective was to collect the main difficulties of MSMEs in the export process, identify documents and processes necessary for the export process;
(3) Commercial area in a food industry - the objective was to understand how the company's export process occurs, detailing the step-by-step process, and describing the main difficulties and the most critical steps;
(4) Customs Brokers - the objective was to map the processes required for export and collect the difficulties that a small company faces when executing this process;

(5) Consulting Companies - the objective was to collect data on the international requirements for the entry of food products into the European Union and the main difficulties of MSMEs in the export process.

Finally, the study followed the export process of a small food industry that was beginning an export to Europe, in order to understand all the requirements and procedures involved. The company is located in Curitiba, State of Paraná, Brazil, and the study followed the steps below, as [19] proposed for a Case Study:

(1) Choice of the theoretical framework: the study delimited the theme "Exports; Barriers and Export Models";
(2) Case selection: The study took place in an industry that started an export process to Europe, carried out between April and September 2016;
(3) Data collection protocol design: Data survey through interviews, documentary analysis and direct observations in order to collect the following information: company history, size, product lines, if there is a methodology for product development, if the company has any kind of certification, if it exports its products or want to export them, if the company knows any methodology to assist in the exportation of food products, which ways would it seek to help in exporting and especially identify if the company use any methodology to develop the products for export and finally, identify whether it would be interested in a model that helps in food exports;
(4) Conduct of Case Study: the authors of this work conducted the study, accompanied by the company owner and some employees who assisted in the visits and data collection;
(5) Report development: the data was organized and analyzed in order to provide an overview of the requirements and barriers that a small company finds when it exports its food products from Brazil to a European country for the first time, without the support of a specialized company;
(6) Standardization and Theoretical Modification: Due to the collections and analyzes, the study offered some suggestions about the implementation of procedures.

With the collected data mentioned above, the study concludes with the list of "Documents for the export process", the "Technical and normative requirements needed to export food from Brazil to Europe", the "Most cited barriers in the export-related literature", the "Main difficulties found in an export process, according to experts in the field" and, finally, "Reports of a real Brazil-Europe food export experience".

3 Export Motivations, Requirements, and Restrictions

Export is the way for a country to increase its economy by selling goods and services in international markets [20] and it is a key activity for the economic health of nations [3, 18, 21, 22].

Export operations may be carried out directly or indirectly. In the direct operations, the manufacturing company ships its products without external intervention and in the indirect operation, the manufacturing companies sell their products on the domestic market to Trade Companies export them [23].

In spite of these initiatives, there are requirements and barriers such as standards, documentation, regulations and agreements needed to be met during this process. The geographical barriers, for instance, make international trade be slightly difficult. In order to expand this access, the Commercial or Free Trade Agreements are used. The main treaties clause is the reduction of import tariffs. The main economic blocks of which Brazil is part and has trade agreements are: Southern Common Market (Mercosur); Global System of Trade Preferences among Developing Countries (GSTP); Generalized System of preferences (GSP) and Latin American Integration Association (ALADI).

3.1 Export Process and Associated Requirements

According to [1] and [2], the export process involves 22 steps described below:

(1) Planning: step to identify new markets, verify scale production and sales, talk with partners, enable the company for the export process and perform necessary training;
(2) Market Research: evaluate competitors, check technical barriers, perform research and know the chosen country as the destination for the product;
(3) Negotiation with the Importer: classify the goods by the harmonized system;
(4) Preparation of the Proforma Invoice: similar to the commercial invoice, in which all the negotiated items are written down, but it has no commercial value yet;
(5) Sending the Proforma Invoice to the Importer: the invoice is sent to generate the purchase order;
(6) Request for credit opening at the bank: the importer goes to his bank abroad and delivers the letter of credit to the bank manager;
(7) Exporter analyzes letter of credit: the exporter verifies if the information is correct: descriptions, values and deadlines;
(8) Preparation of Commercial Invoice: international document issued by the exporter that, in the external level, is equivalent to the Invoice;
(9) Preparation of Goods: the exporter prepares the goods as requested in the letter of credit and requests the start of the Export Record (RE) in SISCOMEX;
(10) Preparation of Packing List: document required for clearance of goods and for guidance of the importer upon arrival of the products in the destination country;
(11) Issue of invoice: used in transit of exported goods, accompanying it to the point of clearance abroad;
(12) Transport to port: transport of goods to the port or border of destination;
(13) Customs Clearance: fiscal procedure by which the customs clearance of goods destined abroad is processed;
(14) Freight and Insurance Payment: payment required if agreed with the importer;
(15) Receipt of Bill of Landing (B/L) or Air Way Bill (AWB): document of the transport company certifying the receipt of the cargo, the transport conditions and the obligation to deliver the goods to the importer;
(16) Clearance at Federal Revenue: the Tax Auditor of Revenue Service (AFRF) registers the customs clearance in SISCOMEX. The registration is the final act of the export clearance and consists in the confirmation, by the customs supervision, of the shipment of the goods and the carrier's data recording;

(17) Issuance of Proof of Export: after the export operation, the exporter, upon request, is provided with the documentary evidence of export, issued by SISCOMEX in the Goods Clearance Unit;
(18) Documentation Consolidation: the exporter consolidates all documentation and sends a copy to the importer: Invoice, Export Registration, Commercial Invoice, Letter of Credit, Bill of Lading, Insurance Policy and Export Proof;
(19) Exchange Contract: the exchange closing is when the exporter sells the foreign currency resulting from the export operation to the Bank;
(20) Documentation delivery to the bank: the negotiated way for the delivery of foreign currency is the fulfillment of the obligations detailed in the Letter of Credit;
(21) Exchange settlement and receipt: delivery procedure of foreign currency to the authorized Bank which, in turn, pays the equivalent amount in national currency, considering the rate agreed on the exchange date;
(22) Sending Thank-you Letter: Send a thank-you email as you close deals and maintain regular correspondence with the client, strengthening trade links. If possible, visit the client to know the market and their local needs.

There are some documents employed during the process described below, according to the Brazilian Foreign Trade Association [24]:

1. Proforma Invoice - in which the conditions of purchase and sale of the goods are stipulated.
2. Commercial Invoice - this document consolidates all information about the negotiation of purchase and sale of goods, containing all the points inherent in this process.
3. Packing List – it is a list of the volumes to be exported and their contents.
4. Bill of lading - this document is a guarantee that the goods have been shipped abroad or the border has been crossed
5. Certification of Origin - to certify that the product is effectively originated from the exporting country and grant tariff preferences.
6. Export Registration - The SISCOMEX is a set of commercial, financial, exchange and tax information and defines its legal framework.
7. Export Clearance Declaration (DDE) - presented to the competent Federal Revenue unit where the clearance and/or shipment is taking place.
8. Credit Operation Register (RC) - information with exchange and financial nature related to exports with a payment term of over 180.
9. Sales Register (RV) - completed in the case of products traded on international commodity exchanges or in case of primary products (commodities).
10. Invoice - this document must accompany the goods and contain all operations and party information.

In addition to documentation, some standards are required for the export process of products, mainly to the European Union.

Legislation and Standards

According to [13], the awareness raising for food safety issues culminated in sanitary and phytosanitary measures, and quality-related regulations and standards, imposing demands on exporting countries around the world. However, recent studies have shown that food safety standards have significantly affected exports of agricultural commodities from developing to developed countries [12]. To minimize this impact, it is important to understand the rules.

The requests, regulations and requirements can be classified into national and international and include food safety certifications that can facilitate the product entry into the European Union [18]. [25] presents the certifications in the food area and the regulations and requirements from their production to the customs clearance of the product at national and international agencies. These are basic requirements, intended to any kind of food. Depending on the product, it could contain more requirements, especially if they are of animal origin. Considering the limited space, the data did not present in this document, but they were indicated through a link in the bibliographic reference. In addition to the abovementioned requirements that hamper the export process, there are some barriers, especially for MSMEs.

Barriers to the Export Process

According to several authors and considering the MSMEs, the main difficulties/barriers found in order to meet these requirements are: limited information regarding the localization and analysis of foreign markets, untrained employees to execute the processes, knowledge of how to obtain the necessary financing to export operations, the lack of experienced staff to devote time to export activities, and banks willing to support the international business activities [22, 26]. Table 1 presents the barriers mentioned by several authors in the literature, classified into thirteen aspects involved in the export process. This study s source includes the following references: [7, 8, 14, 22, 27–33].

Table 1. Barriers mentioned in the literature.

Categories	Barriers
1. Customer	Different habits of foreign customers
2. Costs	Risks and excessive costs due to the large geographical and psychological distances that separate nations; Cost management; High labor costs; Risk of losing money in the process; Lack of financial resources
3. Documents	Bureaucracy and documentation

(*continued*)

Table 1. (*continued*)

Categories	Barriers
4. Financing	Lack of banks willing to support the companies international activities; Credit and financing difficulties; Need to honor letters of credit; Banks prepared to promote the companies international activities or local trading companies that allow indirect export operations
5. Information	Lack of information, knowledge, communication process, formal public education, knowledge of how to obtain the necessary financing to export operations and about the export process, and limited information regarding the target market
6. Legislation	Rules and regulations of the international trade Lack of knowledge in the commercial practices; non-tariff barriers; Quality control and safety standards that involve product adaptations to the requirements of different foreign markets
7. Marketing	Inappropriate marketing strategy; Difficulty when conducting promotional activities for foreign markets
8. Market Research	Differences between business environments; Difficulty in gathering information about potential markets and identifying opportunities; Competition faced in the foreign market; Lack of business opportunities; Political instability in foreign markets
9. Planning	Limited human, organizational and management resources; Inefficiency in resource allocation; Activity planning; Export management principles; Lack of experience to export; Lack of training
10. Customs Procedure	Logistics obstacles; Customs bureaucracy; Release time of loads; Customs clearance; Choice of sales channels; Slow customs clearance; Transport and distribution difficulties in the foreign market; Difficulty in finding a reliable distributor in the destination country
11. Product and Development	Adequacy of products and production processes; Lack of production capacity
12. Tax Treatment	Lack of awareness of the economic and non-economic benefits of export markets; Risk of exchange rate variation; Import tariffs; Brazilian exchange-rate policy; Exchange rate
13. Government	Government policy of incentives; Government barriers

As can be seen in Table 1, the categories that most present barriers are related to Planning, Market Research, and Information. Planning becomes compromised due to the lack of staff prepared for this procedure type. Market Research and Information report similar problems, related to the difficulty in obtaining information from the destination country, as well as other factors.

Added to these barriers, recently, [34] showed that EU set out an agenda for responsible trade and investment in its "Trade for all strategy". They promise greater economic value to smaller enterprises, transparency in negotiations, but call for the European Commission to adopt a negotiating approach that "involves using trade agreements and trade preference programs as levers to promote values like sustainable development human rights, fair and ethical trade and the fight against corruption", extending the interest across the production chain [35–39]. The Mercosur agreement, for example, includes commitments to fight deforestation, that is, the private sector must avoid buying meat from farms in recently deforested areas. According to [40], the Global Trade Analysis (GTAP) framework is used to simulate the implementation of the June 2019 "EU-Mercosur Agreement in Principle".

4 Export: The View of the Industry and Its Representatives

In order to understand the reality of the food export process, this study carried out a survey of the main difficulties during the process, through questionnaires in four food MSMEs that export their products, and seven interviews with specialists from the foreign trade area, as previously mentioned. The study also followed the first export process of a company located in the south of Brazil, aiming to understand the practical difficulties of this industry.

4.1 Difficulties Mentioned by Exporting Companies

The survey aimed to identify: the difficulties that exporting companies have or once had, if they have already used the support of any agency, how did they carry out a survey about the requirements of the destination country, how did the use of the transport and the International Commercial Terms (INCOTERM) occur and what are the main demands of export support. The answers showed that there are difficulties because the companies:

(1) Do not know the complete export process;
(2) Do not understand and are unable to organize the documentation to take the process forward;
(3) Do not understand the foreign market demand to identify potential customers, consumers and potential countries.

Despite this, sometimes the importer informs the company about these local market requirements, facilitating the process. However, all exporters would like to have a list of requirements on the exported product.

4.2 Difficulties Mentioned by Export Specialists

Seven interviews were conducted with experts in the field and were considered in this work, aiming to identify the main difficulties of the food export process, but only two were described in detail in Table 2.

Table 2. Main difficulties found in an export process.

Professionals from food internationalization sectors at FIEP	Difficulties reported in the interview
Manager of the International Innovation Center of FIEP-PR (March/2016)	To understand the general situation about food industries exportation: Lack of process knowledge, qualified person to perform the activity, excessive documents, price formation, target market identification and cultural differences. The manager informed the contact of a company for case study of research and monitoring of an export process in practice
Business Analysts at the International Business Center (CNI) of FIEP-PR (2) (March/2016)	To identify the main difficulties that the industries find: Difficulties related to the fluency in another language, qualified staff to conduct the process, as well as better understand the support activities that FIEP offers

According to the experts, the fact of not having the complete process control and a qualified person to carry it out impacts on the lack of knowledge of the target market, on the correct identification of the final consumer's needs, on the correct choice of transport and freight, on the preparation of the correct documents, pricing and others. As a result, many companies are afraid to export products for due to the lack of knowledge or damage caused by sloppy negotiations. They also mention that the obstacles to conduct exports make the start-up companies reluctant to export, and the more experienced companies suffer from the performance of the export process, which threatens the international market. Another obstacle is related to the difficulty of conducting a market study to place properly products in the destination country.

Analyzing 13 categories of difficulties and some barriers that some professionals mentioned, categorized similarly to those found in the literature, there the follow synthesis:

(1) Market and target audience identification: Perceptions and needs of the consumer and target market and cultural differences; international market research; identification of products in the portfolio that are of interest to world consumption, not just regional and typical products; identification of the product concept that could be well regarded in the market; identification of methods for placing the product on the new market; correct identification of demand for numbered lists;
(2) Lack of relationship network in the exporting country;

(3) Excess of Documentation: Preparation of documents required for export, such as: Certificate of Origin and Packing List;
(4) Qualified staff: process and required steps understanding;
(5) Fluency in another language: understanding of the language and culture of the place;
(6) Pricing: Pricing of goods; Payment methods and financing tools; currency definition;
(7) Correct packaging suitability: Storage of goods so as not to spoil the products or expire the shelf life;
(8) Product classification: classify the product according to the tariff nomenclature; bureaucratic process; importance in defining the product classification (INCOTERM) for the process. Reported doubts in performing the steps, preferring to pay someone to do the process;
(9) Logistics: Define the transport type, if it will be necessary to have a cargo agent to bring the goods to the port or not; Customs processes; container loading/stuffing, container transport to the port taking into consideration the product type that, because it is food product, has its shelf life controlled and often must be under controlled conditions;
(10) Country s legislative and regulatory context: The main requirements for the entry of food products into the European Union and area certifications. (Additional information: Some professionals or exporting companies commented that the customers are those who inform about the requirements to be met by the products for the entry in the foreign market; however, they confirm that having a standard procedure of the requirements would help in the process. The phase of surveying the requirements are uncomplicated as it is the importer's responsibility, but the importer does not always provide the information properly. They use FIEP and AMCHAM - they would like to understand better the support activities offered by FIEP and other agencies).

4.3 Requirements and Barriers Identified in an Export Experience

In order to understand the actual export process, this work conducted a case study in a company in Southern Brazil. For commercial confidentiality reasons, the company will not be identified without compromising the relevant information.

The study began by visiting the company to learn about the products, processes and export goals. First, the company's director and founder was interviewed to establish a partnership for this study. After this interview, the authors had monthly meetings with the company and importers. At first, the export target was Portugal. One of this study s authors participated in all this company s export-related activities, including meetings with other potential clients, participation in fairs and business missions.

The Planning of activities took place through an export project, developed through the following steps:

- Meeting with the importer: presentation of the company's products, characteristics, differentials and results of research carried out in the national market;

- Organization of the bureaucratic aspects necessary for exportation: Sanitary Surveillance (ANVISA) authorization to operate and Federal Revenue release of the System for Tracking of Customs Agents' Activities (Commercial Radar). Product identification related to the Mercosur Common Nomenclature (NCM) which, despite being several products, all have the same classification in the harmonized system. Definition of INCOTERM to be used in the process (Ex-Work – EXW - goods delivered to the buyer at the seller's establishment). Decision taken due to safety reasons for the exporting company, and due to the most competitive price for the importer; therefore, the importer assumes the responsibilities from the output of the exporting company's products;
- Survey of requirements for thee product entry into the European Union: use of the Mercosur Common Nomenclature (NCM) as a reference. Activity performed by one of this study s authors;
- Participation in the International Business Meeting promoted by CIN/FIEP: Business roundtables with potential importers of the products. This activity was relevant to identify the product impact on potential customers and to exchange information with companies in the same sector. Discussions of some subjects such as types of packaging, product adaptations and pricing. The study verified that these are common doubts among the participating companies;
- Product pricing using INCOTERM EXW as the basis, sent to interested importers;
- Second meeting with the importer interested in transporting the product to Portugal: Presentation of similar products sold in the region of Portugal, including comparisons with the company's products: packaging, price, taste, appearance, ingredients, among others. The company found that some raw materials were not well regarded in the target market and therefore the product would have to undergo adjustments and changes in packaging;
- Meeting with trademark and patent company to request brand safety in the foreign market: the product formulation is patented and has no similar in the national or international market;
- The company's director and founder visit the target markets, Portugal and Argentina: In Portugal, there was a need to obtain an organic product certificate, for organic products are a trend in this market. In the Argentinean market, there was greater difficulty in placing the product in the region. It would require a gradual entry, with market research and promotion strategies in order to obtain public acceptance. At this point, the company found that the prior market research is essential before starting an export process.

Until this study s completion, the company had not completed the export process. Therefore, it was not possible to follow the complete process within the company, but rather the initial procedures of market verification and product suitability to external requirements. With this study, it was possible to identify the following difficulties faced by the company until that moment:

- The proper way of placing the product on the market;
- Perceptions about the needs of the target audience;
- The correct demand identification;

- The survey of regulatory matters in the destination country.

This field survey corroborates the findings of [28] and [14]. They mention that the main difficulties of start-up companies in the export process are the lack of information about potential markets, information for the adequacy of products and production processes, implementation of promotional activities for foreign markets and knowledge of the target countries legislation abroad.

5 Conclusion

This study verified that, despite the economic motivations that promote the export of food products, there are excessive standards, documentation and many procedures that tend to intimidate some companies. The study identified 22 steps that constitute an export process, requiring at least 10 documents, including national and international regulations and standards, mainly for food safety reasons. These documents are: Proforma and Commercial Invoice, Packing List, Bill of Lading, Certificates of Origin, Export Registration, Export Clearance Declaration, Credit Operation Register, Sale Registration and Invoice. In addition, the research conducted a survey of the requirements in the theoretical and practical field, identifying difficulties during the export process, classifying them into 13 categories: Customer, Costs, Documents, Financing, Information, Legislation, Marketing, Market Research, Planning, Customs Process, Product and Development, Tax Treatment and Government. Several barriers identified in the academic material and in the interviews with experts in the field were similar. These barriers are: perceptions of the target audience and cultural differences, lack of networking in the destination country, excessive documents for export and financing, lack of complete process control, product classification and certification, getting qualified staff for export, logistics and customs, pricing, mastery of the country s legislative and regulatory context.

In order to complement this study, the authors followed a first export process of a medium-sized Brazilian company, aiming to export food products to Portugal and Argentina. The first difficulties found were the lack of knowledge of the process and the necessary documentation for its referral. Other difficulties were related to foreign trade practices, such as the correct identification of the final consumer s needs, the correct choice of transport and freight, the preparation of documents, the pricing, as well as the differences between business environments and the excessive risks and costs, due to the great geographical and psychological distances that separate nations. The study verified that the process knowledge and understanding are extremely important for companies to address this procedure and minimize its obstacles. Although the importers help the companies with the destination country s requirements, all companies would like to have a list of the basic requirements of the exported product. The obstacles to conducting exports make start-up companies fearful of exporting and the experienced companies suffer from the performance of the export process, which threatens the international market. Considering the demands of various professionals in the area, mentioned in the academic studies analyzed, the authors suggest, as a future work, the proposition of an export guide that addresses the procedures and requirements demanded in an export process, depending on the destination market.

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Managing New Product Development in the Fashion Industry with PLM: Based on Market Classifications

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Abstract. Product Lifecycle Management (PLM) has become a crucial element to handle request for quotation management, throughout the product development process, bill of material management, product data management etc. The use of traditional PLM software has increased, having been applied to traditional manufacturing, and product development efforts. However to date the integration of PLM in the fashion industry has been limited with varying success. Although certain variables such as size, range, color, or collection have been integrated into the management system with ease, the specific functionalities of the PLM remain unclear. This is often contributed to the fact that fashion industry has a shorter product lifecycle and greater variation of product offerings. Based on the available literature and a use case study, the purpose of this research is to establish a set of standard PLM functionalities based on the needs of the fashion industry. By leveraging unique set of industry specific functionalities the conceptual framework developed aims to provide a competitive advantage to those involved by supporting the production of goods in mass market, premium market and luxury market fashion products.

Keywords: Product Lifecycle Management · PLM · Sustainability · Fashion

1 Introduction

PLM is the process of managing the entire lifecycle of a product from engineering design and manufacture to service and disposal of manufactured product. From the concept design to the ultimate disposal, the whole lifecycle of a product is described through

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a detailed data collection. From this viewpoint, Product Lifecycle Management can be described both as a product-focused database and a communication process among different entities (e.g., manufacturing, marketing, and commercial departments).

By helping people understanding how a product is designed, produced, and finally disposed of, PLM leads to many different benefits such as reduced time to market, increase full price sales, improved product quality and reliability, reduced costs, more accurate request for quote generation, ability to quickly identify potential sales opportunities and revenue contributions, savings through the re-use of original data, reduced waste [1–3]. PLM helps to ensure that the right data is available to the right person at the correct phase of the development process. At the same time, increasing consumers' awareness about product safety and error reduction can increase sales opportunities and revenue [4].

Fashion companies manage different product categories (e.g., leather goods, clothing, shoes, and accessories) and might belong to different market positioning (from fast fashion to luxury), but the critical success factors driving the industry are above all quality and time-to-market (TTM) [5]. The search for quality is revealed in the selection of materials and care in manufacturing processes, which are in some cases still bound to handcrafting traditions (especially for luxury brands). Then, the need to streamline TTM in order to please demanding consumers is pushing the fashion industry to revise its own processes and to reduce the bottlenecks within the entire supply chain.

The fashion market is characterized by rapid changes, where cases of success and failure can often be linked to organizational flexibility. These markets exhibit typical characteristics: short lifecycles, high volatility, low predictability, and high impulse purchasing [5–7]. As fashion industry is complex and diversified, we need to segment it in order to have a better understanding about the company, the product and the processes that company follow to produce the product. Therefore, a distinction has to be made in the fashion industry. In this research, the main criteria have been considered as the market that particular servers, mainly divided into mass market and luxury market, in order to understand distinction of the fashion industry.

1.1 Problem Statement and Research Objectives

PLM puts the focus on "the product". The company's products are what the customer buys. PLM addresses the heart of the company, its defining resource, the source of its wealth, its products. Considering a product development process in which a core team of professionals from many disciplines sets out to create a product that satisfies a specific customer need [8]. In case of fashion industry, companies need to be agile, sensitive to changing customer needs, constantly monitoring customer buying behavior and delivering high quality. What often takes second place is the way these features are managed and balanced. Fashion companies currently are facing challenges to improve their competitiveness; a demand for innovation is currently affecting the whole supply chain, from product development [2, 9]. The information pertaining to fashion industry needs and its usage of PLM system is little and scattered. It is necessary to compile the information to understand how fashion industry is currently using the PLM to overcome those challenges. Therefore, the research question is formed, "How PLM solution has been adopted in the fashion industry?" To answer it, the approach to answer this is to have a systematic literature review pertaining to definition of PLM systems and fashion industry. The second approach is to have the interaction with the industry experts in the PLM and fashion industry. By answering this research question current scenario of PLM usage in the fashion industry can be captured which will help to identify PLM functionalities used to solve the needs and challenges of the fashion industry.

Speaking about the fashion industry, today's fashion business demands a high degree of collaboration and global business skill. What often takes second place is the way these features are managed and balanced. Fashion companies currently are facing challenges to improve their competitiveness; a demand for innovation is currently affecting the whole supply chain, from product development, through PLM systems and 3D software, to retailing, thanks to the 'digital revolution'. The economic pressures bearing on fashion companies come from both end users and retailers expect lower and lower prices, while the costs of sourcing, manufacturing. Fashion industry, in particular, is characterized by trends that change rapidly and consumers across the world expecting to choose the latest product. Managing a large repository of information involving stakeholders from different parts of the world brings down the operational efficiency of the company [4, 5]. PLM strategies aim to integrate information throughout a products life cycle from the imagination of the product to the design and realization of the product and information about the use and recycling of the product. PLM system supports everyone in the organization, from purchasing and selecting the raw materials, to product designs, production preparation. The notion of cohesion and traceability of information is reported as being crucial for improved data management of PLM systems [10]. After understanding the adoption of PLM solution in fashion industry, the problem still remains on recognizing which PLM functions can help optimize activities of fashion industry because the PLM system is very complex as it covers full lifecycle of the product. Hence, the second research question of this paper, derived from the first one, can be formed, "How PLM functionalities can suffice the characteristics which are affecting the fashion industry, leading to the specific needs?" Firstly, it is important to understand the PLM functionalities through the literature. A conceptual framework is developed to understand the link between needs of the fashion industry and PLM functionalities. This research questions puts a different perspective to understand the fashion industry.

1.2 Research Methodology

This research focuses on PLM system functionalities and the fashion industry. A new perspective towards the adaptation of enterprises to PLM systems will be analyzed as well as the current challenges in the fashion industry, also unlocked certain characteristics that did not exist before. Following Fig. 1 represents the flow chart of the approach.

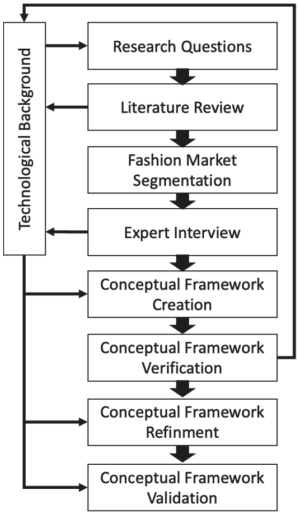

Fig. 1. Research framework

2 Technological Background

The literature review started by understanding the PLM system. PLM is able to manage the data concerning a product, and all the internal and external factors involved in the development of this product [1, 10, 11]. PLM has marked the transition from a departmental approach in product development, when each department defined its own activities independently of the other functions, to a collaborative and holistic approach [9]. PLM is viewed as a system that supports the evolution and change of data during the product lifecycle. PLM enables the optimization of business processes, improved integration and reduced costs [5].

Many research have characterized the literature about PLM in the last two decades [9]. A limited number of contributions related to retail companies exist, such as the ones belonging to the high-end and low-end market segments of the fashion industry [4, 5].

The first step in achieving the goal of this study has been the examination of the relevant literature. Three main sources were used to gather relevant research papers which are “Scopus”, “Google Scholar” and “sci-hub”. The main key words used to understand the PLM systems were “PLM”, “Product data management”, “PLM deployment”, “PLM software implementation”, “PLM definition”, “PLM functionalities”. After looking at the literature, it is understood that that there had been many published papers and case studies pertaining to PLM systems and its usage particularly in automotive and industrial sector. To see the relevant literature pertaining to fashion companies, “fashion industry”, “luxury market”, “classification of luxury market”, “mass market”, “needs of the fashion industry”, “characteristics of the fashion industry”. The most relevant papers were found by the keyword “PLM fashion industry”. Through this, research and usage of PLM functionalities used in fashion industry were found. These functionalities were used as a key word in order to look for the definition of these functionalities. Moving forward the detailed explanation regarding PLM systems, fashion industry, PLM usage in the fashion industry, fashion industry characteristics and needs have been discussed.

2.1 Fashion Market Segmentation

Definition of luxury is not merely a philosophical or academic exercise. Most studies in the research literature do not differentiate between the term's "prestige", "status", and "luxury" [12], although the first two terms display different nuances of meaning for consumers. Some researchers have investigated luxury as a property of brands and have described it using vague terms such as "dream value" or "impression" [13]. Finally, a few studies have differentiated between the concept of "luxury" and the luxury product or service. For instance, researchers have focused on what the concept of luxury means to consumers (e.g., "luxury for me is having more leisure time in the day"); other researchers have examined the meaning of luxury in the marketing context (e.g., what differentiates a luxury product from a high-quality product). An additional confusion is whether the term "luxury" primarily refers to a product or to a brand [14].

On the one hand, consumers confused using the word luxury for a wide range of goods progressively lose the ability to recognize the characteristics that justify the premium price of a luxury good or service, increasing the risk of dissatisfaction with the products they purchase. On the other hand, manufacturers who have noticed that the return is much higher when premium prices are charged for slightly above-average products might be less motivated to engage in a quest for excellence, leading to a slow but steady decline in product quality [15].

The transformation of luxury into precious objects and lavish living was necessary to open the realm of luxury to any social class. Finally, the second industrial revolution at the end of the nineteenth century gave the concept of luxury the modern meaning of the "habit of indulgence in what is choice or costly" or "something enjoyable or comfortable beyond the necessities of life". Of course, this transformation contributed to the different interpretations of the concept of luxury, such as status symbol, personal indulgence, and leisure time, among others [16].

Luxury goods are not consumed for their intrinsic value but to impress others and signal wealth and conspicuous consumption. Luxury goods are defined by their relative price and are valued because they are costly and exclusive. In contrast, luxury cannot be defined solely in terms of higher price, [12] note that expensive products may not necessarily be viewed as luxuries. For luxury goods, perceived high cost – in absolute or relative terms – is a necessary but not sufficient condition. In addition to high price, luxury brands feature excellent quality and specialized distribution channels [6].

From a subjective point-of-view, the term luxury might refer to "things you have that I think you shouldn't have" [17]. Most luxury products are also associated with a strong brand name and logo, as well as a tradition of craftsmanship and high performance [18]. The role of the brand in evoking exclusivity; in their view, current luxury products have a well-known brand identity, enjoy high brand awareness and perceived quality, and maintain customer loyalty and sales levels. Hence, luxury objects should be recognizable, stimulate an emotional consumer response, and become incorporated into the customer's lifestyle. [19] proposed to divide luxury brands into two categories: those that primarily have symbolic value for the customer and are valued due to lifestyle rather than functionality (e.g., Louis Vuitton), and those that primarily are valued due to their technical features (e.g. the world-class performance of Porsche vehicles).

Another important feature is the prestige associated with the brand and its uniqueness or exclusivity [6]. Luxury brands such as Rolex are perceived and marketed as timeless, and modern through the selection of materials, and the premium price that is attached. Balance between these characteristics is difficult to achieve, luxury brands exist in a highly exclusive market niche that is driven by unique marketing phenomena which suggests why uniqueness and exclusivity are relevant. Furthermore, this suggests that specific management approaches for luxury businesses are worth developing in departments other than marketing. [20] suggest that success in the luxury market is primarily related to:

- Excellence. For the consumer, the feature most strongly associated with luxury is the superior quality of the product and associated services, which is essential to justify the premium paid by consumers.
- Brand aura. For the consumer, continued excellence over time allows the brand to acquire a strong reputation and maintain a first-class position. To achieve luxury status, brands need to have a strong, legitimate, and identifiable aura.
- Desirability. Luxury goods companies must create and maintain desirability. One feature of desirability is a strong aesthetic appeal that is modern but related to traditional values; another feature is high price, which strengthens the product's social status. The product's rarity and uniqueness also increase desirability.

The luxury market separates into exclusive goods and accessible lines. Exclusive goods rely on rarity due to natural shortages of materials and manufacturing capacity, limited editions, or artificially maintained rarity, while in accessible lines, rarity is information based and achieved through selective distribution, exclusive shopping atmosphere, price, provenance from heritage centers, packaging, or combination of two brands [21].

A new luxury category in which consumers are less interested in the product itself and more interested in the image associated with the brand. New luxury refers to goods that are not necessarily rare or manufactured in low volume; these goods acquire the luxury label due to design, additional services or the aura created by the brand. The emergence of "accessible luxury" products is due in part to the tendency to trade up that currently characterizes consumption habits. Heritage and prestige have always been the hallmarks of many luxury brands. Because some luxury brands are hundreds of years old, the enduring quality of a particular luxury good can be part of its appeal, and this is especially true for the traditional view of luxury. However, some consumers – particularly those who are young and fashion-conscious – prefer a product with a fresh and unusual look and an exclusive aura rather than actual rarity [22]. To attract this category of consumer, the brand image – focused on a label, a logo or a symbol – is crucial. This is the idea behind accessible luxury (or new luxury) as opposed to old luxury (or traditional luxury), which targets elite consumers and relies on product authenticity based on precious materials, heritage, craftsmanship, and natural rarity. Instead, new luxury targets the upper middle market, is positioned at a lower price, and includes three types of products [23]:

- Accessible super-premium goods. Products that are priced at near the top of their category that middle-market consumers can afford.
- Old luxury brand extensions. Lower priced versions of goods that traditionally only the wealthy could afford.
- Masstige (merging mass with prestige). Premium products midway between mass-produced and first class, which are well below the highest priced goods in their category.

Based on the literature it is appropriate to segment the market in luxury market and mass market. Following Fig. 2 is the chart which explains the distinction between luxury market and mass market.

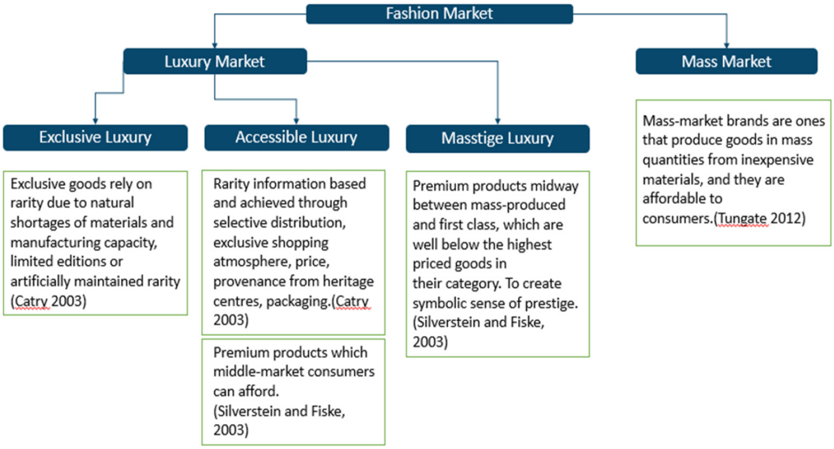

Fig. 2. Fashion market segmentation

2.2 PLM Functionalities in the Fashion Industry

The literature review was conducted on papers related to PLM functionalities with a specific focus on the fashion system, due to the evidence that there is a lack in a unique definition of the overall functionalities of a PLM software for that industry. More specifically, a single reference that exhaustively collects all the functionalities has not been found. Therefore, this gap is filled with the expert interviews and the case study and the research is focused on a selection of them. In addition, a specific functionality is often differently named in different papers, making the identification of a complete and clear set of unique PLM functionalities for the fashion industry difficult to figure out.

Based on the literature, a review of the PLM functionalities has been carried out. The results of this part of the work are not included into this paper due to limit restriction.

3 PLM Conceptual Model

The Industry 4.0 revolution has pushed PLM software houses towards the introduction of new functionalities that cover a wider range of supply chain (SC) processes, especially in the fashion industry [4]. According to this, a research framework has been created to understand needs and characteristics of the fashion industry.

Conceptual framework is focused on six main characteristics which are affecting the fashion industry. These characteristics as shown in the table below are linked with the needs of fashion industry based on the literature (Table 1).

Table 1. Fashion industry characteristics

1. Ability to meet delivery time [24, 25]
2. Sufficing demands of the fashion products based on weather, seasonality, current and near future trends [10, 26]
3. Globalization, new product design and development activity [15, 16]
4. Features, style and patterns of product [5, 25]
5. Quality inspection from raw materials to the delivery of the final products [27, 28]
6. Complexity of the fashion industry [29]

These characteristics push the company towards the specific needs that we have listed based on what we have found in the literature. We are analyzing relationship between characteristics and needs of the fashion industry in the framework. How these characteristics are affecting the fashion industry and PLM system, PLM functionalities can cover those needs. Moving forward we have correlated these characteristics to more than one need of the fashion Industry (Fig. 3).

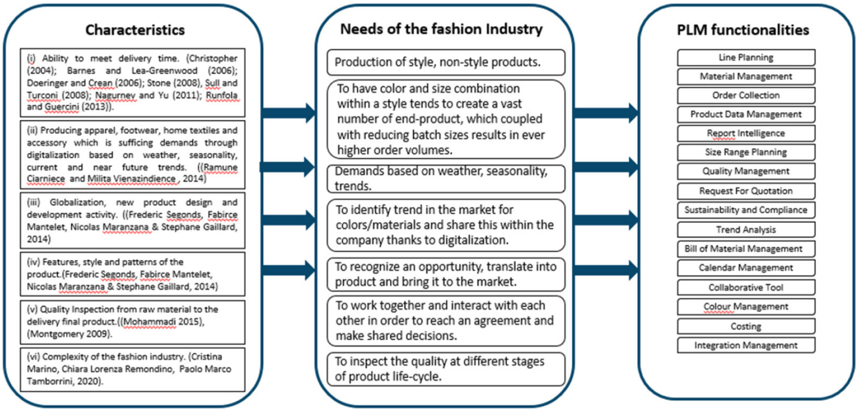

Fig. 3. Conceptual framework

Further, each characteristic has been deeply explained, in terms of needs and PLM functionalities. Due to space limit, only the first characteristic is reported in the paper (Fig. 4).

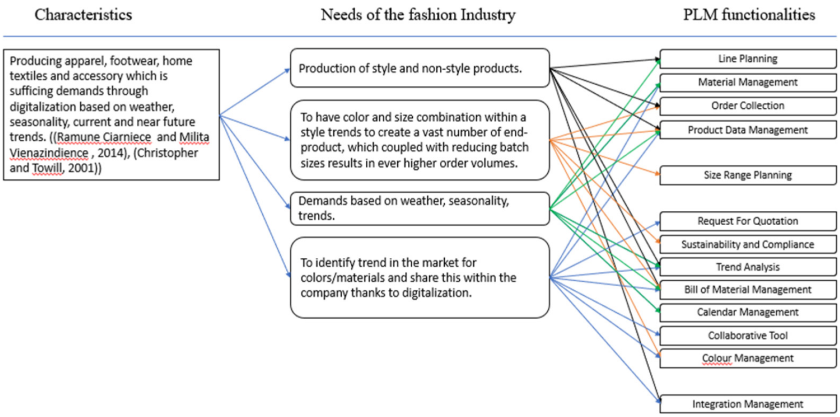

Fig. 4. Product apparel, footwear, home textile and accessory which is sufficing demands through digitalization based on weather, seasonality, trends

Apparel, footwear, home textiles and accessories manufacturers mainly produce a mix of style-based and non-style-based products. The combination of color and size combination within a style tends to create a vast number of end-product, which coupled with reducing batch sizes results in ever higher order volumes. At the same time, customers are demanding shorter and shorter lead times, increasing the pressure to make decisions more quickly. Demand for these products is rarely stable or linear. It may be influenced by many external factors such as the shifts in weather, seasonality and social trends.

Fashion companies produce goods based on trends and seasonality, in order to sell higher volumes. As far as exclusive luxury is concerned, they create the market trends and companies who belong to Masstige luxury and Mass market follow that trend. Based on the seasonality appropriate color, material, size combination is selected. Companies consists of multiple departments with multiple locations, digitalization plays an important role to collaborate with each other.

Digitalization is also helping companies in a current pandemic situation where employees of the companies are interconnected with each other as well as since many touchpoints with customers are closed online channels are working very efficiently. Exclusive luxury companies never put their goods on a wholesale channels. They have their own platforms to present their collection.

Exclusive luxury companies focused heavily on inhouse product design and development of goods. Their exclusivity can be seen from their very high-quality standard and heritage aura of the product. As far as mass market is concerned even though they have some design activity may be inhouse or outsource, they start their line plan with the design activity or even before design activity.

4 Outcomes

In order to verify the conceptual framework exposed in the previous section, a focus interview is dedicated with a shoe industry PLM expert. Through the practical and theoretical information obtained the conceptual framework was refined and validated.

Speaking about the organization he is working, the company is in Detmold, Nordrhein-Westfalen, Germany and is part of the Shoe Stores Industry. The company is one of the largest shoe production and distribution companies in Europe.

Based on the needs and characteristic, the company representative supported the validation of the conceptual framework, whereby sustainability and compliance and were further addressed. Especially when it comes to the sustainability, from the beginning it is the request of the market and consumers are also focused on this now more than the past. Companies have demands on laws which are coming now, and companies must consider sustainability of the product. Due to these reasons, sustainability and compliance has become the important need of the fashion industry. The verification of the framework ensured that the relationships between characteristic and the quality inspection from raw material to the delivery of the final product is well founded.

5 Discussion

The research proposes a framework to support PLM implementation in the fashion industry. The main result of the research study is a conceptual framework based on needs of the fashion industry drawn from its characteristics and linking the needs of the fashion industry to the PLM functionalities. The framework is based on the evidence collected from the literature, case study and expert's opinions on current scenario of PLM and fashion industry. After the development of the framework, it has been validated through structured focus interviews with an expert from fashion industry company. From a scientific point of view, the proposed framework gives a new perspective to understand the needs of the fashion industry and creates the link between needs and PLM functionalities in the fashion industry which answers the research question pertaining to how PLM functionalities can suffice the needs of the fashion industry drawn from its characteristics.

To strengthen the validation of the proposed framework, a wider sample of companies should be involved, differentiating both in terms of managed products (shoes, accessories, etc.) and market segmentation (mass market, masstige, accessible luxury, exclusive luxury).

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The Repurchase Intention of Organic Food: Comparison Between a Theoretical and a Nested Model

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Abstract. The Studies concerning environmental awareness seek to understand the problems and the impact that human behavior can cause to the environment. In this sense, in this research, we investigated some of the main determinant factors of organic product repurchase intention, among them, environmental awareness and consumer attitude. For this purpose, the research was operationalized through a survey, comprising a sample of 249 organic food consumers from Serra Gaúcha - Brazil. For data analysis, we applied structural equation modeling, comparing the results of the initial theoretical model with a nested model. The results proved that the relationship between environmental awareness influencing consumer attitude (theoretical model) presents better fit indexes and higher explanation power than the relationship between consumer attitude influencing environmental awareness (nested model), even confirming that these two constructs are determinants of organic food repurchase intention. It should also be noted that in the case of the coefficient of determination, the Theoretical Model presented a better explanatory power (87%) compared to the Nested Model (86.3%) of organic food repurchase intention by Brazilian consumers. From a managerial perspective, this study provided a broader understanding of the importance of expanding the supply and exposure of organic food (or products), taking advantage of the distribution networks that expose in greater quantity and with more quality the possible benefits associated with the consumption of these products, and the potential associated with greater environmental awareness and a more favorable consumer attitude.

Keywords: Environmental awareness · Consumer attitude · Repurchase intention · Structural equation modeling · Nested model

1 Introduction

The environment has changed considerably worldwide because of factors such as climate change, air and water pollution, waste generation, and natural disasters (Maichum et al. 2016). We have then perceived that environmental problems and their adverse impacts on human beings have become an important issue to be analyzed by academia (researchers),

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governments, and private or third sector organizations. Following this reality, the consumer begins to demonstrate this concern with the environment, opting at certain times for ecologically correct, sustainable, or green products (Yadav and Pathak 2016).

In this sense, we need to overcome difficulties in the field of production, distribution, dissemination, marketing, and consumption of organic products, more specifically, organic food. In emerging or developing countries, such as Brazil, there is a more significant concern for causes related to environmental degradation. Therefore, public policies and future work should direct their efforts towards overcoming problems such as the reduced volume of agroecological production, little diversity, and regularity in the supply of eco-friendly or organic products, disarticulation between supply and demand, infrastructure and logistics problems (Darolt et al. 2016).

Similar to conventional food production, organic food production begins with the consolidation of the land and ends with the packaging of the final products. This involves many time-consuming processes, including the preparation of resources such as soil and water resources, sowing seeds, pest control, harvesting, and processing (Han et al. 2017), not to mention product distribution, increasing access to consumers (Anninou and Foxal 2017).

Consumer demands for authentic and natural products with health-giving properties led to the development of several studies (Soares et al. 2017). As a result, consumer selectivity has become a challenge for organizations (Wisenblit et al. 2013). Therefore, the objective of this study was to propose and test a theoretical model and a nested model that contemplated environmental awareness and consumer attitude as antecedents of organic food repurchase intention by Brazilian consumers. When prioritizing organic foods, consumers also prioritize a healthier lifestyle, which tends to enhance the quality and perceived value of consuming this type of food (Suh and Lumbers 2015; De Toni et al. 2017).

This study's research problem aims to help to understand the determining factors associated with consumers' intention to repurchase organic food, contributing with theoretical and managerial implications on this growing niche market in the world and Brazil. After all, there is multiple evidence that motivates the consumption of these foods, from altruistic aspects related to the environment, environmental awareness, animal welfare, and fair trade, to individual aspects such as health concerns, better nutrition, food safety, taste or food preference, and product freshness (Bravo et al. 2013). Consequently, the hypothesized relationships and the influence of one construct on the other guided the research: (i) environmental awareness and consumer attitude; (ii) consumer attitude and repurchase intention; versus (iii) consumer attitude and environmental awareness; and (iv) environmental awareness and consumer intention to repurchase organic food.

2 Theoretical Background and Research Hypotheses

Afonso et al. (2016) point that environmental awareness is the willingness of individuals to deal with issues related to the environment, ecology, being fundamental to the solution of the problems of waste generation and also emphasizing the role of environmental education (He and Liu 2018), which can improve the consumption profile and quality of life of populations.

Besides, environmental awareness drives people to make greener purchasing decisions, tending to change their behavior to improve the environment and their quality of life (Suki and Suki 2015; Journeault 2016). Thus, the consumption behavior of organic products can be facilitated by better disclosure and proper labeling, because by demonstrating the contribution to environmental protection to consumers, they have the opportunity to make more appropriate choices through a better level of information (Maniatis 2016; Uehara et al. 2016) about the foods they consume.

The aggravation of environmental problems has concerned nations and governments. However, it has also increased pressure from organizations on politicians (or governments) and managers (or companies) who, together with consumers' environmental awareness, are driven to take specific actions and begin to stimulate or produce environmentally friendly products to prevent environmental pollution and minimize or eliminate hazardous waste (Ari and Yilmaz 2016; Akerlof 2017).

Ecological products, in this case, organic food, will become a trend with increased consumer awareness and government regulations. Because of this, for a manufacturer who aims at long-term sustainable development and profits, green production can be an essential strategy adopted in business (Yu et al. 2016). In this sense, the promotion of organic food consumption has been growing worldwide, driven by consumer demand, which in turn has been stimulated by a series of government measures. Such measures include campaigns to alert consumers to the use of pesticides, or to promote these products, organic food labeling schemes and requirements, as well as initiatives by actors in the food chain, especially retailers (Mørk et al. 2017), involving large global or national networks up to small commercial establishments (Zhang et al. 2019).

In the context of sustainable consumption, the attitude towards behavior can be considered an individual or intrinsic value (Suki and Suki 2015). Attitude is a composite of various behaviors, and any behavior performed involves costs or sacrifices (monetary or non-monetary), as it requires personal resources such as time, money, or physical effort. Given this, a variety of different acts express one's level of attitude, and its manifestation can be anticipated through analysis of the individual's behavior in evidence (Wated and Sanchez 2015).

Concerning sustainable or environmentally friendly food, positive attitudes relate to consumer recognition of aspects such as quality, safety, freshness, and health benefits. However, as much as there is a favorable manifestation of the consumer attitude, the available budget may be a limit to the consumption of this type of product (Elen et al. 2013).

In contrast, companies can influence attitudes, the multifaceted mental state of consumers, which involves beliefs, feelings, values, and character associated with the propensity to act in an environmentally friendly manner, presenting environmentally correct or more appropriate behaviors. These acts will motivate consumers' purchase and repurchase intentions, influencing their normative beliefs, changing their assessments, and modifying them with new concepts (Barber et al. 2012). In the choice and consumption of organic food, values related to health and environmental concerns strongly influence consumer attitudes towards repurchasing this type of food (Kriwy and Mecking 2012).

The repurchase intention refers to the willingness of the consumer to repurchase a product in the future, being influenced by consumers' perceptions of utility and hedonic values that affect their behavior (Wang and Yu 2016). It is worth noting that the intention or willingness to repurchase allows the consumer to perceive the recognition of the existence of a particular product for their consumption and the solution of their existing problem or demand (Paul and Rana 2012).

Thus, the intention to repurchase organic food is an individual's judgment about the purchase of the same product or service from the same origin or company that takes into account its current situation and the likely circumstances generated by its consumption, i.e., consumers have the perception that the given product offers quality or characteristics appropriate to their needs, wishes or expectations (Lee and Yun 2015; Wu et al. 2015).

Therefore, understanding and gauging repurchase intention presupposes that the consumers' future behavior depends on their attitudes, and internal and external norms, beliefs and values support the intention to repurchase even other products of the same brand (Keiningham et al. 2015; Lee and Yun 2015; Wu et al. 2015). In light of this, the tested Initial Theoretical Model verifies the relationship of environmental awareness and consumer attitude constructs as determinants of consumers' intention to repurchase organic food. Thus, the proposed Initial Theoretical Model is presented in Fig. 1, as well as the respective research hypotheses.

H_1: Consumer's environmental awareness positively influences consumer attitude towards organic food consumption; and.
H_2: Consumer's attitude positively influences organic food repurchase intention.

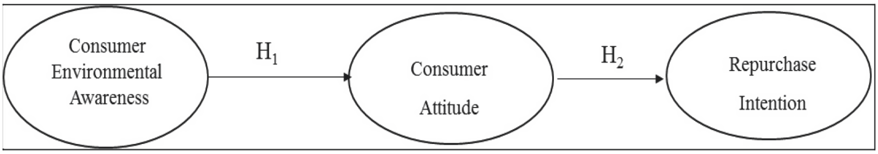

Fig. 1. Initial theoretical model and research hypotheses.

From a marketing perspective, the intention to repurchase is linked to the central attitudes to which consumers tend to respond favorably when evaluating the brands and offers of companies that are perceived to be consistent with their individual values and objectives (Bian and Forythe 2012).

The intention determines the specific behavior of a person, and in order to change this specific behavior, it is necessary to change the intention to perform such behavior. Intention to behave, or behavioral intent, is an indicator that can predict whether consumers will remain or change their choice of a particular company, brand, product or service and, more specifically, in the case of the intention to consume green or environmentally friendly products, can directly influence the repurchase behavior of organic products (Suki and Suki 2015). It is a belief that some consumers are willing to pay more for the privilege of making a green purchase and repurchase, i.e., of an environmentally friendly or organic product (Paul and Rana 2012).

Currently, a significant portion of consumers are increasingly aware of the dangers associated with the possibility of toxic substances in foods and, therefore, prefer the ones labeled as organic (Soares et al. 2017). However, most consumers do not have the technical knowledge to control the basic requirements that distinguish organic food from conventional food, especially regarding the chemical elements (inputs) that may have been used. Therefore, the concept of "organic food" can be treated as a quality and credible "brand," although it is necessary to rely on the integrity of the producer and the distributor or retailer, which is essential for the consumer to start buying this type of product regularly (Nuttavuthisit and Thorgesen 2017).

Green consumption refers to the preference of the individual consumer for companies, brands and products that are less harmful to the environment and their health. It's also related to ethical consumption and to environmental performance on the part of companies and producers, also combined with corporate social responsibility (Rustam et al. 2020; Nguyen and Nguyen 2019).

In this direction, Xu et al. (2020) point out that, recently, some studies have shown that consumer environmental awareness is increasing considerably (Du et al. 2018). Extending this discussion, we also decided to test a Nested Model, verifying consumer attitude and environmental awareness as determinants, in this order, of consumer's intention to repurchase organic food, differently as theorized in the Initial Theoretical Model, presented in Fig. 1. In this way, the Nested Model, the alternative to the Initial Theoretical Model, is presented in Fig. 2, as well as its research hypotheses.

H_3: Consumer's attitude positively influences consumer's environmental awareness regarding the consumption of organic food; and
H_4: Consumer's environmental awareness positively influences organic food repurchase intention.

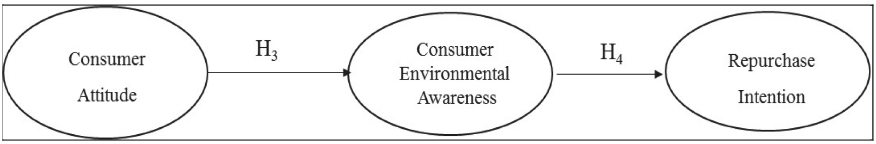

Fig. 2. Nest model and research hypotheses.

3 Research Method

The method employed is of a quantitative-descriptive nature, which is indicated when one wishes to describe the particularities of particular sets of variables (Malhotra et al. 2017; Blair and Blair 2015). The application of the research carried out employing a cross-sectional survey with a convenience sample (Hair Jr. et al. 2018).

In terms of data analysis, we used the structural equation modeling (SEM) technique. SEM is recommended for research with a higher degree of complexity, with different constructs and relationships of dependence, preserving the efficiency of statistics (Kline 2015; Byrne 2016), and through the estimation of the MLE (Maximum Likelihood Estimation) model, which allows the determination of various fit indexes (Hair Jr. et al. 2018; Kline 2015; Byrne 2016).

It is important to note that we chose a Nested Model (Fig. 2) following the propositions of Jarvis et al. (2003), which suggest comparing the respective model fit indexes (initial and nested) and the result of the hypothesis tests, where the nested model is an alternative model to the original (or initial) model, which may generate better results for its validation. The nested model is a model that is contained in the original theoretical model and tested with the same initial data set (Kline 2015), but that specifies at least one additional parameter to be estimated (Newson 2015; Petscher and Schatschneider 2019).

By defining the data collection instrument scales, when it comes to the operationalization of the constructs, a seven-point Likert scale was used, ranging from "1. I Totally Disagree" to "7: I Totally Agree", as it meets the essential requirement of continuous distribution necessary by structural equation modeling (Bearden et al. 2011).

For the Environmental Awareness construct, we used six variables in the scale (EA_1 to 6), adapted from De Toni et al. (2017), the Customer Attitude construct, we used three variables in the scale (CA_1 to 3), adapted from Paul et al. (2016), and the Repurchase Intention construct, we used five variable in the scale (RI_1 to 5), adapted from De Toni et al. (2017) based on Wu et al. (2015).

Next, we proceeded with the data collection instrument validation through face validity (Kinnear and Taylor 1996) and after we submitted the questionnaire to three experts in the area and a pre-test applied to twenty consumers of organic food. Data were then collected and used by the self-filling method (Malhotra et al. 2017).

It is important to note that, since such target population is not fully known, either in terms of sizing or profile, non-probabilistic (n) sampling was adopted for convenience, to facilitate data collection and the feasibility of access to possible respondents (Hair Jr. et al. 2018; Blair and Blair 2015). Thus, the sample was composed of consumers who have access to organic food consumption, residents of Serra Gaúcha - Brazil and, the collection was carried out between June and September 2018.

3.1 Data Preparation Procedures

The preparation and analysis of the raw data began with the analysis of missings (lost data) and outliers (atypical data), purifying the database so that the data acquire a more suitable format for the application of multivariate analysis (Hair Jr. et al. 2018).

We performed two categories of raw data analysis, following the assumptions for the application of multivariate techniques: (i) the identification of missings, which include lost data or missing values and outliers, related to atypical observations; and (ii) the analysis of the assumptions inherent to multivariate data analysis, which includes the verification of normality, homoscedasticity, linearity, and multicollinearity of the data (Hair Jr. et al. 2018; Malhotra et al. 2017; Kline 2015).

Following Byrne's (2016) indications, we only included listwise deletion questionnaires. Because the number of missings was less than 10% and not random, no questionnaire was ignored (Hair Jr. et al. 2018). After the analysis of the missings, we performed the analysis of outliers through two perspectives: (i) univariate analysis combinations, through Z-scores, and six questionnaires were eliminated from the sample because they had indexes higher than 3. In the case of Mahalanobis Distance (D^2) calculation, we considered conservative reference levels for D^2/df (0.005 or 0.001), i.e., values of 3 or 4 (Malhotra et al. 2017), which can assess the position of each observation on a set of variables and, because it is a sample with more than 200 valid cases, two questionnaires presenting values higher than 3 were eliminated. Thus, the final sample totaled 249 valid cases.

According to Malhotra et al. (2017), the last step in data preparation should be the multivariate analysis of statistical tests. We performed the normality tests through the data skewness test and the kurtosis test, the homoscedasticity by the Levene test, the linearity test with Pearson's Correlation Coefficients, and multicollinearity test with the Tolerance Value test and the Variance Inflation Factor (VIF), which presented acceptable levels for all variables (Warner 2013).

4 Results Analysis

4.1 Data Preparation Procedures

We obtained the final sample characterization (n = 249) through the information collection on gender, schooling, the types of organic food consumed, and the place of purchasing organic food. As for the gender of the respondents, the majority is female, corresponding to 59.04%, and 40.96% is male. The analysis of the respondents' schooling shows that the highest concentration of consumers had or has access to higher education, where they obtained incomplete higher education (36.93%), complete higher education (19.50%), but also postgraduate education in progress (9.96%), and postgraduate education completed (29.05%) representing 95.44% of respondents.

Regarding the types of food consumed, we verified that the most consumed items are: fruits with 27.49%, vegetables with 18.11%, eggs with 17.33% and, seeds with 10.78%. We also observed that the majority of respondents buy organic food at producers' fairs (37.67%); in supermarkets (30.75%); in specialized organic food stores (17.17%); in mini-markets and grocery stores (8.03%); and 6.37% in other establishments, sometimes direct from the rural producer.

Next, the convergent validity of the constructs was calculated using Confirmatory Factor Analysis (CFA), considering as parameters values above 0.5 (Kline 2015; Byrne 2016). In this study, we found both the composite reliability with indexes higher than 0.90 and the extracted variance, with indexes higher than 0.70 and therefore met the specifications in the literature (Malhotra et al. 2017), as shown in Table 1.

Table 1. Cronbach's Alpha, composite reliability and extracted variance.

Constructs	Cronbach's alpha	Composite reliability	Extracted variance
Environmental awareness	0.854	0.918	0.789
Consumer attitude	0.876	0.945	0.836
Repurchase intention	0.881	0.951	0.741

The next step in the data analysis was to check the discriminant validity using the method proposed by Fornell and Larcker (1981), by which the variances for each of the constructs are extracted and compared to the shared variances, obtained by calculating the correlations between the squared constructs (Malhotra et al. 2017). The results presented adequate discriminant validity between the constructs, as shown in Table 2.

Table 2. Discriminant validity.

Constructs	Environmental awareness	Consumer attitude	Repurchase intention
Environmental awareness	**0.789**		
Consumer attitude	0.424	**0.836**	
Repurchase intention	0.683	0.715	**0.741**

4.2 Theoretical and Nested Model Validation

The validation of the theoretical model was performed through the analysis of the model fit indexes. In the present study, as shown in Table 4, we chose to use absolute fit measures (GFI and RMSEA); incremental fit measures (AGFI, TLI, and NFI); and a parsimonious fit measure (CFI), to verify the quality of the model fit (Kline 2015).

Observing the fit indexes, we found satisfactory results for the GFI (0.917), IFI (0.931), TLI (0.957), and CFI (0.957) of the Initial Theoretical Model (Fig. 1). The RMSEA (0.078) is also adequate for the parameters recommended in the literature, as the values between 0.05 and 0.08 are acceptable (Byrne 2016). The AGFI measure (0.862) presented value in the boundary zone because it is higher than 0.80 but lower than 0.90, as recommended (Kline 2015), according to Table 3. It is noteworthy that, according to Bagozzi and Yi (2012), GFI and AGFI, in many cases, may result in values below 0.90, showing a lower performance than other measures. In the case of the nested model, all measures presented themselves in the boundary zone of the values indicated in the literature.

Table 3. Theoretical and nested model fit indexes.

Model fit indexes	Values	
	Initial theoretical model	Nested model
GFI	0.917	0.840
AGFI	0.862	0.734
NFI	0.931	0.873
IFI	0.957	0.898
TLI	0.938	0.850
CFI	0.957	0.896
RMSEA	0.078	0.120

The next step to validate the model was the hypothesis test, which contemplates the structural paths, non-standardized coefficients, standardized errors, t-values, and probabilities, which is presented, respectively, in Tables 4 and 5.

Table 4. Hypothesis test of the initial theoretical model.

Hy	Structural path	Non-standardized coefficients (b)	Errors	Standardized coefficients (β)	t-values	p	Result
H_1	EA → CA	0.854	0.136	0.586	6.276	0.000	Supported
H_2	CA → RI	0.926	0.095	0.929	9.748	0.000	Supported

Note: Significance level at 0.05.

Table 5. Hypothesis test of the nested model.

Hy	Structural path	Non-standardized coefficients (b)	Errors	Standardized coefficients (β)	t-values	p	Result
H_3	CA → EA	0.522	0.077	0.863	6.761	0.000	Supported
H_4	EA → RI	1.597	0.230	0.933	6.950	0.000	Supported

Note: Significance level at 0.05.

As shown in Tables 4 and 5, the hypotheses formulated in the Theoretical Model were statistically supported, being $\mathbf{H_1}$ (consumer's environmental awareness positively influences consumer attitude towards organic food consumption, $\beta = 0.586$, $p < 0.001$) and $\mathbf{H_2}$ (consumer's attitude positively influences organic food repurchase intention, $\beta = 0.929$, $p < 0.001$), confirming the indications of Lee and Yun (2015) and Wu et al. Similarly, the assumptions proposed in the Nested Model **H_3** (consumer's attitude positively influences consumer's environmental awareness regarding the consumption of organic food, $\beta = 0.863$, $p < 0.001$) and **H_4** (consumer's environmental awareness positively influences organic food repurchase intention, $\beta = 0.933$, $p < 0.001$) as pointed out by Suki and Suki (2015) and Paul and Rana (2012).

Present the structural models formed by latent variables (constructs), observable variables (indicators), and measurement errors, inserted for each of the constructs, both of the Initial Theoretical Model and the Nested Model, as well as their respective hypothesized relationships.

By checking the strength of the relationships tested, we observed in the path diagrams, in the Initial Theoretical Model, the coefficient of the path EA → CA is 0.85 and of CA → RI it is 0.93. In the Nested Model, the coefficient of CA → EA is 0.52, and of EA → RI, it is 1.60.

When analyzing the results, we found that the research hypotheses of both the Initial Theoretical Model and the Nested Model were statistically supported; however, the Initial Theoretical Model presented superior model fit indexes. To expand the validation of the models, another way to verify the explanatory power of the model is through the coefficients of determination (R^2) (Malhotra et al. 2017). Table 6 presents the R^2 of the Initial Theoretical Model and the Nested Model.

Table 6. Coefficients of determination (R^2).

Constructs	Coefficients of determination (R^2)	
	Initial theoretical model	Nested model
Environmental awareness	0.341	0.699
Consumer attitude	0.344	0.745
Repurchase intention	0.870	0.863

The Initial Theoretical Model presented the following coefficient of determination (R^2): 0.870, that is, 87.0% of the variance of the intention to repurchase organic food by consumers (dependent variable) can be explained by its independent variables, in this case, environmental awareness and consumer attitude. This result represents a reliable explanatory power of the model (Malhotra et al. 2017). Regarding the Nested Model, the coefficient of determination presented an $R^2 = 0.863$, that is, 86.30% of the variance of the intention to repurchase organic food by consumers (dependent variable), which is explained by its independent variables, in this case, the consumer attitude and environmental awareness. Therefore, it is possible to conclude that the Initial Theoretical Model, taking into account the fit indexes of the model (Table 4) and its R^2, presents a better fit and a superior explanatory power in comparison to the Nested Model.

5 Discussion and Conclusion

The interest in this research field was motivated by the opportunity to generate evidence on consumer behavior concerning the consumption and repurchase of organic, ecologically correct food, in order to test determinants of consumers' repurchase intention (Paul and Rana 2012; Ari and Yilmaz 2016). This objective is based on future research indications from the primary studies in the area, and which highlight the need for new discussions in the literature, when dealing with a perspective on environmentally responsible healthy consumption (Anninou and Foxal 2017).

When reflecting on the testing of the Nested Model, the confirmation of the relationship of Environmental Awareness as an antecedent of Consumer Attitude stands out as a theoretical contribution. This relationship was also presented and confirmed in the model proposed and tested by Wang et al. (2018) and Paul and Rana (2012). The highlight of this contribution is the fact that the Initial Theoretical Model presented higher model fit indexes, as well as the coefficient of determination (R^2) (Table 4). This result confirms the results of several studies in which environmental awareness is evidenced as an antecedent of consumer attitude, as pointed out by the studies of Suki and Suki (2015) and Zhang et al. (2019), besides these two constructs are configured as determinants of consumers intention to repurchase organic food.

An essential contribution in this study is the testing of alternative models, an initial theoretical model, and a nested model, a procedure recommended to verify the relationship between two models that intend to show which model, comparatively, has the best explanatory effect (Huang 2017). Because of this, the dependent variable, the Repurchase Intention, in the Initial Theoretical Model presented a coefficient of determination ($R^2 = 0.870$) with strong explanatory power, slightly higher than that of the Nested Model ($R^2 = 0.863$). This result, in addition to the model fit indexes and previous evidence found in the literature, sustains that the consumers' preference for repurchasing organic food is a behavioral effect. This is linked to consumers' personality traits, their environmental awareness and their attitudes towards organic food, which suggest that values and environmental concern are determinants of environmentally healthy consumption, due to their involvement with conservation practices and concern for the environment and society, in addition to their concern for better well-being and quality of life (De Toni et al. 2017; Farias et al. 2019).

Even if the nested Model's fit measures did not generate a result superior to the Theoretical Model (Table 3), all the hypotheses that emerged from this model have been confirmed. These results, very close to the Theoretical Model, reinforcing the relationship of environmental awareness in the consumer's attitude as antecedents of the repurchase intention, in a way, help to partially validate the proposed Theoretical Model, as well as the justifying the nested model, improving its parsimony and, as a result, the confirmation of the hypotheses.

Specifically, concerning organic food, it is worth mentioning that these products were cultivated, processed and commercialized according to organic standards, free of artificial inputs, such as chemical fertilizers, pesticides, veterinary drugs, hormones, antibiotics, and genetically modified organisms, produced through natural processes, through sustainable energy, taking into account soil protection. In this sense, they can be included in consumers' purchasing habits due to the benefits they bring to human health compared to conventional or industrialized products (De Toni et al. 2017).

Taking into account the results evidenced in this research, it becomes clear the need for business strategies and government actions to strengthen the consumption of organic food through public policies that mobilize the consumption of these products even in schools and other public institutions.

As managerial implications, we point that there is room in the market for company managers (producers, manufacturers, distributors, and retailers) to disseminate a higher volume of information (differences, benefits, advantages) of organic food compared to industrialized food, adopting more effective communication strategies to reinforce consumers' environmental awareness, not only related to the consumption of organic food but also an awareness focused on the preservation of the environment and respect for nature, life and other people. In this context, the creation of stamps of the origin or even designations of origin could add value to organic food, not only strengthening environmental awareness but also reinforcing a favorable attitude of consumers towards organic food, which may win not only a preference but perhaps repurchase or loyalty on the part of consumers.

As a limitation of the study, we point out that because it is a study applied to a non-probabilistic sample, for convenience, the scope of the sample is restricted because it has been applied to a profile of usual buyers of this type of food, with specific characteristics (profile), giving up a market of potential future consumers, which may have personal characteristics or related to the consumption of different organic foods.

In future researches, we suggest, therefore, studies with greater representativeness that take into account the reason why consumers do not consume organic food, with a larger sample, with different profiles, even contemplating regionalities, nationalities, and diverse consumer cultures. There is also the possibility of applying the Initial Theoretical Model, which showed better results in a different context from the one investigated, relating the consumption of organic food or industrialized food, in addition to the possibility of researching the alternative of purchasing organic food online. On the other hand, instead of investigating, as a model-dependent variable, the repurchase intention, the retention or loyalty to certain types of organic products or the brands of manufacturers of this type of products could be tested.

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Resilient Sustainable Supplier Selection Criteria Assessment for Economics Enhancement in Industry 4.0 Context

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Abstract. In recent years, market globalization and natural disasters that companies have experienced oblige them to consider technologies from Industry 4.0, and smart manufacturing to improve their supply chain performance and customer satisfaction. Digitalization leads companies to a faster, flexible, and efficient supply chain. The improvement of organizations' performance and high competitiveness depends on their suppliers. In our days, companies need to include other criteria such as resilience, smartness, and sustainability in supplier selection to acquire a competitive advantage. This paper aims to discuss supplier selection criteria in digital, resilient, and sustainable supply chains, examine the relationship between them and prioritize them. This study presents a questionnaire survey addressed to professionals' experts to determine the main criteria related to the resilient, sustainable, and digital context that impact the supplier selection in different industries. To analyze and prioritize the supplier selection criteria, the authors use the approach of the analytical hierarchy model (AHP). The results are useful for practitioners and academics as they illustrate the decision-making with multiple criteria.

Keywords: Supplier selection · Digital supply chain · Resilience · Sustainability · AHP · Multicriteria

1 Introduction

The main objective of the managers has always been to have an efficient supply chain, faster and at the lowest cost. In the meantime, supply chains have become more complex, more expensive, more uncertain, and more vulnerable. Unexpected exchange rates, supply fluctuations, volatile economies, political instability, unpredictable demand, and natural disasters are examples of significant uncertainties in an organization's environment [1–3]. To effectively deal with this dynamic complexity and growing challenges, supply chains need to become much smarter and resilient [4].

One of the principal factors in increasing the organizations' competitiveness is to select the right supplier for the right mission [5, 6]. In other words, in smart supply chain management, supplier selection is highlighted as a critical and sophisticated decision problem (Chattopadhyay et al., 2016). Evaluating and selecting suppliers is a complex

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task for decision-makers as they have to consider different criteria. Therefore, it is crucial to choose the appropriate criteria for supplier selection that will allow companies to reduce purchasing risk and increase the profitability of the entire supply chain [7].

In previous studies, much attention has been paid to the issue of supplier selection [8] (Chattopadhyay et al., 2016). Several authors have considered the multi-criteria methods for supplier selection using AHP, TOPSIS, DEMATEL, and ISM. Others have used a hybrid multi-criteria approach. However, most of these researches have considered the quality, cost, reliability, and delivery time as the main criteria for selecting a supplier [9, 10]. Further ones show that other factors must be included in the process of supplier selection for a smart supply chain in a crisis environment [3]. Therefore, it is important to include new criteria that deal with the smart supply chain implementation and crisis situation to achieve sustainability, agility, and resilience. To do so, the main criteria to include are those related to 'resilience' and 'smartness' beside the ecological, economic and social concern to keep sustainable, smart, and resilient supplier selection.

A supply chain's resilience is its inherent capacity to maintain or recover stable actions and performance, enabling it to continue regular operations after a disruptive event. Resiliency is achieved by the acquisition and implementation of technology through industry 4.0. Thanks to Industry 4.0's technological advancements, the supplier will acquire new technology and technical assets for research and development activities and processes in order to enhance the product creation process in terms of quality and quantity while also reducing development time.

This study aims to fill the gap by prioritizing supplier selection criteria in the context of digitalization and resiliency. It addresses the new category of criteria born with supply chains 4.0. In addition, this paper aims to provide academicians with other criteria that enable the supply chain to cope with crises. Therefore, due to its mathematical simplicity and flexibility, AHP method has been widely used by numerous researchers in various fields, such as education, manufacturing, food, health, etc., to solve multi-criteria decision problems. According to this, the AHP method is used to prioritize supplier selection criteria in the digital era, and then rank the suppliers. More clearly, we provides a framework for dealing with logical, quantitative, and qualitative dimensions of multiple criteria situations by: (1) Identifying the criteria and sub-criteria related to supplier selection in a context of resiliency, digitalization, and sustainability; (2) Addressing a survey to collect professionals' opinions to attribute weights to the criteria; (3) Developing an AHP model to prioritize suppliers and (4) Illustrating the findings with a case study.

This article is organized as follows: in the following section, we present the literature review to well understand the smart supplier selection and methods used in the literature to select suppliers. Section 3 describes the research methodology used for the study. And finally, Sect. 4 illustrates the application of AHP for smart supplier selection.

2 Literature Review

2.1 Smart Supplier Selection

The transformation of the classical supply chain into an intelligent supply chain requires the recent deployment of advanced intelligent technologies (the Internet of

Things (IoT), blockchain, CPS (Cyber-Physical System), large data analysis, virtual and augmented reality (VR and AR) and artificial intelligence (AI) techniques. All actors of the supply chain will be perceptible, intelligible, transparent, and optimized, through this transformation [11]. The digital supply chain challenges the option of suppliers through dynamic order allocation and offers new possibilities by using digital data to improve purchasing decisions [1].

When we mention the supplier, it refers to all parties directly and indirectly engaged by the manufacturer [12]. Supplier selection is an intensively researched process due to its impact on supply chain purchasing management [13]. Indeed, suppliers play an essential role in supply chain management. It focuses on evaluating supplier selection and ensuring a productive relationship between different segments of the supply chain [12]. Therefore, the careful selection of the right supplier for the right mission is essential for improved performance [5, 6].

The issue of partner selection in the supply chain is the subject of several kinds of research. Previous studies have shown that the evaluation and selection of suppliers cannot be based on a single criterion, and therefore they use multi-criteria decision-making techniques (MCDM). To classify a set of suppliers in an intelligent logistics environment [8], have developed a decision support system to integrate and process imprecise heterogeneous data in a unified framework. Ref. [14] adopted a multi-agent systems (MAS) approach to handling the process of evaluating and selecting sustainable suppliers in order to provide an appropriate communication channel, structured information exchange, and visibility among suppliers and manufacturers. To identify smart supply chain management practices, Ref. [11] present a new framework for supplier selection criteria in a sustainability context. Its proposed approach is a hybrid approach that combines the approximate and fuzzy DEMATEL-TOPSIS method for selecting sustainable suppliers for an intelligent supply chain. Ref. [1] developed a hybrid approach combining simulation and machine learning. This author examines its applications to data-based decision support in the selection of suppliers in a resilience context. Ref. [15] used the approach of the analytical hierarchy model (AHP) to analyze the supply chain 4.0 risks.

The authors examined Supply Chain Risk Factors 4.0 and categorized them into 11 risks under five major risk factors. Other researchers used other techniques like Artificial intelligence (AI), methods based on cost, or mathematical programming methods (MP) to evaluate and select suppliers [16]. However, papers dealing with the analysis of supplier selection criteria while considering the integration of resilience and digitalization are not undertaken.

2.2 Supplier Selection Method

Since the nineties, there has been an evolution in the role and structure of the purchasing function, and the supplier selection problem has become one of the crucial issues for establishing an efficient supply chain system [17]. Supplier selection is a strategic process for organizations due to the high firms' dependency on the purchasing process. The supplier selection process is based on the selection of suppliers with the highest potential to meet the needs of a manufacturer and with acceptable overall performance. The selection of the right supplier from a large number of possible suppliers depending on various levels of capabilities and potential becomes a difficult task [18]. Indeed, each process of supplier selection is different due to many factors that are taken into consideration when making that selection, such as the needs of the manufacturer, the type of product, the type of industry, etc. Companies must intelligently delineate their supply chain strategy, considering the value of the supplier selection. There is no best way to select the right supplier. However, several methods and approaches are used by decision-makers for the selection process. There are many methods for supplier selection and evaluation according to the literature [17] (Table 1).

Table 1. Classification of the supplier selection methods

	Supplier selection method	References
Statistical approach	Cluster Analysis (CA)	[19, 20]
	Multi-Nominal Logit (MNL)	[21]
	Utility Theory (UT)	[22]
	Factor Analysis (FA)	[23]
	Interpretative Structural Modelling (ISM)	[24, 25]
Multi-Criteria Decision Making (MCDM) or Multi-Attribute Decision Making (MADM)	Analytical Hierarchy Process (AHP)	[15, 26–29]
	DEMATEL	[5, 6, 30]
	Analytic Network Process (ANP)	[31–34]
	Technique for the Order Performance by Similarity to Ideal Solution (TOPSIS)	[35–37]
	Multiple Attribute Utility Theory (MAUT)	[38]
	Outranking Methods (ELECTRE, PROMOTHEE)	[39]
	Fuzzy set theory	[11, 40, 41]
Methods based on cost	Activity Based Cost (ABC)	[42]
	Total Cost of Ownership (TCO)	[43, 44]
Mathematical Programming models	Linear Programming (LP)	[45]
	Multi-Objective Linear Programming (MOLP)	[46–50]
	Goal Programming	[51–53]
Artificial intelligence	Case Based Reasoning (CBR)	[54]
	Artificial Neural Network (ANN)	[55, 56]
Combined approaches	Fuzzy + AHP	[57, 58]
	Fuzzy + TOPSIS	[59–61]
	ANP + TOPSIS	[62, 63]
	Fuzzy Neural Network	[3]
	Fuzzy DEMATEL-TOPSIS	[64]
	AHP + MOLP	[65]

3 Research Methodology

To prioritize supplier selection criteria and select the best supplier using the AHP method, we propose the following research methodology. For the research methodology, three main steps are followed to the supplier selection decision model: criteria identification, data collection, and supplier prioritization. Figure 1 shows the structure of the model.

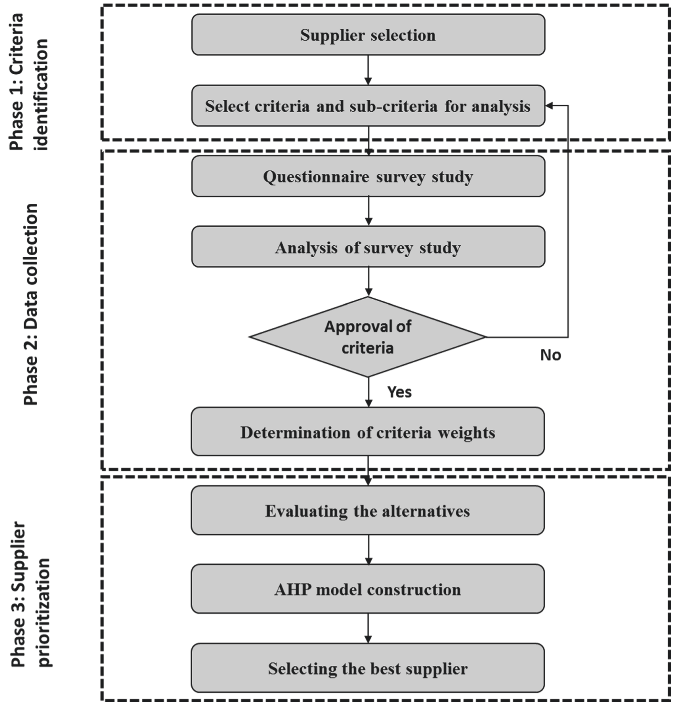

Fig. 1. Structure of proposed supplier selection model

4 Criteria Identification and Data Collection

4.1 Criteria Identification

The perfect combination of identifying the decision-making criteria and the method used to select suppliers is the main factor determining the growth and competitiveness of a company. The importance of choosing the right supplier has several benefits like reducing purchasing risks, maximizing overall value for the buyer, reducing project delays (on-time delivery), improving customer satisfaction, reducing costs, and developing strategic alliances between supplier and buyer, ultimately leading to competitive advantages. Traditionally, supplier selection has followed a price-based approach. However, companies today have become aware that price, while important, is not enough to achieve a competitive advantage. Indeed, a more comprehensive multi-criteria approach is needed to solve the problem of selecting appropriate suppliers. In the last decade, companies integrated a new perspective for the supplier selection criteria, such as supplier's resilience, environmental aspect, social aspect, etc.

As a result of the literature review regarding the selection of suppliers, 8 main criteria and 14 sub-criteria are presented in the following Table 2. Each criterion is identified by considering the characteristics of the domestic construction industry (e.g., size of the industry, general procurement trends, etc.).

Table 2. Supplier selection main criteria and sub-criteria

Criteria	Sub-criteria
Cost	–
Quality	–
Delivery	–
Flexibility	–
Technological capability	Responsiveness
	Reliability
	Real time data
	Leagility
	Innovation
Resilience	Collaboration
	Viability
	Risk awareness
Ecological concern	Environmental cost
	Environmental management
	Reverse logistic
Social concern	Employee right
	Mutual trust
	Effective communication

4.2 Questionnaire Survey

Once the criteria are selected, the next step is to collect the expert opinion to determine the weights of each criterion. The structure of the questionnaire survey includes all the main criteria and sub-criteria, as well as an open-ended question that allows the respondent to introduce additional criteria for selecting suppliers that are important to consider. This question is optional. As a measurement scale, the five-point Likert scale is used to assess the significance of each criterion: (Low importance, less important, important, very important, extremely important).

The questionnaire is addressed to 250 professionals in the industrial sector. The target professionals for this survey are project managers, site managers, and purchasing managers of different sectors. The sectors chosen for this study are the aeronautics, automobile, electronics, and textile sectors. 81 answers out of 250 questionnaires are obtained, 21 of them are removed for lack of information (incomplete questionnaire). The analysis was made based on information from 60 surveys. The distribution of survey participants by sector is shown in Fig. 2. Verification of the validity and reliability of the 60 surveys was done through the use of the SPSS software. Indeed, correlation analysis and a coefficient are obligatory to determine the reliability of the study. To verify the reliability of the study, SPSS uses Cronbach's alpha value, which is between 0 and 1. To be considered highly reliable, the value must be between 0.8 and 0.9 [66].

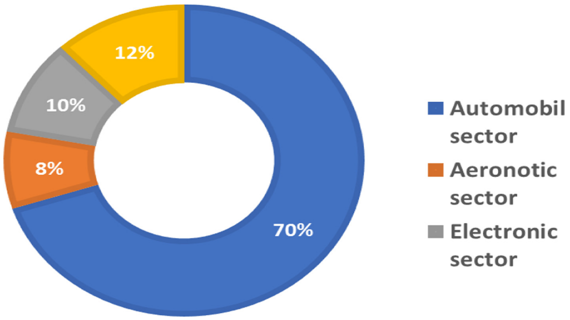

Fig. 2. Distribution of survey participants by sectors

5 Supplier Selection Prioritization with AHP Method

The Analytical Hierarchical Process (AHP) was introduced by Thomas L. Saaty in 1980 and is recommended for solving complex problems. Indeed, AHP is a decision-making method that allows factors to be structured in a hierarchical way when multiple criteria have to be considered when making a decision. Deconstructing a problem is usually done through three different levels that include objective, qualitative or quantitative criteria, and alternative.

5.1 Developing the AHP Model

To develop an AHP model, it is necessary as a first step to formulate a hierarchy containing the objective, the factors, and the choices, as shown in Fig. 3. The first level concerns the objective of the study, which is the selection of a suitable supplier. The second level consists of the criteria that we will use for decision-making. Thus, we determine nine criteria for decision support, namely: cost, quality, delivery, flexibility, technological capacity, resilience, reliability, environmental concern, social concern. The third level of this hierarchy consists of the results. In other words, it is the choice of suppliers.

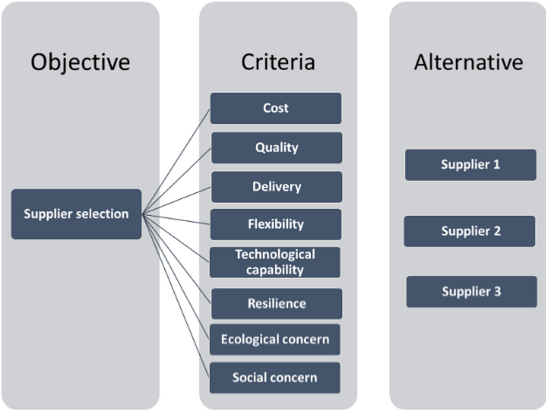

Fig. 3. Hierarchy of supplier selection

5.2 Weights Evaluation and Pair-Wise Comparison

The AHP presumes that the criteria do not have the same importance. Therefore, it is mandatory to determine the relative priorities of the criteria (the weights). To generate the weights of the criteria, the paired comparison decision matrix must be developed. Then to determine the relative importance of each alternative, a pair-wise comparison must be made for each criterion. In this way, decision-makers express their preferences. AHP generally uses a nine-point numerical scale, called the Saaty scale, used for translating human judgment to make criteria comparisons. The weights of the alternatives reflect the relative importance of the criteria in achieving the objective of the hierarchy [17]. The values of the AHP pair-wise comparisons are determined by Saaty's (1980) scale. Table 3 presents the corresponding comparison matrix between the considered criteria.

Table 3. Pair-wise comparison matrix

	C1	C2	C3	C4	C5	C6	C7	C8
C1	1	1	1	5	7	5	9	7
C2	1	1	1	5	5	5	9	9
C3	1	1	1	3	7	5	9	9
C4	1/5	1/5	1/3	1	3	1	5	5
C5	1/7	1/5	1/7	1/3	1	1	5	7
C6	1/5	1/5	1/5	1	1	1	5	7
C7	1/9	1/9	1/9	1/5	1/5	1/5	1	1
C8	1/7	1/9	1/9	1/5	1/7	1/7	1	1
Sum	3.79	3.82	3.89	15.73	24.34	18.34	44	46

To allocate a relative weight to each criterion, it is necessary to standardize the previous comparison matrix. Normalization is done by dividing each value in the table by the total value in the column. At this stage, it is necessary to measure the estimated level of consistency of the vectors. The AHP calculates a Coherence Ratio (CR) comparing the Coherence Index (CI) of the matrix in question to the Coherence Index of a random type matrix (RI) (Saaty, 2012). In our study, CR = 0,08 < 10% so the vectors are consistent. After developing the pair-wise comparison matrix and calculating the consistency ratio, weights are generated, as shown in Table 4.

Table 4. Criteria weights

Criteria	Cost	Quality	Delivery	Flexibility	Technology	Resilience	Ecology	Social
Weight	25%	25%	24%	6%	8%	7%	2%	2%

As shown in Table 5, cost, quality, and delivery are the main criteria for selecting a relevant supplier with the following percentages: 25%, 25%, and 24%, followed by technological capability with 8% and resilience with 7%. Then we have flexibility with 6%. Finally, the respondents did not give much importance to ecological and social criteria. These results confirm that, besides the traditional criteria for supplier selection such as cost, quality, and delivery, companies are beginning to be aware of the importance of including the resilience and digital factors as criteria to select a supplier to achieve competitive advantages.

5.3 Case Study in Automotive Sector

A case study was conducted in a company in the automotive sector to prioritize suppliers. To obtain the wheels, the company has to decide which of the three suppliers is the most suitable one, namely supplier "X" supplier "Y" or supplier "Z". This step consists of ranking the three suppliers according to the criteria defined and weighed previously. As was done with the initial group of criteria, it is necessary to assess the relative weights of the criteria for the second level of the hierarchy. This process is conducted in the same way as the evaluation step for the first level of the hierarchy (group of criteria). Having the comparison matrix allows us to compare the different knowledge taking into account the criteria defined in step 2. After this, we calculate the matrix by inserting the average solutions after normalization in the first column and the decision criteria in the first row. Thus, we can rank supplier "X" as the most relevant taking into account the nine criteria with a percentage of 69% followed by supplier "Y" which represents 24%, and supplier "Z" which represents 7%.

According to Table 5, the most relevant supplier is determined according to the score of each criterion. The most relevant supplier is Supplier "X" due to its openness, in addition to the traditional economic criterion such as cost reduction, quality increase, and on-time delivery, to other criteria that allow increasing its competitiveness and ability to face the crises. The criteria of resilience, technological capacity, and flexibility enable the realization of a digital supply chain. Besides, the supplier "X" expresses his interest in ecological criteria and social criteria. Combining economic with ecological and social criteria enables the supplier to join the sustainability. The supplier “Y” is not relevant due to its only interest in some traditional criteria such as reducing cost, increasing quality, and technology. Not considering the criterion of on-time delivery is one of the reasons for the dysfunctionality of the supply chain. Supplier “Y” does not consider the resilience criteria. Yet, these criteria allow the supply chain to deal with uncertain events. The digitalization of the supply chain and its ability to deal with crisis contexts are two complementary elements.

Table 5. Supplier alternative rankings

	Cost	Quality	Delivery	Flexibility	Reliability	Technology	Resilience	Ecology	Social	Average
Supplier « X »	0.65	0.68	0.75	0.67	0.75	0.67	0.78	0.65	0.65	69%
Supplier « Y »	0.29	0.24	0.18	0.27	0.18	0.27	0.17	0.29	0.29	24%
Supplier « Z »	0.06	0.08	0.07	0.06	0.07	0.06	0.07	0.06	0.06	7%

6 Managerial and Researcher Implications

The information provided in Table 4 is useful for our study. Using the AHP process allowed us to prioritize the criteria according to their importance. The main objective of using the AHP was first to determine the most important criteria to select the relevant supplier in a resilient and smart context. Then, choosing the important criteria in a smart and resilient context is essential for creating a good relationship with suppliers while providing future risks that may be incurred due to market fluctuations.

According to Table 4, the most important criteria are cost, quality, and delivery with respective weights of 25%, 25%, and 24%. These results mean that companies consider these criteria as determining factors for choosing the right supplier. These criteria allow companies to increase their economic performance. In the second place, we have technological capability criteria with a weight of 8%. Results prove that considering the technological capability, improves the capacity to respond and provide the information on time. Also, it increases their reliability. Considering technologies from industry 4.0 lead managers to an improvement of their economic strategy. Besides the smart criteria, the resilient criteria, being in the third place with a weight of 7%, enable managers to prevent potential blockage in the collaborative supply chain due to market globalization and natural disasters. According to companies, the flexibility criteria is classified in the fourth place with a weight of 6%. This criterion should be considered while choosing the supplier to increase the capacity of the supplier to respond to changing demand. Ecological and social concerns are the last criteria chosen by the companies with a weight of 2% for each criterion. This not means that they don’t take into consideration these criteria, that means that they become aware that these criteria are important to the improvement of their sustainability. However, managers have to be careful when they develop business relationships with suppliers. Because trust and cooperation become critical ingredients in a collaborative supply chain. The information must be collected and shared all along the supply chain in both forward and backward flows. Mutual trust criteria and effective communication combined with technologies from the smart industry provide adequate visibility across both internal supply chain functions and organizational. Suppliers are nowadays obliged to consider the respect for the environment that includes reducing the negative impacts of reverse logistics on the environment and limiting the use of natural resources for a better future.

To better classify the supplier selection criteria, Fig. 4 presents the criteria classes with sub criteria.

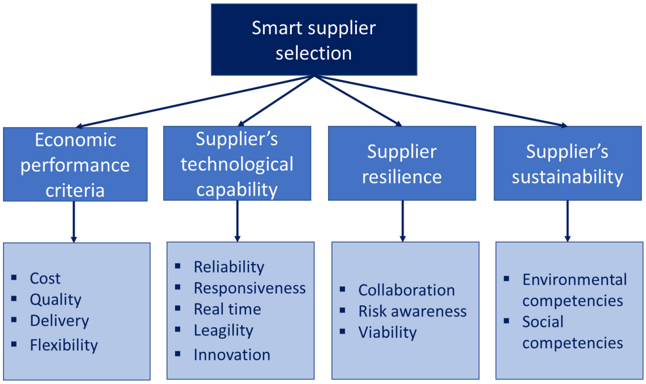

Fig. 4. Supplier selection criteria and sub-criteria.

7 Conclusion and Future Works

Choosing the relevant supplier is a crucial task for a manager due to the complexity of the decision-making. Selecting the right supplier for the right mission is the main objective of managers to increase their profitability and performance improvement. Facing multiple supplier selection criteria requires companies to define their supply chain strategy. To do so, our study used the MCDM method, and more particularly the AHP process, to classify the criteria according to their importance.

The AHP is an appropriate method for supplier selection. It helps to solve complex decision issues. In our study, the AHP contributes to prioritize selection criteria and ranking suppliers according to these criteria. In fact, we used an algebra metrics-based mathematical approach to determine the relevance of the eight criteria. First, we used the qualitative approach to convert issues into a hierarchy. Then, based on a quantitative approach, we used the pair-wise comparison strategy to achieve more reliable responses and reliability.

As a practical contribution, this paper proposes an architecture of decision method for supplier selection that will help improve the selection process and choose the appropriate supplier in the digital supply chain. In addition, this study highlights the necessity of considering other criteria that increase organizations' competitiveness such as the 'resilience' and 'smartness' in supplier selection. The findings of this study enable managers and practitioners to improve the performance of the supply chain by considering the main criteria for selecting the relevant suppliers. However, this study also presents some limits related to the variety of criteria for supplier selection. In fact, our results remain to be discussed and reinforced in future works by introducing new criteria that could affect the process of supplier selection. In addition, it is preferable to review the AHP calculations taking into account the new criteria to be introduced.

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Selection of Abandoned Areas for Implantation of Solar Energy Projects Using Artificial Neural Networks

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Abstract. The increasing demand for energy has intensified recently, requiring alternative sources to fossil fuels, which have become economically and environmentally unfeasible. On the other hand, the increasing land occupation in recent centuries is a growing problem, demanding greater efficiency, particularly in the reuse of abandoned areas, which has become an alternative. An interesting alternative would be installing energy facilities like solar, wind, biomass, and geothermal, in these areas. So, in this way, the aim of this work is to classify these abandoned areas to verify which ones would be suitable for solar energy facilities specifically, to reuse those areas. Artificial Neural Networks (ANNs) trained with the Levenberg-Marquardt Algorithm (LMA) were used for the classification task. The main innovation of this work is the optimization of the initial weights of the ANN using the Quantum-behaved Particle Swarm Optimization (QPSO) metaheuristic, through QPSO-LMA proposed algorithm. In terms of Mean Squared Error (MSE), the QPSO-LMA approach achieved a decrease of 19.6% in relation to the classical LMA training with random initial weights. Moreover, the model's accuracy showed an increase of 7.3% for the QPSO-LMA over the LMA. To validate this new approach, it was also tested on six different datasets available in the UCI Machine Learning Repository and seven classical techniques established in the literature. For the problem of installing photovoltaic plants in abandoned areas, the knowledge acquired with the solar dataset can be extrapolated to other regions.

Keywords: Solar energy · Soil reuse · Artificial Neural Networks · Quantum-behaved Particle Swarm Optimization

1 Introduction

The growing demand for energy has intensified in recent decades, requiring alternative sources to fossil fuels [1], which have become economically and environmentally unfeasible [2–4]. In addition, the increasing occupation of urban spaces in recent centuries has become a problem [5], requiring greater efficiency in land occupation, especially in the reuse of abandoned areas, one of the major current challenges [6].

This problem is more serious when these areas are large and contaminated, constituting a risk to the environment, health and the economy [6, 7]. Therefore, renewable

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energies, such as solar energy, have proved to be feasible alternatives that enable productivity and social and environmental wellness [8]. They are abundant, clean and, above all, free [9, 10], and can be used in energy generation projects in areas that are currently unused, reconciling the demand for energy and the recovery of these areas.

These abandoned areas, contaminated by substances harmful to the environment and human health, have attracted the attention of governments and non-governmental organizations [11, 12]. Examples can be cited, such as: abandoned mines, generally contaminated by heavy metals [13]; brownfields, which are abandoned industrial installations; areas of the Superfund, an American federal government program for locating and cleaning up contaminated areas; landfills, mainly for the disposal of food leftovers and packaging [14]; and areas for solid waste, as defined by the Resource Conservation and Recovery Act (RCRA).

Today, around the world, there is installed power of approximately 2,180 GW. Together, all the 81,533 points analyzed in this work have an estimated potential of more than 6,775 GW, approximately 3 times what is generated worldwide. This potential is equivalent to over 44,000,000 tons of carbon dioxide (CO_2) that would no longer be released into the atmosphere. There are over ten million jobs in the renewable energy sector. With the creation of renewable projects in areas that are currently out of use, it would be possible to multiply this number, making a positive impact on the environment, the economy and society.

The objective of this paper is to develop a classification methodology, based on Artificial Intelligence (AI) and Quantum Theory (QT), to automatically carry out the classification of abandoned areas suitable for the settlement of these power plants. This innovation will be tested using the classification problem of abandoned areas suitable for solar energy facilities as well as another six classic problems from the literature. The results will also be compared with seven classification algorithms established in the literature.

The main contributions of this article are:

- Improvement of Artificial Neural Network (ANN) performance by optimizing initial weights using the Quantum-behaved Particle Swarm Optimization (QPSO);
- Automatic selection of suitable areas for the implementation of renewable energy projects.

This paper is organized as follows. Section 2 presents the theoretical framework. The methodology for the proposed problem is presented in Sect. 3. Section 4 shows the results and a discussion about them for the set of solar data; besides, this section shows six datasets from the literature and other seven classical algorithms used for comparison and validation of the proposal. Finally, the conclusions are presented in Sect. 5.

2 Theoretical Framework

Traditional AI aims to represent intelligent behaviors through exact and complete representations of knowledge. However, many real-world problems cannot be described exactly, or the appropriate knowledge of their operation is not available (they are "black boxes"). Computational Intelligence (CI) emerged as a solution to these difficulties, without requiring much a priori knowledge of a problem, producing robust and adaptable (flexible) solutions for diverse scenarios [15].

The field of CI involves paradigms of Computational Science and Operational Research with a view to implementing systems that represent intelligent behavior (which may be defined as the ability to learn and apply this learning to new scenarios) in complex decision-making processes. Of these paradigms, those inspired by nature are predominant, such as ANN, Fuzzy Systems (FS) and Evolutionary Computation (EC), in addition to hybrid systems, which have advantages such as flaw tolerance and incompleteness or inaccuracy of the data used as an input for the algorithms [16].

One type of problem addressed by the CI is the pattern classification problem, such as text recognition [17, 18], image recognition [19], classification of bone fractures [20, 21], endometriosis [22], arrhythmia [23, 24], mineral quality [25] and the identification of medicinal herbs [26].

Among the many techniques available to address classification problems, we may cite Naïve Bayes [17, 27], Decision Trees [28, 29], Support Vector Machines [29, 30], Gaussian Process Classification [31, 32], k-Nearest Neighbors [33–35], Ensemble methods [36–38] and Neural Networks [39–41].

With the rapid advances in the field of AI in recent years, many approaches have been implemented to improve ANNs. To achieve a general overview of the field, scientific articles were collected from the Scopus, Science Direct and Web of Science databases, which were searched using the terms “computational intelligence”, “artificial neural network”, “hybrid optimization” and “machine learning”.

Analyzing the most cited articles published between 2019 and 2020, hybrid models use metaheuristics in two main ways. First, for the optimization of the ANN hyper-parameters, such as the number of hidden layers, the number of neurons in each hidden layer and the damping factor (in the case of the Levenberg-Marquardt Algorithm, LMA) or learning rate and momentum (for the Gradient Descent Algorithm, GDA). Second, metaheuristics, mainly evolutionary strategies, are used to replace traditional optimization methods, such as the LMA. Our proposal is to use the qualities of both algorithms (QPSO in the initialization of synaptic weights and LMA in the training phase) to improve the performance of the ANN to classify abandoned areas suitable for solar energy facilities to reuse them based on the solar dataset obtained from the website of the United States EPAs, as explained ahead at Sect. 3.1.

2.1 Quantum-Behaved Particle Swarm Optimization

In the quantum version of the PSO algorithm, the state of the particle is given by a wavefunction $\psi(x,t)$, instead of its trajectory (velocity and position). In the quantum realm, the term trajectory is meaningless because of the uncertainty principle [42]. The probability that a particle is in each position can be calculated from its probability density distribution $|\psi(x,t)|^2$.

Employing the Monte Carlo method [43], the particles update its position according to Eq. (1):

$$\begin{cases} X_{i+1} = p + \beta \cdot |Mbest_i - X_i| \cdot \ln\left(\frac{1}{u}\right), \; if\; k \geq 0.5 \\ X_{i+1} = p - \beta \cdot |Mbest_i - X_i| \cdot \ln\left(\frac{1}{u}\right), \; if\; k < 0.5 \end{cases} \tag{1}$$

where β is the contraction-expansion coefficient [44], u and k are random numbers in the range $[0, 1]$, generated from a uniform distribution. The global mean best (*Mbest*) of the population is defined as the mean of the *pbest* positions of the swarm.

The contraction-expansion coefficient β is the only parameter to be tuned in the QPSO algorithm, and this can be done through Bayesian optimization [45]. The local attractor to guarantee convergence of the QPSO algorithm [44, 46] is defined by Eq. (2).

$$p = \frac{\varphi_1 \cdot pbest + \varphi_2 \cdot gbest}{\varphi_1 + \varphi_2} \tag{2}$$

φ_1 and φ_2 are random numbers generated from a uniform distribution in the range $[0, 1]$. Alternatively, this numbers can be generated from a positive Gaussian distribution with zero mean and unit variance, which leads to a large number of small amplitudes in the movement of the particles [46].

QPSO algorithm is proven to be more effective than other implementations of evolutionary algorithms in most scenarios [43, 47–50].

3 Methodology

In this section, the methodology used in the work is presented, along with the QPSO approach used for ANN initialization (Fig. 1).

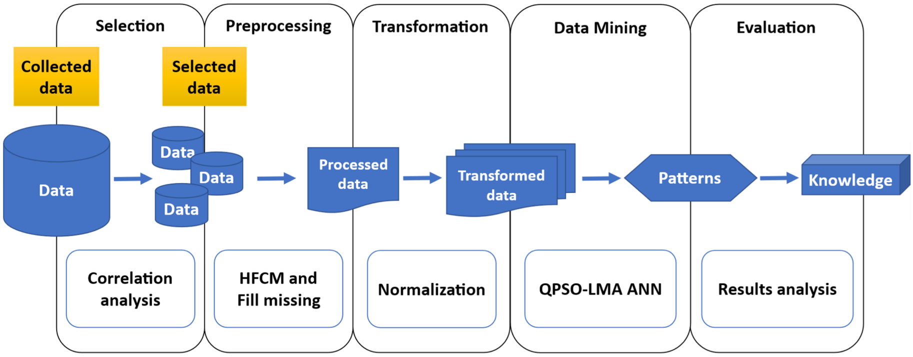

Fig. 1. Methodology phases. Source: the authors.

The methodology was proposed in five main stages: data selection, pre-processing, transformation, data mining and evaluation of the results. In the selection stage, the data were collected from government databases and selected for use in the proposed algorithm. The pre-processing involved filling in missing and removing correlated variables. In the third stage, transformation, the data was normalized to be used as input to the ANN. The data mining stage represents the execution of the algorithms and, finally, the results were analyzed.

3.1 Data Collection and Pre-processing

The solar dataset used in the problem was obtained from the website of the United States Environmental Protection Agency (EPA). The agency oversees the RE-Powering America's Land initiative, which identifies abandoned areas with a potential for recovery and the implementation of renewable energy projects.

With the RE-Powering Mapper tool, it is possible to visualize and download information on renewable energy potential in contaminated lands. Using screening criteria developed in collaboration with the National Renewable Energy Laboratory (NREL) and other state agencies, the EPA has pre-screened over 81,000 sites (at the time of this research) for their renewable energy potential.

The raw data totals 81,533 instances, each of which has 13 independent variables, in addition to 3 dependent variables. The dependent variables have to do with the potential of the location for photovoltaic solar facilities.

Of the 81,533 points analyzed, one or more of the variables were lacking for 32,429 data points, which needed to be filled. To make up for this deficiency, the average of each variable could be used, which might lead to discrepancies, as the range of the set was significant. With this in mind, it was proposed that the instances could be clustered into smaller sets, using the HFCM algorithm [51], with a view to reducing the scope of each variable in order to perform linear interpolation to supply the missing data.

The new generated data have a lower variance compared to those generated by an interpolation performed for the whole set at once, without the linear interpolation carried out in each cluster. As the Neural Networks demand that all variables have the same dimension in the training and testing phases, it was necessary this stage of data preprocessing.

Compared to the use of a complete data set, without missing data, a deterioration in the results and a consequent loss of accuracy can be assumed. Therefore, this pre-processing phase is important in reducing this deterioration.

It was necessary that no variable, in each instance of any of the clusters, should be left empty. At the same time, the clusters had to be small enough to minimize distortions. Therefore, after many preliminary tests, the number of clusters was experimentally set at 200, with the number of instances per cluster varying from 42 to 1,863, with an average of 407. The clusters that were formed allowed a reduction in the amplitude of each variable, making the interpolation of the missing data more realistic.

After collection and preprocessing, the data were separated into input and target sets for the ANN initialized by the QPSO algorithm, using the holdout strategy, considered one of the most reliable when estimating the accuracy of a predictive model [52]. The data were divided into two sets, training and test, with 50% of the data in each, randomly selected, with a view to a more secure evaluation of the quality of the classification and greater computational simplicity in relation to the k-fold cross-validation [53–55]. For equivalence, Bayesian Regularization was used in the neural network, which dispenses with the use of the validation set.

3.2 Proposed Algorithm (QPSO-LMA ANN)

The proposed initialization process consists of minimizing the mean squared error (MSE) between the target values of the ANN and the values predicted during the learning process, using the QPSO algorithm, called here by QPSO-LMA ANN, or simply, QPSO-LMA. The set of weights and bias, w, corresponds to the position of the particles to be optimized by the QPSO algorithm (w is initialized as an array of random values).

In the pseudocode shown in Algorithm 1, H is the number of neurons in the hidden layer, N is the swarm size for the QPSO algorithm, D is the dimension of the problem (function of the number of variables in the problem: inputs and targets dimensions, and the number of neurons in the hidden layer), and f is the error function (MSE) that should be minimized.

```
Input: input, target, H, iter, N
Output: w_best, output
i ← size(input)
t ← size(target)
D ← (i + 1) * H + (H + 1) * t
w ← random(1, D)
f ← MSE(w, input, target)
while ¬ StopCondition
        [output, w] ← QPSO(f, D, N, iter)
end
w_best ← w
Return(w_best, output)
```

Alg. 1. QPSO pseudocode for ANN initialization.

As *output*, we will have the values predicted by the network, which will be compared with the *target* values to measure the percentage accuracy, and the optimized weights (w_{best}), which were also used for the initialization of the LMA in a feed-forward ANN, as they have a strong influence on the convergence of the algorithm.

The difference between this methodology and other proposals [56, 57] is in the fact that here the metaheuristic was used in the initialization phase of the algorithm, aiming to bypass the trap of local minimums to which the LMA algorithm is subjected in its initial phase [58]. Thus, the algorithm became more effective in the search for the global minimum without becoming computationally expensive, as in the proposals presented in the literature.

4 Results and Discussions

In this section the results of the solar dataset are presented, as well as the other six datasets from the scientific literature. The datasets testing is intended to compare the performance of the proposed technique and its validation alongside what has already been developed regarding classification problems. An Intel i7–2600 (3.40 GHz) computer was used, with 16 GB of RAM. All the algorithms were implemented in MATLAB, version R2018b.

4.1 Solar Energy Dataset

Considering the solar dataset presented at Sect. 3, the QPSO-LMA hybrid technique achieved a decrease in terms of MSE of 19.6% in relation to the classical LMA training with random initial weights. An analysis of the percentage accuracy (see Table 1), for the test set, showed an increase of approximately 7.3% for the QPSO-LMA over the LMA, rising from 75.5% accurate to 81.0%. Figure 2 shows the classification results and the correctly classified locations for the best result obtained by the QPSO-LMA algorithm.

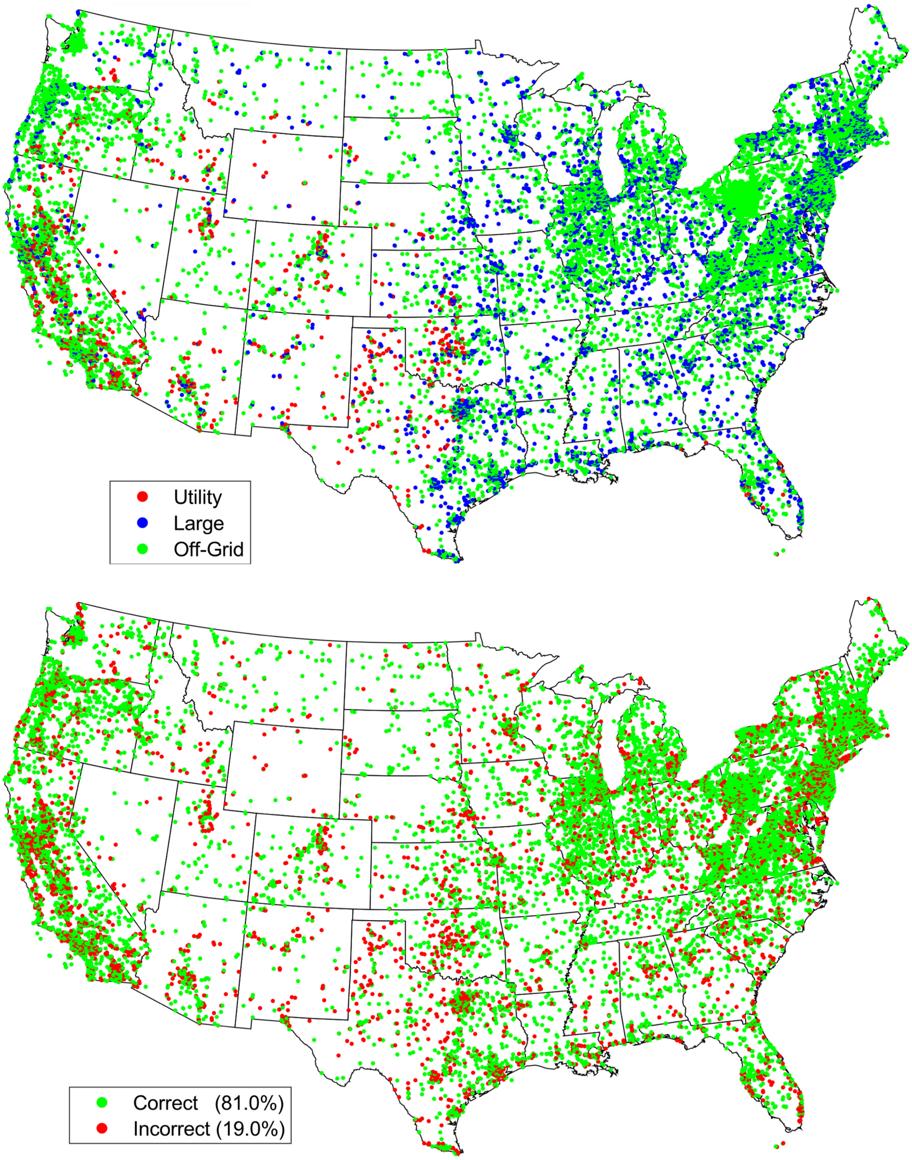

Fig. 2. Classification results (top) and accuracy (bottom) with QPSO-LMA.

The incorrectly classified points are distributed throughout the American territory, as well as each type of abandoned area, leading to the conclusion that there was no prejudice to the classification due to the imbalance of the dataset. The classification accuracy for off-grid, large scale and utility scale are 83.9%, 71.6% and 70.9%, respectively. Errors regarding off-grid areas (class 1) were concentrated in class 2 (large scale) because it has more similar attributes than class 3 (utility scale). The same happened with the other classes.

4.2 Datasets from Literature

The proposed algorithm was also tested on six datasets from the literature, the most cited in the UCI Machine Learning Repository on the date of data collection, to confirm its effectiveness. The results were also compared using some classical algorithms: Linear Discriminant Analysis (LDA), Naive Bayes (NB), Decision Trees (DT), Support Vector Machines (SVM) and Random Forest (RF), an ensemble learning strategy. These techniques have also been tested with Bayesian parameter optimization. Two hybrid techniques from the literature were also tested, which combine metaheuristics and neural networks with parameter optimization [56, 57]: Artificial Bee Colony Based Levenberg-Marquardt Algorithm (ABC-LMA) and Accelerated Particle Swarm Optimization Based Levenberg-Marquardt Algorithm (APSO-LMA).

All the best results were obtained with the QPSO-LMA algorithm, achieving the objective of the work of proposing a new and efficient initialization strategy of the weights and bias for ANNs to solve, with maximum accuracy, the classification of abandoned areas problem which could be suitable for solar energy facilities. Table 1 shows the accuracy results for the test dataset with each algorithm. The datasets are: 1 – Solar; 2 – Breast Cancer; 3 – Crab Gender; 4 – Ovarian Cancer; 5 – Thyroid Function; 6 – Parkinson Disease; and 7 – Ionosphere.

Table 1. Results for seven comparative techniques.

	1	2	3	4	5	6	7
LMA	75.5%	90.1%	91.4%	89.9%	90.2%	81.3%	88.3%
QPSO-LMA	81.0%*	93.4%*	93.9%*	94.0%*	93.6%*	84.2%*	89.7%*
LDA	69.7%	84.8%	88.5%	72.9%	90.7%	80.4%	85.1%
NB	61.0%	90.7%	73.3%	90.7%	91.9%	76.2%	86.7%
DT	71.2%	91.7%	87.0%	85.1%	91.4%	79.3%	83.9%
SVM	74.3%	92.2%	91.0%	92.5%	92.1%	83.4%	87.8%
RF	75.5%	90.8%	86.0%	87.8%	92.7%	80.4%	88.1%
ABC-LMA	79.2%	89.4%	90.1%	88.7%	90.3%	79.8%	85.7%
APSO-LMA	78.1%	90.2%	92.0%	90.2%	92.5%	80.8%	88.4%

* indicates the best result for each dataset.

For the solar energy scenario, the increase in accuracy represents a reduction in error, consequently greater efficiency in choosing the best suitable areas for generating renewable electricity. It is worth mentioning that, in the references found in the literature, there is normally no division of data in training and testing, with only the training phase, where the error is significantly smaller.

5 Conclusion

The aim of this work was to classify abandoned areas where solar energy facilities could be installed to reuse those areas (it is also possible to implement similar decision systems for wind, biomass, and geothermal energy, among others). There is enormous energy potential in these abandoned areas, although they are currently neglected. To achieve the classification goal, an ANN was trained with the LMA, in which the initial weights were obtained through the QPSO metaheuristic.

Currently, renovation projects in these areas are poorly prepared, without the use of data analytics in the decision-making process, which leads to mistaken and often inefficient choices [59]. The only criteria used by EPA and NREL to classify abandoned areas are, usually, value ranges with respect to some of the project's variables (estimated capacity, direct normal irradiance, land area and distance to transmission lines).

Using methodologies like the one presented in this work, it is possible to improve this decision process, reducing errors in choosing the most suitable areas, allowing for efficiency gains in the allocation of resources for the implementation of new energy projects. The areas correctly chosen for renovation will provide greater energy generation and consequently greater return on the investment made, making renewable energies even more competitive.

The results obtained with the solar energy dataset were validated in six of the most cited datasets in the UCI Machine Learning Repository and showed that the proposed strategy was more efficient in all of them. In addition, seven other classification techniques were tested with the seven datasets, with the QPSO-LMA achieving the best result in all cases. This means that QPSO-LMA could improve the accuracy of ANNs, combining the optimization capacity of the QPSO algorithm with the versatility of ANNs in classification problems.

The knowledge acquired by ANNs with the solar dataset can be extrapolated to other regions of the planet, as only technical variables for solar energy were used. This enables the identification of land in locations that do not yet have adequate classification tools. The QPSO-LMA technique could also be used in other classification problems, including other fields of renewable energies, such as wind and geothermal energy and biomass.

Suggestions for future works also include the application of QPSO-LMA algorithm in other databases, since here we had applied just in the seven databases (on solar energy, our problem, and on six datasets from the UCI repository) which, of course, is a limitation of this paper. In the same way, it will be interesting to use other Data Mining techniques, to compare to QPSO-LMA proposed algorithm as well as new metaheuristics in addition to QPSO. The application of dataset balancing algorithms, be they undersampling techniques (removal of instances belonging to the over-represented class), or oversampling (generation of new instances, through clustering and interpolation, relative to the under-represented class) could also be used. Data encoding [60] could also be performed. It will also be possible to test other methods of unrestricted nonlinear optimization as alternatives to the LMA algorithm.

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AI and Blockchain Integration with Enterprise Applications

Barriers of Blockchain Technology Adoption in Viable Digital Supply Chain

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Abstract. In recent years, blockchain, the foundational technology of Bitcoin, has attracted substantial interest from industry and academics. Specifically, blockchain technology becomes regarded as a rapid innovation joining the global supply chain in the digital era. Adopting blockchain technology makes digital supply chain operations more transparent, safer, traceable, and resilient. Despite this rosy outlook, many barriers prevent its adoption considering the digital supply chains' viability performance. This paper aims to explore crucial barriers to the implementation of blockchain technology in viable digital supply chains. In this context. a total of 12 barriers were identified through a comprehensive literature review and discussion with team experts. This paper presents a DEMATEL-based method for investigating identified blockchain technology adoption barriers and developing a causality diagraph. The elaborated diagraph illustrates the causality relationship between barriers. This study gives stakeholders an overview of the barriers that should be prioritized and addressed to ensure Blockchain technology's successful implementation in viable digital supply chains.

Keywords: Blockchain technology · Digital supply chain · Viability · Sustainability · Resilience · Agility · DEMATEL

1 Introduction

In recent years, industries have seen global changes due to digitalization, globalization, or natural disasters [1]. More clearly, industry 4.0 technologies directly impact performance and produce significant advancements in different industries [2]. In this context, blockchain adoption is revolutionizing many organizations [3]. Since its introduction in the financial industry, blockchain technology has given a new paradigm for creating collaborative platforms. Since then, it has been used to a variety of industries, including supply chain, health care, corporate systems, and product lifecycle management (PLM). In this context, Blockchain technology (BT) allows digital supply chains (DSCs) to increase resilience, sustainability, and agility benefits [4]. It permits organizations to

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enhance viability performance. However, despite its strengths, many organizations are still doubtful about its adoption [4]. Because BT adoption has many barriers especially considering the digitalization and viability aspects.

Few authors have published scientific studies on the barriers to BT adoption. Some of the studies that have already been done are focused on Technology-Organization-Environment classification [5]. Further research focused on the construction and analysis of a systemic model of barriers [6]. Other authors have studied the BT adoption barriers in the traditional [7–9] or sustainable supply chains (SCs) [5, 10]. The scientific discussion on this subject is still ongoing, and further evidence is required before a consensus can be achieved [11]. In this context, there is no available comprehensive study where BT barriers in viable digital supply chains (VDSCs) are evaluated using Decision making trial and evaluation laboratory (DEMATEL) approach. This paper aims to fill this gap by discussing and examining the BT adoption barriers in VDSCs. First, it identifies the barriers to the adoption of BT in DSC considering the viability performance. Second, it analyzes the cause/effect relationship between 12 barriers using DEMATEL to determine each barrier's overall degree of influence over the other barriers. Finally, it discusses the findings to allow practitioners and managers to overview the barriers that should be classified as priorities to address. To sum up, the research questions discussed in this article are as follows:

- RQ1. What are the BT adoption barriers in the VDSC?
- RQ2. What are the dependencies and causalities between the studied barriers?
- RQ3. What are the hierarchical levels among these barriers?
- RQ4. What are the implications for both practitioners and decision-makers?

This article is organized as follows: in Sect. 2, we present the methodology opted for conducting the study. Section 3 presents the literature review. Section 4 presents the application of DEMATEL for BT adoption barriers in VDSC. Section 5 analyzes and discusses the findings. Section 6 presents implications for practitioners.

2 Research Methodology

The goal of this paper is to assess and analyze BT barriers adoption for VDSC. Figure 1 presents an overview of the overall research methodology used in this study. It illustrates the step-by-step approach adopted to discuss the study's objective. Hence, the presented methodology comprises three phases. The first phase consists of identifying BT adoption barriers throughout the literature review and experts' validation. It consists of creating a comprehensive list of barriers that could inhibit or slow BT's adoption in the VDSCs. Hence, to address a wide range of academic productions, Elsevier, Emerald, Taylor &Francis, Springer, IEEE, Scopus, and Google Scholar databases were used to identify the related publications. The second phase is about the evaluation of the identified barriers. At this point, the previously established BT barriers will be thoroughly investigated using the DEMATEL approach. This approach is implemented considering five steps:

- Aggregating results and establishing pairwise direct- relation matrix;

- Determining the initial influencing matrix (N) by normalizing;
- Calculating the total relation matrix (T);
- Determining column and rows sums from the total relation matrices;
- And (5) Determining the net effect and overall prominence values.

The third and final phase includes analyzing and discussing the preceding phases and presenting some managerial implications and directions for future research.

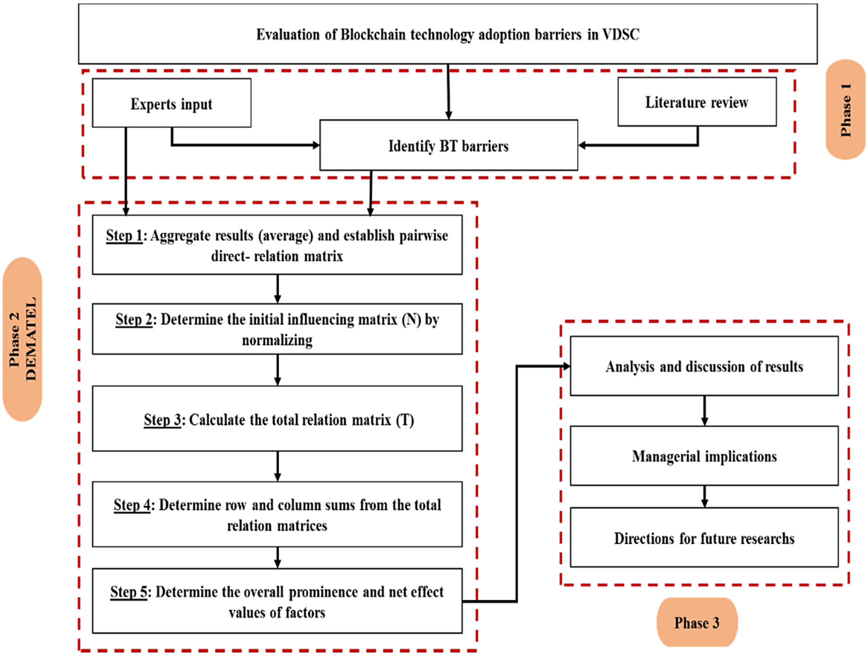

Fig. 1. The adopted methodology for this research

3 Literature Review

3.1 Blockchain Technology

Blockchain technology (BT) (called distributed ledger technology) is a peer-to-peer IT network maintaining digital asset transactions records. It uses distributed ledgers instead of standard centralized databases [4] which are connected by cryptographic methods through a consensus mechanism [12]. In other words, a blockchain refers to a chain of blocks. Those blocks consist of digital bits of data such as transactions, participating actors, and distinction from other blocks. The chain corresponds to their storage in a distributed database [13]. These decentralized databases can be distributed through a network of different geographies, sites, or organizations [14]. Besides, Blockchain includes nodes that classify transactions into blocks [13]. It is the nodes' role to determine the transactions' validity and if the transactions should be stored in the blockchain. Add to this, in ledgers, a single actor cannot change or erase block transactions [13]. Hence, BT's key innovation lies in its capacity to openly and publicly verify, register, and share transactions in encrypted and unchangeable ledgers [14]. Thus, Blockchain offers a digitally open and transparent public ledger for all stakeholders in a timed data architecture [13]. The transparent, open, decentralized, and cryptographic essence of BT generates trust. This provides many security advantages [4] and can significantly reduce costs and improve performance [15]. According to [16], Blockchain allows organizations with four capabilities. First, it provides a shared ledger wherein data architecture is locally shared and distributed among various participants. In addition, permissioning capability guarantees data privacy and transparency by securing and protecting transactions. Moreover, smart contracts refer to storing organizations' terms in databases to carry out transactions. Finally, consensus transactions are supported by relevant users who guarantee data traceability and stability. These capabilities depend on the used platform. For instance, Blockchains permit the emergence of decentralized cryptocurrencies like Bitcoin, the self-execution of digital contracts ("smart contracts"), and smart properties that may be managed through the internet [14].

3.2 Blockchain Technology in Viable Digital Supply Chain

Due to technical advances, particularly in information management, the use of BT is essential to help handle supply chain processes [15–17]. Nevertheless, blockchain technology's introduction brings a modern viewpoint about managing the supply chain [18, 19]. SCs are becoming more unpredictable day after day due to numerous factors such as human error, disrupted systems, and environmental issues [20]. Therefore, the Traditional Supply Chain (TSC) struggled to satisfy the customer's demand. The current trend consists of having interconnected, smarter, agile, sustainable, and resilient supply chains [19]. This SC's novel trend refers to have more VDSCs. This last can be defined as an intelligent, adaptable value-added network that can respond agilely to positive changes, be resilient and recover from disruption, and survive considering a sustainable environment. Thus, viability is a fundamental SC asset covering three dimensions, i.e., resilience, sustainability, and agility [21]. In the following, we identify the BT use in the different dimensions.

BT for Resilient Digital Supply Chain

BT, designed as a new kind of revolutionary internet technology, could help in dealing with intermediary intervention risks, namely violated privacy, hacking, political instability, financial institutions' volatility, pricey compliance with government regulations, and contractual conflicts [4]. BT helps participating actors to monitor digital data, considering various other functions, like smart contracts to prevent and respond to digital disruptions, such as fraud [15]. BCT may promote resilience approaches during disruption to ensure DSC' communication, agility, efficiency, and visibility [22].

BT for Sustainable Digital Supply Chain

The relevance of considering sustainability is outlined in the SCM literature [16]. [19] pointed out that to ensure value chain competitivity in the long term, DSCs should consider sustainability [23]. In this context, Blockchain plays a very significant role in SC sustainability development because it can transform sustainability management [5]. For this reason, with increasing sustainability concerns, organizations are implementing BCT to solve a variety of environmental supply chain issues using decentralized and unchangeable, and accurate data, traceability, transparency, and smart contracts [22]. The Blockchain helps to minimize data fluctuations that may undermine financially and socially SCs [5]. Indeed, reducing illegal practices also enables BT to enhance the social dimension of the sustainable supply chain [24]. Besides, Blockchain maintains a comprehensive track of the supply chain flows that help organizations strengthen trust in product sustainability authenticity [5] and minimize product recall and rework [16]. It can also calculate the organizations' carbon tax price due to the real-time traceability of goods footprint. Moreover, it can identify social and environmental issues that could threaten environmental concerns. According to [22], the reliability, security, and transparency BT characteristics add socio-environmental sustainability value to SCs flows. With these properties, blockchain technology might be the most promising technology for sustainable supply chain management [9].

BT for Agile Digital Supply Chain
According to [25], agility is known as the ability to instantly identify and exploit competitive opportunities. That is, agility is about bringing improvement in an appropriate, flexible and adaptive way to follow changing market trends. For this reason, particularly with the COVID-19 pandemic, there is a need for having more agile SCs [22]. In this context, adopting BT can help supply chain agility. It not only increases responsiveness and performance but also increases supply chain authenticity, visibility, and traceability. Besides, it assists the End-to-end actors in sharing, communicating, collaborating, and compromising as well as increasing productivity [22]. Besides, using transparent BT, in production planning and inventory management, provides transparent and accurate information that makes production technologies more agile [19]. Thus, it improves supply chain agility, especially when used with different industry 4.0 technologies.

3.3 Blockchain Technology Barriers in Viable Digital Supply Chain

Over the years, the relevance of introducinAdoptiong BT has been increasing. Organizations are engaging in BT projects to achieve high performance. However, unfortunately, many barriers and challenges discourage its implementation. Appropriate identification of the relevant barriers that impacted BT's adoption in the VDSC helps to ensure its successful implementation [26, 27]. The identification of BT barriers is based on a literature review, which is a crucial step in collecting pertinent research articles on the subject. It is also about producing an extensive list of barriers that challenge the BT adoption in organizations. Those barriers are classified into five groups: inter-organizational barriers, intra-organizational barriers, industry 4.0 technology barriers, external barriers, and social and environmental barriers. As it is not possible to evaluate all the barriers in this research. An initial list of the BT barriers in VDSC was collected from a literature review (see Table 1).

Table 1. Barriers in implementing Blockchain technology in VDSC

Barriers	Sub-barriers	References
Inter-organizational barriers	Lack of awareness	[4, 12, 20]
	Collaboration and network establishment issues	
	Lack of technical expertise	
	Issues with transparency and disclosure of "critical" data	
Intra-organizational barriers	Lack of trust	[4, 12, 28, 28]
	Lack of management support	
	Missing infrastructure	
	Financial constraints	
Industry 4.0 Technology barriers	Immaturity of technology	[4, 12, 28, 28]
	Lack of standardization	
	Complex protocol selection	
	Limited knowledge of the complex technology	
	Security and technical vulnerability	
	Interoperability	
External barriers	Legal uncertainties (smart contracts)	[4, 12, 20, 28]
	Market competition	
	Speed of technological development	
Social and environmental barriers	Information sharing (environmental and social aspects)	[5, 8]
	Wasted resources	
	Lack of awareness and tendency about sustainability	

From the literature review, it was found that there is a lack of studies on BT adoption barriers for VDSC. Besides, as far as we know, no study has addressed the BT barriers adoption considering digitalization, resilience and sustainability capabilities using DEMATEL. Lastly, especially with the increase of disruptions that SCs face, it is essential to comprehend barriers from the point of view of cause and effect. Since only determining their dependency or driving power or ranking them is not enough. For this reason, the purpose of this paper is to evaluate the BT adoption barriers by determining the cause/effect interrelation.

4 DEMATEL for Blockchain Technology Adoption Barriers in Viable Digital Supply Chain

DEMATEL is a structuring method used to analyze and identify the cause and effect interaction between the studied factors [29]. This approach aims to incorporate a digraph and a cause and effect connection diagram. In other words, the diagram and the cause and effect connection diagram illustrate the results of each aspect on the other [29]. DEMATEL has several benefits across AHP and ISM [30]. Using the AHP approach considers the criteria as independent of each other, which is not practical in realistic scenarios. ISM approach determines relationships between variables based on their dependency and driving power but does not identify the significance of their effects. Therefore, DEMATEL has an advantage over these Multi-Criteria Decision-Making Methods approaches since it indicates the factors relationship and ranks them according to their importance and the nature of their impact on each other.

The first step to be taken is data collection to assess the prominence and cause/effect relationship between the BT adoption barriers. As the DEMATEL technique is built on expert insights, a cross-functional team of 4 academic experts and 6 practitioners is formed. The experts team has a role to discuss the identified barriers and to establish the relationship between them. Besides, three online-meeting were arranged with experts. In the first one, the initial 20 identified barriers were discussed. Based on their response, we have selected the 12 most relevant barriers to BT's adoption for VDSC. In the second meeting, the expert's team was asked to determine each barrier's influence on the other. And the final meeting was arranged for discussing and validating the findings.

After selecting the comprehensive list of BT barriers to be evaluated, we begin calculus according the DEMATEL following steps:

The first step consists of generating a pair-wise comparison matrix based on the following scale:

- 0 if there is no influence;
- 1 if there is very low influence;
- 2 if there is low influence;
- 3 if there is medium influence;
- 4 if there is high influence;
- 5 if there is very high influence

$$A_k = \begin{bmatrix} 0 & a_{12k} & a_{13k} & \cdots & a_{12k} & a_{1nk} \\ a_{21k} & 0 & a_{23k} & \cdots & 0 & a_{2nk} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ a_{(n-1)1k} & a_{(n-1)2k} & a_{(n-1)3k} & \cdots & 0 & a_{(n-1)nk} \\ a_{n1k} & a_{n2k} & a_{n3k} & \cdots & a_{n(n-1)k} & 0 \end{bmatrix} \tag{1}$$

This matrix $A_K = [a_{ijk}]_n$(Eq. 1) represents the influencef barrier i over j where n is the number of barriers and k is the number of experts. Besides, its diagonal has a value of 0 because barriers don't influence themselves. Then, we obtain the overall direct relationship matrix A (Table 2) using (Eq. 2) where a_{ij} is the average of a_{ijk} of all experts.

$$A = \frac{[a_{ij}]}{k} \tag{2}$$

Table 2. Average scores for barriers interaction

Barriers		B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	Sum
Lack of awareness	B1	0	1,4	3,2	0,6	0,4	2,2	1,2	2,2	1	2,6	3	1	18,8
Data transparency	B2	1,4	0	3,4	0,4	2,6	3	3,6	1,2	0	3,8	3,4	0,4	23,2
Lack of trust	B3	1,6	0	0	1,2	1,4	1,6	1,4	2,8	0,2	3,8	0,2	0,4	14,6
Financial constraints	B4	0	1	0	0	3,6	3,4	0	2,6	4	1,8	3	3,2	22,6
Immaturity of technology	B5	2,8	3,4	3,2	1,6	0	3,2	2,8	2,8	1,8	2	3,2	2,2	29
Lack of standardization	B6	2,2	2,8	3,6	2,2	2,8	0	3,2	1,8	2,6	3,2	3,2	1,8	29,4
Security and technical vulnerability	B7	2,2	4	4	1,2	2,8	3,2	0	3,2	2,4	3,6	3,6	1,4	31,6
Legal uncertainties	B8	1,2	1,6	3,2	2	1,2	2,2	0,8	0	0	2,8	1,4	2,2	18,6
Missing infrastructure	B9	1	3,4	2,4	2,8	3,8	3,6	3,4	0,6	0	3,6	1,8	1,4	27,8
Information sharing	B10	3,2	3,6	3,4	1,8	0,6	2,2	1,4	1,6	0,6	0	2,8	3,4	24,6
Wasted resources	B11	1	3,8	3,2	2,6	2,8	2,8	3,2	1,4	3,6	3,2	0	3,6	31,2
High Sustainability Costs	B12	0	0	0	4	1,2	2	0	1,4	2,8	3,4	0,4	0	15,2

The second step consists of normalizing the obtained overall direct relation matrix A. Thus, the normalized overall direct-relation matrix N is obtained using (Eq. 3).

$$N = \left[b_{ij}\right]_{n*n} = \frac{A}{\max\limits_{1 \le i \le n} \sum_{j=1}^{n} a_{ij}} \quad \text{where } 0 \le b_{ij} \le 1 \tag{3}$$

The third step consists of calculating the total relation matrix (T). We obtained total relation matrix (T) (Table 3) by using (Eq. 4) where I refers to the identity matrix.

$$T = \left[t_{ij}\right]_{n*n} = N[I - T]^{-1} \quad (4)$$

Table 3. Total relation matrix

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12
B1	0,118	0,207	0,292	0,153	0,160	0,248	0,178	0,207	0,149	0,296	0,252	0,172
B2	0,202	0,220	0,361	0,181	0,265	0,325	0,291	0,224	0,157	0,391	0,319	0,196
B3	0,144	0,131	0,155	0,139	0,151	0,190	0,146	0,195	0,097	0,276	0,140	0,126
B4	0,148	0,246	0,246	0,180	0,301	0,339	0,187	0,251	0,280	0,328	0,300	0,278
B5	0,262	0,351	0,396	0,251	0,228	0,378	0,301	0,301	0,293	0,395	0,351	0,278
B6	0,251	0,344	0,414	0,273	0,317	0,294	0,318	0,279	0,267	0,436	0,358	0,274
B7	0,264	0,393	0,448	0,256	0,328	0,402	0,241	0,330	0,267	0,469	0,385	0,275
B8	0,148	0,200	0,277	0,188	0,175	0,240	0,155	0,138	0,118	0,289	0,200	0,201
B9	0,217	0,360	0,376	0,285	0,344	0,394	0,322	0,241	0,190	0,438	0,321	0,259
B10	0,236	0,303	0,340	0,221	0,203	0,295	0,216	0,226	0,171	0,275	0,289	0,272
B11	0,225	0,385	0,415	0,300	0,334	0,394	0,330	0,278	0,308	0,456	0,280	0,336
B12	0,099	0,144	0,160	0,237	0,169	0,221	0,118	0,160	0,194	0,279	0,159	0,128

The fourth step consists of determining the row and column sums from the total relation matrix (T). The sum of column and the sum of rows are denoted C and R (see Table 4). The fifth step consists of determining the net effect and overall prominence values (Table 4).

DEMATEL is one of the key instruments that have to be well presented to be effectively interpreted. For this reason, we established a causal diagram based on the previous analysis. After determining the overall prominence and net effect values, a causal diagram is drawn by placing ($Rij + Cij$, $Rij - Cij$) values and then drawing a directed graph to understand the BT adoption barriers' interrelationship. The causal diagram is presented in (Fig. 2).

Table 4. Direct-indirect matrix

Barriers	R	C	C + R	Rank	R-C	Cause/effect
B1	2,432	2,314	4,75	12	0,12	Cause
B2	3,132	3,284	6,42	6	−0,15	Effect
B3	1,89	3,88	5,77	8	−1,99	Effect
B4	3,084	2,664	5,75	9	0,42	Cause
B5	3,785	2,975	6,76	5	0,81	Cause
B6	3,825	3,72	7,55	1	0,1	Cause
B7	4,058	2,803	6,86	4	1,26	Cause
B8	2,329	2,83	5,16	10	−0,5	Effect
B9	3,747	2,491	6,24	7	1,26	Cause
B10	3,047	4,328	7,38	3	−1,28	Effect
B11	4,041	3,354	7,4	2	0,69	Cause
B12	2,068	2,795	4,86	11	−0,73	Effect

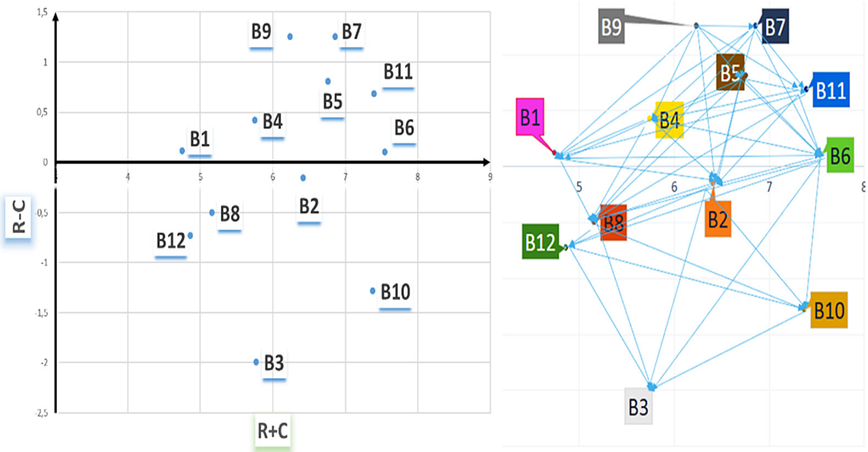

Fig. 2. Prominence-causal diagrams

5 Analysis and Discussion of Results

Based on the previous section and as the objective is to examine the interconnections between the identified barriers for the BT adoption in the VDSC, we analyze three barriers categories (influential, prominent and the resulting). Influencing barriers have a higher net effect value (R-C). Hence, the five most significant influencing barriers that have a crucial impact on the adoption of BT in VDSC are "Missing infrastructure (B9)", "Security and technical vulnerability (B7)", "Immaturity and interoperability of technology (B5)", "Wasted resources (B11)" and "Financial constraints (B4)". Adopting

BT may be a specific issue in DSCs if the infrastructure is missing or not properly set, as it is the most influential barrier outlined in this study. These B9, B7, B5, B11 are linked to technological advancement and security concerns. In fact, according to [4] BT' technical vulnerability and security limits further diffusion. Thus, managers should invest in infrastructure to sustain technological assets to avoid failures in BT's implementation. Besides, research on governance models needs to intensify.

Prominent barriers (causal barriers) have a high prominence score, reflecting the strong connection with other barriers and having a considerable effect on other ones. Thus, stakeholders must recognize and address these barriers to ensure the effective adoption of BT within their VDSCs [31]. As we can observe, "Lack of standardization (B6)", "Wasted resources (B11)", "Information sharing (B10)" and "Security and technical vulnerability (B7)" are the most significant elements barring the effective implementation of BT in the VDSC. According to [32] lack of standardization is a critical barrier since it leads to technological uncertainty. Besides, [4] argues that Blockchain standards, specifying how transactions are structured, secured and validated in the networks, should be established. Hence, organizations structures are necessary for decentralizing the networks and allow end-to-end transparency to ensure a standards application [4]. Thus, Managers should carefully prepare to monitor business strategies, resolve the primary causes of the barriers and engage in resources investment that will help implement BT in VDSC. Stakeholders should rely on concrete strategies to better achieve the opportunities of BT.

The resulting barriers are the most affected ones. Hence, organizations need to think about these barriers after assessing other ones. The resulting barriers, with a negative net effect value are "Lack of trust (B3)", "Information sharing (B10)", "High sustainability cost (B12)", "Legal uncertainties (B8)", and "data transparency (B2)". As seen in Fig. 2, several barriers have a significant impact on the resulting factors. For instance, multiple arrows point to "Lack of trust". Also, data transparency is still perceived as a significant risk by industries. In other words, according to [33], data transparency could be a blocking point while sharing sensitive information in real-time.

To sum up, organizations need to adopt plans and roadmaps to address various causes, and the resultant elements can be considered only after the primary influencing barriers have been addressed. Thus, it is crucial to begin by mitigating the most significant barriers then tackling the resulting one.

6 Implications

The findings discussed in this paper enable many research contributions. They offer implications for practices and researchers. They discussed barriers that may be considered a reference for stakeholders since this research addresses the most crucial barriers to BT's adoption in VDSCs. In other words, the results will assist in selecting the most relevant barriers, the least critical barriers, and how the barriers interact with one another. Besides, it will help stakeholders increase their awareness of the barriers and prioritize the barriers to be addressed. Thus, organizations must develop effective practices and strategies to ensure the effective adoption of BT in DSCs. Our findings indicate that managers should worry about improving the technology barriers to addressing BT's adoption barriers. It is important to note that technology barriers are a crucial concern independently of the organization's structure. To improve technological capability, managers should emphasize developing roadmaps and short and long-term strategies to benefit from the BT opportunities. More clearly, managers should identify the blockchain functionalities interoperable with other technologies and examine potential use cases.

Furthermore, researchers from other manufacturing and industry areas can use the suggested approach and analyses on the derived results. The findings remind executives that to increase and improve the effectiveness of blockchain implementation, they must employ members in their supply chains so that BT's benefits can be put to meaningful. Moreover, under developing and developing countries should plan to enhance policies to support BT implementation. Some limitations and questions raised by this research give multiple study pathways. For instance, our research is based on a particular number of experts.

7 Conclusion

Blockchain is a potential technology having numerous advantages like encryption, transparency, cost-saving, and traceability transforming many industries [3]. However, implementing BTs in DSCs is still in its infancy and is surrounded by several barriers that limit its adoption. Consequently, this paper aims to evaluate and examine the BT adoption barriers in VDSC. More clearly, it presents a causality diagram that illustrates the cause/effect relationship between the identified barriers. Also, it analyzes and discusses the findings to present implications for practitioners and managers.

Barriers that may impact the adoption of BT present real challenges for technical experts and managers. However, 12 barriers have been identified in this analysis and are evaluated in terms of cause/effect interaction using DEMATEL. Analysis results have shown that "Lack of trust (B3)", "Information sharing (B10)", "High sustainability cost (B12)", Legal uncertainties (B8)", and "data transparency (B2)" are known as a resulting barrier, while Missing infrastructure (B9)", "Security and technical vulnerability (B7)", "Immaturity and interoperability of technology (B5)", "Wasted resources (B11)" and "Financial constraints (B4)" were categorized as influencing barriers. Thus, the "Lack of standardization (B6)", "Wasted resources (B11)","Information sharing (B10)" and "Security and technical vulnerability (B7)" are prominent barriers and have an impact on many other barriers. Therefore, these barriers should be prioritized in order to have a successful adoption of BT in VDSC.

This paper has certain limitations that present improvement potential for future research. First, this work studied 12 barriers that impact BT adoption only. More barriers have not been identified and have not been studied. Second, the initial matrix retrieved from the experts' team has a probable uncertainty over specific interactions. This uncertainty can be overcome by incorporating gray and fuzzy set theories. Finally, this work has not studied the disruptions caused by Covid-19 impact on BT adoption. Thus, future research can explore how covid-19 epidemics affect the implementation of BT in VDSC.

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Data-Driven Framework for Electrode Wear Prediction in Resistance Spot Welding

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Abstract. Smart Manufacturing (SM) can be defined as the extensive application of computer-integrated manufacturing and advanced intelligence systems to enable rapid manufacturing of new products, dynamic response to product demand, and real-time optimization of manufacturing production and supply-chain networks. For this reason, SM is now attracting a huge interest in both academic and industrial communities and will probably drive the manufacturing evolution in the next decade. In SM, data play a key role. They can support decisional systems and human operators by helping them to improve production and process control, to monitor continuous production flows, to prevent or detect equipment failures at an early stage, to minimize inefficiencies through the overall supply chain, and so on. In fact, data can be exploited by combining a wide variety of advanced technologies to give machines the ability to learn, adapt, make decisions, and display new behaviours. In this regard, the aim of the study concerns the proposal of a data-driven framework to predict the electrode wear in Resistance Spot Welding process. Electrode wear is the most important factor that introduce high variability and uncertainty in the quality of spot welds. Using an equipped medium-frequency welding machine, various data such as thermal maps of the spot surfaces by passive thermography, electrode surface diameters, electrodes-workpiece contact conditions, process variables, and electrode displacement curves can be collected. These data can be provided as input to a Machine Learning algorithm to predict electrode wear over time, thus ensuring a reliable spot weld process and joint quality.

Keywords: Resistance Spot Welding · Electrode wear prediction · Industry 4.0 · Data-driven prediction

1 Introduction

Product Lifecycle Management (PLM) can be thought of as a tool for the creation, organization, and dissemination of product-related knowledge across the entire company. In such a context, maintenance activity plays a crucial role [1]. Indeed, nowadays, the functionality of maintenance is no longer limited to the operative phase of the production systems. It is an important part of PLM in terms of providing the desired availability

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of components or systems, minimizing the wastes, lowering the materials usage and the energy consumption to satisfy both the sustainability and efficiency requirements [2].

The impact of maintenance activity in the manufacturing world takes from 15% to 60% of the overall production costs [3]. This highlights the need for companies to improve the available tools to maintain their systems. It would ensure to reduce the overall cost of the entire production and, thus, of the product.

Maintenance is a broad field where many approaches can be adopted but, it turns out three main macro strategies can be used by the enterprise [4]: corrective maintenance, preventive maintenance, and predictive maintenance.

The first type is a Failure-Based strategy, and it requires the waiting for the fault occurrence to perform maintenance interventions. Corrective maintenance can only be implemented for systems or components not critical for both economic and functional standpoint [5].

Preventive maintenance can use a Time-Based or Use-Based criterion and it aims to avoid the failure of a machine with a predetermined scheduled maintenance activity. In this way, sometimes faults can be avoided, and machine parts can be replaced or repaired before that significant damage is accumulated. Such strategy is adequate whenever the time to failure of a component or system is adequately ascertainable [2]. However, often modern manufacturing processes operate in environments characterized by high dynamicity and uncertainty, so, their operating conditions can be variables and difficultly predictable. This makes the preventive maintenance strategy unusable in contexts where a just-in-time philosophy is required.

The latter philosophy allows the factory to minimize the downtimes of machines and to replace or repair the components at the opportune moment before the achievement of their critical conditions.

A tempting methodology toward such direction is to monitor some condition indicators of the machine health and predict the maintenance intervention on the ground of the inspections carried out. This is a Condition-Based technique that enables a Predictive Maintenance strategy. It can be interpreted as an industrial prognosis process assessing the remaining useful life of the system based on the status of the monitored condition indicators [5, 6].

The decreasing cost in sensor equipment and computing resources is making possible the advent of Industry 4.0, with Big Data and Industrial Internet of Things enabling the possibility to extend the predictive analysis for the whole production sector, and not only for the most critical ones [7].

Welding processes have always been widely used in manufacturing and, in the Industry 4.0 era, it becomes crucial to exploit the information directly from the process itself both for performance improvement and life-cycle evaluations in the whole industrial supply chains [8].

Control the weld quality in Resistance Spot Welding (RSW) process requires the knowledge of the weld nugget size and/or the weld strength, but a direct measure of the weld nugget size is not possible because it remains between the two sheets. Therefore, joint quality has normally been assessed through destructive tests. This has fostered the research activity toward the implementation of many indirect measurement methods for the evaluation of the joint quality, many of them exploiting process signal curves and non-destructive analysis.

Wan et al. [9] used some features extracted from the voltage curve during welding to feed Neural Networks and predict the failure load of the joints. The same researchers [10] used the signal of the dynamic resistance of the sheet stack to estimate the nugget size and the failure load. Zhao et al. [11] extracted many features from the electric power signals to predict the nugget size. Some studies [12, 13] have predicted weld quality by using the electrode displacement signal. Alghannam et al. [14] have proposed an interesting image-based approach combined with fuzzy logic to predict joint quality. Many efforts for the prediction of weld quality in RSW process have also been made through thermographic techniques. Some examples can be found in the literature [15–22].

Although there are many studies in the literature relying on the processing of one signal type and, hence, on one sensor only, the multi-sensor fusion monitoring is regarded to be a more effective technique since it combines different sensor signals to understand in more detail and different aspects of the welding process [8–23]. Moreover, there is a lack of predictive techniques pertaining the electrode wear, which is one of the primary factors affecting the quality of the weld spot.

By implementing a suitable IoT infrastructure on the machine and by carrying out a proper experimental plan, it is possible to collect different kind of data and build a data-driven framework capable to predict the electrode wear during the process.

The aim of this work is to propose a data-driven methodology for the electrode wear prediction in Resistance Spot Welding (RSW) process.

Next section describes the RSW process presenting the monitorable process signals and the electrode wear phenomenon. Section 3 discusses both the proposed experimental procedure and the data processing activity needed to build the predictive model. Section 4 concludes the paper by outlining the possible advantages attainable by such framework and the future developments.

2 RSW Process

Resistance Spot Welding (RSW) is a joining technique widely used in the automotive industry. In the RSW process, two electrodes are pressed first against the sheets to weld for a certain amount of time (squeeze time). Then, a high current flows through the electrodes and the sheet stack for a prefixed time (weld time). The heat generated by the Joule effect provides the thermal energy to locally melt the sheets and form a nugget, which is the junction. Figure 1 shows a schematization of the RSW process.

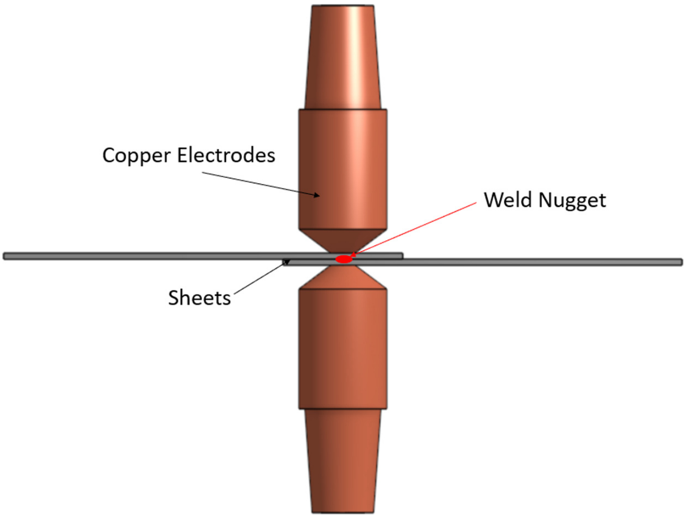

Fig. 1. Schematization of RSW process

The mechanical strength of a RSW joint depends strongly on the nugget size, which is the main key indicator of the joint quality. To achieve the desired nugget size, the first step is the correct setup of the spot weld cycle, schematically displayed in Fig. 2. This requires the setting of the following process parameters.

- Squeeze time, Weld time, Hold time.
- Weld current.
- Electrode pressure.

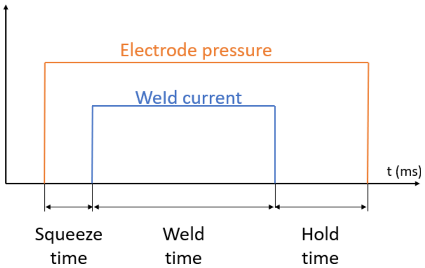

Fig. 2. Schematization of a spot weld cycle

However, the proper setting of the process parameters does not ensure a defect-free joint. Other phenomena such as shunting, edge proximity, initial sheet gaps and electrode wear can be sources of weld defects and hence, responsible for poor joint quality [24]. The first three causes can be avoided with a correct joint design, whereas electrode wear plays a critical role.

2.1 Electrode Wear

In many manufacturing plants, 60% of the defective spot welds are due to worn electrodes [25]. Typically, a modern body car contains from 4000 to 7000 spot welds [12]. Having an accurate control of the electrode wear can ensure the required quality level by the joint and, thus, it would allow to reduce the number of weld spots needed to assembly a body car.

As the number of welds increases, the electrode damage by wear due to different and complex electrical, chemical, mechanical and thermal phenomena, which also interact one another. Overall, three main different types of wear mechanisms occur on the electrode surfaces: radial wear, axial wear, and pitting. The radial wear causes an enlargement of the electrode tip diameter. The axial wear reduces the electrode length. Pitting concerns the erosion of the electrode surface [26].

When the electrode tip diameter enlarges, and the contact surface oxidizes, the current density decreases. This leads to a reduction of the nugget size, and, hence, to a lower joint quality.

2.2 Process Signals in RSW

RSW machine can be equipped with different sensors to measure during the welding the voltage between the electrodes (V), the electrode force (F), the electrical energy (E), the electric resistance of the sheet stack (R) and the electrode displacement (D). Furthermore, a thermal imaging camera can be also used for the detection of the temperature field (T) in a point of the sheet surface close to the working area, as shown, illustratively, in Fig. 3.

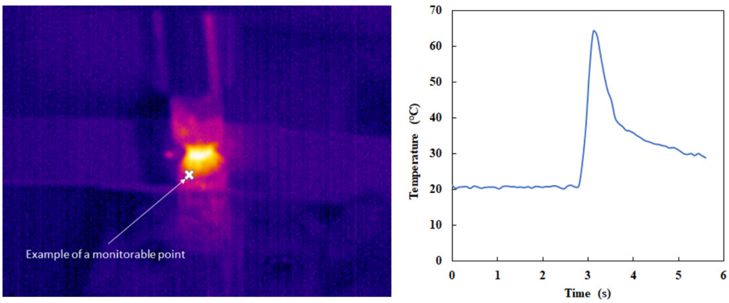

Fig. 3. Example of an infrared camera record with the associated transient thermal curve in RSW

The process signals and the infrared camera records can be processed to extract a set of explanatory features (predictor variables) to map wear parameters of the electrode (target variables), as described in the following section.

3 Proposed Methodology

The scope of this section is to describe a data-driven methodology to predict the electrode degradation through a multi-sensor fusion monitoring of the RSW process. The basic idea is to monitor different process signals from hundreds and successive RSW spots and relate them, after a data analysis, to electrode wear indicators.

3.1 Experimental Procedure for Data Acquisition

The first step requires a proper experimental plan to collect the following data.

- Process signals over time to extract predictor variables (Electrode wear welds).
- Electrode wear indicators to get target variables (Carbon imprint tests).
- Mechanical strength of the joints to establish the service life of the electrodes (Shear tension tests).

The experimental plan consists of replicating the same welding cycle hundreds of times until the end of the electrode life with an optimal setting of joining parameters.

The process signals can be extracted automatically from any weld carried out in the experimental procedure without adding costs or time-consuming activities. Conversely, electrode wear measures and mechanical strength of the joints need of proper tests. For this reason, the latter are not performed at each weld, but with an established temporal frequency.

Electrode Wear Welds

With the aim of deteriorating the electrode over time by acquiring the corresponding welding signals, hundreds of welds on a sheet stack made of two overlapped sheets can be executed, as shown in Fig. 4. For this scope, the AWS D9.8 standard [27] can be adopted. It defines the position of the several spots on the sheets: the minimum distance of the spots from the edge of the sheets (edge distance), the minimum distance among adjacent spots (pitch), and the correct sequence for the execution of the weld spots to

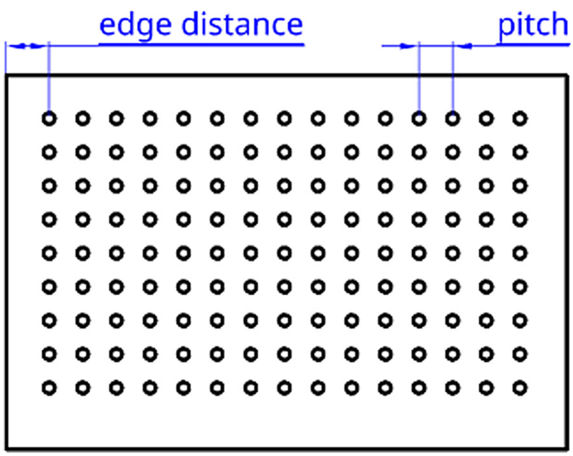

Fig. 4. Example of weld spots distribution on two overlapped sheets

avoid excessive heating of the sheets during the welding, which would alter the electrode condition (i.e., excessive electrode heating).

Carbon Imprint Tests

The AWS D8.9 standard [27] defines a simple and reliable method to evaluate electrode wear through a carbon imprint test. In this test, a layer of white paper and a layer of black carbon paper cover one sheet. Then, a weld cycle is carried out without passage of current. In this way, the electrode face imprint remains visible on the white paper. Based on the electrode impression, some considerations on the electrode wear can be made. A schematization of this test is shown in Fig. 5.

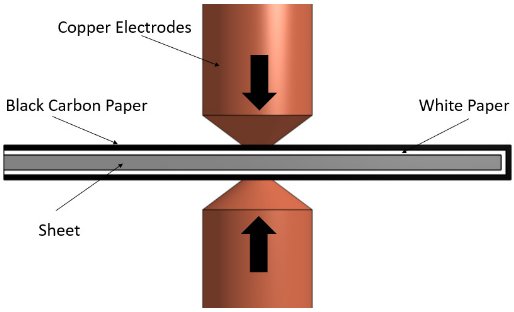

Fig. 5. Schematization of the carbon imprint test

Shear Tension Tests

Mechanical tests are needed to acquire and monitor the strength of the joint with the increase of the number of welds and hence with electrode wear. The mechanical strength of spot welds falls over time because of the electrode wear, which mainly reduces the nugget size. Therefore, the mechanical strength can be used as a factor to define the critical level of electrode wear. For instance, when the mechanical strength of weld spots reduces of 20% with respect to the initial value, the electrode can be considered worn and to be replaced [27, 28]. However, other threshold values can also be used. The most common mechanical test for spot welds is the shear tension test, as illustrated in Fig. 6. The weld strength can be defined as the maximum force, F_{max}, reached during the test according to the [27].

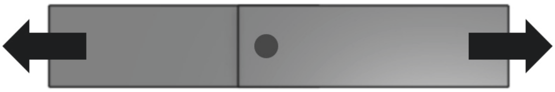

Fig. 6. Schematization of the shear tension test

Firstly, the mechanical strength of the weld spots needs to be evaluated at the beginning of the experimental plan, when the electrode is still new. Then, the shear tests are performed every time a couple of sheets is completely welded, as shown in Fig. 4. At least three repetitions for each shear tension test should be carried out.

In the proposed methodology, the maximum load F_{max} is only used as parameter to establish the end-of-life of the electrode. When an electrode is considered worn, the experimentation can be repeated with a similar electrode, but different settings of the process parameters in order to enlarge the observation domain.

Figure 7 summarizes the experimental procedure adopted in this study to obtain data for electrode wear prediction.

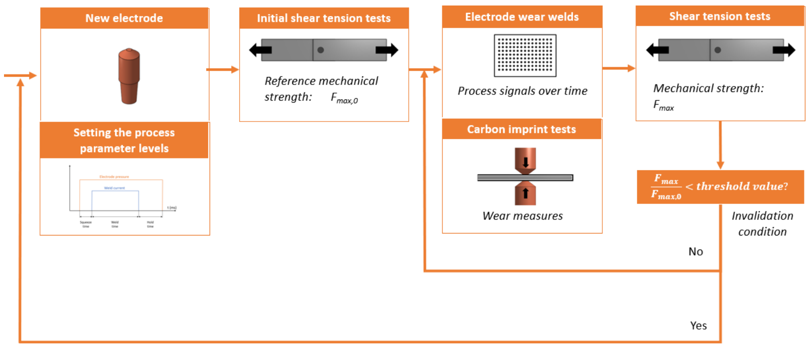

Fig. 7. Experimental framework for data acquisition

It should be noted that carbon imprint tests are carried out with an established frequency. The latter can be equal to the frequency of the mechanical tests, even if a higher acquisition frequency of the electrode imprints would enhance the accuracy of the methodology.

Once the experimental procedure is ended, the electrode imprints can be processed to obtain wear indicators (target variables of the framework), and the weld signals can be manipulated to get explanatory features (predictors of the framework). Next section discusses how to perform such data processing activity.

3.2 Data Processing

Data processing activity can be thought as a transformation of industrial raw data into predictor and target variables suitable for feeding a Machine Learning (ML) algorithm.

Target Variables

In this study, the target variables are the electrode wear indicators, which come from the carbon imprint tests. The raw data, constituted by the electrode face imprints on white paper (Fig. 8), need to be converted into image format to be processed. A simple scanner machine can be used for this task.

Then, an image processing tool can be adopted to extract the geometrical features characterizing the electrode wear and use them as wear indicators. In the following, some suggestions are presented inspired by the work of Peng et al. [28].

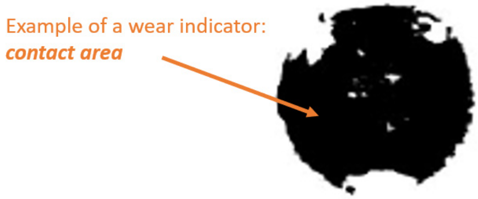

Fig. 8. Example of an electrode face imprint and identification of a target variable

- Diameter of the electrode imprint can be computed and normalized with respect to the nominal diameter when the electrode is still new.
- Eccentricity can be evaluated as the distance between the centroid of the electrode face imprint and the geometric centre of the electrode, normalized by the actual electrode diameter.
- Electrode pitting can be evaluated as the ratio between the eroded zone (i.e., the white area of the imprint) and the contact zone (i.e., the black area of the imprint).

These measurements can be used to characterize the electrode health state.

Predictor Variables

Predictor variables come from the manipulation of the process signals acquired during the experimental welding procedure. By following the scheme proposed by Traini et al. [29], a procedure to get predictor variables from the raw data of multiple sensors during a RSW process is described in the following paragraph.

Pre-processing

A pre-processing activity is needed to check the validity of data and get manipulable time series data. It can be summarized as data cleaning and validation phase, and usually, in an IoT infrastructure design context, it is assigned to the edge computing components of the system. The main functionalities of this step are:

- evaluation of the level of need to acquire data (deciding whether to carry out a process inspection)
- general validation of the data relating to a single weld (welding process carried out correctly)
- validation of each individual measurement from different sources (data acquisition process carried out correctly)
- selection of the time window of interest (selection of the range of data relating exclusively to the period of machine operation).

For data validation, time-series anomaly detection techniques are used. The interquartile rule for outliers can be an effective method [29].

The electrode force signal can be exploited for the identification of the machine activity period in RSW. As shown in the previous sections, the weld spot cycle starts with the squeeze time and ends with the hold time.

Feature Extraction
At this point, information can be mined from the time series data through feature extraction techniques. In this way, computational costs can be saved in the future learning activity of the algorithm. Time-domain statistics can be extracted from every kind of process signal. Depending on the type of the sensor measurement, several features like the mean, the maximum, the minimum, the increasing time, the decreasing time, the increasing rate, the decreasing rate, the amplitude increase, the amplitude decrease, the variance, the skewness, the Euclidean distance between subsequent curves, and so on, can be extracted. The same reasoning can be applied in the frequency domain to enrich the dataset with valuable information.

Feature Normalization
Once features are extracted from time series, they need to be normalized to deal with their magnitude. Feature normalization activity yields to get data roughly in the same range by improving the convergence of the future algorithm. Min-max normalization and standardization are two suitable techniques.

Feature Selection
Finally, a feature selection activity is useful to further reduce data dimensionality by only keeping the most explanatory ones. For this purpose, many techniques can be used to build an effective feature selection strategy, such as correlation-based analysis between predictor variables themselves, correlation-based analysis between predictor variables and target variables, hypothesis testing, monotonicity and prognosability analysis [29].

3.3 Predictive Algorithm

The task of the predictive algorithm is to take in inputs the predictor variables and make predictions of the target variables. Even if these tasks can be performed by any supervised statistical model, given the huge amount of data generated by the different sensors equipped on the machine, ML algorithms with high degrees of freedom are preferred in order to use the information contained in hundreds of features, as the size of the available processing sample increases. For this purpose, different ML algorithms can be used and tested against each other to choose the most accurate one. It is important to split the whole dataset obtained by the data processing phase into training set, validation set, and test set. The training set is used to train the ML algorithms, the validation set is used to tune the hyperparameters of the models, while the test set generalizes the overall performance of the chosen algorithm.

According to Biggio et al. [30], regarding of traditional ML algorithms, three subcategories of models frequently employed in prognostics activities can be identified: Neural Networks (NNs), Support Vector Machines (SVMs), and Decision Trees (DTs).

NNs are models inspired by the neural connections in the human brain. NNs are organized in layers where each of them includes several computational units, called neurons. Each neuron firstly computes a weighted sum of its input, and then apply a non-linear function, called activation function [31]. In this way, starting from the data feeding the Input Layer, going through the Hidden Layers, until to reach the Output Layer, complex relationships between inputs and outputs variables can be mapped. For this reason, NNs are suitable when the predictor variables have a non-linear relationship with the target variables. The architecture of the specific NN (number of neurons and number of layers) depends mostly on the task to be executed and by computational resource.

SVMs is a supervised classification algorithm. It can be thought as a large margin classifier because its decision boundary has the property that it is as far away as possible from the nearest data of each class. It turns out to be a linear classifier, but this condition does not often deal with the real-world scenario. So, a kernel can be used in cases where it is needed to address the non-linearity of a data, such as Gaussian Kernel. Typically, in problems where a high-dimensionality of features is involved, SVMs show good performance, even if the computational cost of the kernel matrix can be prohibitive [30].

DTs is a class of non-parametric supervised ML algorithms commonly employed for regression and classification problems [30]. A decision tree is a predictor applying a series of simple decision rules on the given point. This process can be outlined as a tree, where in the non-leaf nodes of the tree there are the conditions to be applied to go on. After descending the tree in the way prescribed by each node condition, the leaves of the tree contain the predictions of the algorithm [31].

Choosing a specific algorithm depends on many factors. The algorithm can be selected on the ground of a set of performance metrics for each candidate model, but there also other aspects to be considered, such as the specific task to be performed, the characteristics of data, the interpretability and transparency required. However, NNs are expected to be the most suitable candidate due to the high non-linearity of the welding processes [8].

The aforesaid classes of algorithms are only a suggestion to predict electrode wear in RSW, in fact other models can also be considered.

Once the algorithm has been trained, measurements of electrode wear are no longer needed since the algorithm is capable to predict the electrode wear only by acquiring the sensor signals during the process.

Since the level of the electrode wear, is usually identified with a set of indicators, the predictive algorithm must be based on a multivariate model that estimates different target variables (i.e., each wear indicator). Once the model(s) is chosen based on data-driven tests, the model is used continuously to monitor the status of the tool and provide the operator with a platform to support operational tool change decisions. To make models able to estimate the wear, a continuous sensors data collection is necessary, so to obtain an up-to-date wear profile that does not compromise production performance by generating downtime. If investment costs for an IoT infrastructure capable of constantly monitoring every asset is unsustainable for a company, these methodologies can provide excellent results also by using data only from periodic machine inspections.

Figure 9 shows a schematization of the data processing activity discussed in this study.

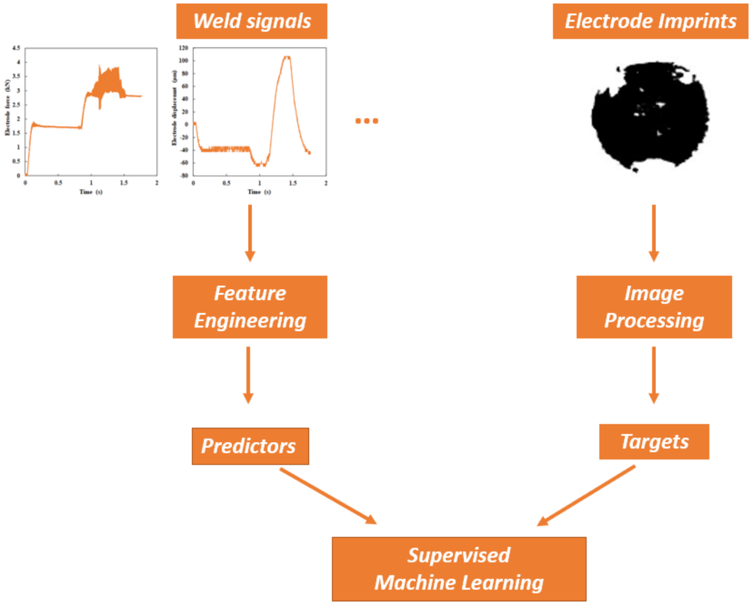

Fig. 9. Schematization of data processing activity

4 Conclusions and Future Developments

Many research works related to prediction of spot weld quality rely on measurements from single sensors. This means the predictive algorithm is only trained with a limited amount of information, so limited conditions can be detected. Moreover, most of predictive models focus on the predictions of joint quality, and not on electrode state prediction.

This paper proposes a methodology to build a Condition-Based Maintenance tool for RSW process according with the primary needs of Industry 4.0. The novelty of the proposed framework is to use multiple sensor measurements to make predictions. Once the algorithm has been set up, it could be potentially deployed directly on the machine and provide a helpful support to the welding operator for the maintenance activities. Indeed, the operator could monitor in real-time the predicted wear indicators by getting quantitative information for the decision-making process pertaining to the replacing or dressing of electrodes. Moreover, based on the quality level required by the company, the critical level of electrode wear can be customised during the experimental procedure.

An accurate prediction of the electrode wear would lead to a just-in-time maintenance activity by fostering the lean production philosophy, reducing the number of defective joints, and avoiding premature electrode replacements.

Future research will be focused on testing the practical feasibility of the proposed methodology and in investigating the most suitable Machine Learning algorithm to be used.

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Anomaly Detection in Blockchain-Enabled Supply Chain: An Ontological Approach

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Abstract. In our work, we propose an anomaly detection framework, for detecting anomalous transactions in business processes from transaction event logs. Such a framework will help enhance the accuracy of anomaly detection in the global Supply Chain, improve the multi-level business processes workflow in the Supply Chain domain, and will optimize the processes in the Supply Chain in terms of security and automation. In the proposed work, Ontology is utilized to provide anomaly classification in business transactions, based on crafted SWRL rules for that purpose. Our work has been evaluated based on logs generated from simulating a generic business process model related to a procurement scenario, and the findings show that our framework was able to detect and classify anomalous transactions form those logs.

Keywords: Anomaly detection · Business process · Supply chain · Blockchain

1 Introduction

Supply Chain (SC) is defined as a network of organizations and entities involved in all the processes and activities related to manufacturing to transporting products and services from source to eventually the ultimate customers [1]. Nowadays, Supply Chain became more complex, due to the involvement of various stakeholders in the global context, and this may increase the complexity of interacting systems, which make them face several vulnerabilities such as downtime, security breaches and forgery, and hence raises concerns related to security, reliability, and treatability of information.

Such limitations of the existing Supply Chain Management systems can be mitigated by incorporating Blockchain, or distributed ledger technology, that was first introduced in 2008 [2], implemented in 2009 [3], and can be thought of as a tamper evident, tamper resistant digital ledger implemented in a distributed fashion and usually without a central authority. Hence, Supply Chain Management Systems can benefit from the Blockchain Technology when it comes to traceability, transparency, and data provenance [4].

The second generation of Blockchain, Blockchain 2.0 [5], allowed for programmable transactions, self-executing code that are triggered when certain conditions are met, known as Smart Contracts [6].

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Smart contracts are programs that run on the Blockchain and add blocks to the network whenever certain conditions are met. They are often defined by translating actual legal contracts, or business processes of a given domain of interest into programs or code, to enforce the legal contracts onto the Blockchain. A smart contract can be thought of like stored procedures in databases, and usually stored on the Blockchain as scripts and executed in accordance with the data that is fed to them to produce output that is anticipated from the original contract. In other words, smart contracts manage the transactions over the network when executed either fully or partially according to the current input fed to them, acting as digital agreement among the transacting parties [7]. Incorporating Smart Contracts in the Supply Chain domain would be of a revolutionary solution, in which they will automate the several complex aspects in traditional Supply Chain systems, related to paperwork and manual workflows. In this context, Smart Contracts can contribute to lowering costs, reduce administration fees, streamline workflows, and securing the Supply Chain Management Systems.

On the other hand, a business process may be defined as a group of linked activities produced for a particular purpose [8]. A business process holds a number of attributes: has a particular goal, needs a certain input, produces a certain output, has a series of events or activities carried out in a predefined order, might need some resources and involve a number of owners [9]. There are several representations and notations of business processes, including: Unified Modeling Language (UML), Business Process Model Notation (BPMN), Event-driven process chain (EPC) and Petri Net Markup Language (PNML) [8].

Business process mining or process mining is an emerging research area that aims at analyzing Business Process Models (BPM), by extracting knowledge from logs generated by various information systems. Such knowledge can support auditing, monitoring and analysis of business activities for future improvements [10]. It is also useful when detecting potential exceptions or anomalies in the logged workflow, and hence help identify the source of such exceptions and modify them accordingly.

On the other hand, ontologies can contribute to the representation of the business process model of interest, in which they play a major role in representing the domain in a uniform and formal representation, that allows both humans and computers to access structured and well-defined knowledge effectively, as well as allows for automatic reasoning and inferring new knowledge easily [11].

The notion of ontology was defined in [12] as a "formal, explicit specification of a shared conceptualization". It captures the concepts of a given domain, along with their relations and associated axioms, which allows for interoperability and performing automatic reasoning and inferring new knowledge about that domain [13–15, 27]. Ontology is developed with "OWL", Ontology Web Language, in which the expressivity and reasoning capabilities can be expressed in terms of SWRL (Semantic Web Rule Language), by providing high-level syntax for Horn-like rules, that are expressed in terms of Ontology concepts (i.e. classes, properties, and individuals) [16]. In our framework, SWRL rules were defined to classify the types of anomalies in each Business process, by analyzing the relationships between the events of that process. An example of a SWRL Rule to classify a consistent process is given below:

$$Process(?P),\ StartEvent(?ST),\ beginsWith(?P,\ ?ST),\ followedBy(?ST,\ ?S),\ EndEvent(?EE),\ endsWith(?P,\ ?EE) \rightarrow ConsistentProcess(?P) \tag{1}$$

In this paper, we would like to propose an anomaly detection framework, for detecting anomalous transactions in business processes from transaction event logs. The proposed work utilizes Ontologies to represent the domain of interest, that will help provide anomaly classification in business transactions, based on crafted SWRL rules for that purpose. Such framework will help enhance the accuracy of anomaly detection in the global Supply Chain, improve the multi-level business processes workflow in the Supply Chain domain, and will optimize the processes in the Supply Chain in terms of security and automation. The three main steps of this research are:

1. Convert the BPMN Model into an Ontology.
2. Simulate the business process and generate event logs that will be adopted and used for evaluating the approach.
3. Build the SWRL rules needed to identify both consistent and anomalous processes.

The structure of this research is organized as follows: Sect. 2 survey some related work in literature, Sect. 3 describes our proposed approach, Sect. 4 demonstrates results and analysis, and Sect. 5 presents a discussion of our research findings and future work to be done in this area.

2 Literature Review

In this section, we survey some of the related work in the domain of Business Process Modeling using ontologies, anomaly detection and classification in business processes.

2.1 Ontologies for Business Process Modeling

Two BPMN ontologies were researched before in literature [17]. The first, sBPMN that incorporated the last release of BPMN 1.0. The classes within this ontology represent the elements of BPMN, examples include: Swimlanes, Artifacts, Processes, Flow Objects and Connecting Objects are examples of such classes. Such ontology includes around 95 defined classes, and 50 defined axioms [18]. The second BPMN ontology was presented by Francescomarino, et al., that was influenced by the BPMN 1.1 elements [19]. Such ontology includes around 95 defined classes, 108 object properties, 70 data properties in addition to 439 axioms [19]. Another ontology that serves for the purpose of BPMN modeling in BMNO, presented in [20], but according to [21] such ontology does not provide a full description of all the BPMN specification in terms of asserted properties. This was justified by the author because it focused more on the execution behavioral aspects of the business processes [21].

Thus, the old releases of BMPN influenced the creation of BPMNO and sBPMN, but with the release of BPMN 2.0, the BPMN metamodel served as a basis for a more powerful ontology that benefits from the expressivity of such new notation and helps better representing the BPMN specifications and standards.

In a parallel research, another ontology was presented, the Publish Workflow Ontology (PWO), which was implemented mainly to satisfy workflow specifications and requirements. PWO focuses on the logical steps of a given workflow and uses the notion of patterns or building blocks in representing such Workflow [22]. Table 1 summarizes the patterns used in PWO, that influenced our work.

In [23], the work of modeling industrial business processes for querying and retrieving was presented. It is a combination of hybrid program that presents modular ontology design, consistent ontology design of each module and cohesive control flow for process and its sub-processes, using both OWL-DL and SWRL, which also influenced our work when developing the ontology.

2.2 Anomaly Detection in Business Processes Using Ontologies

In the area of utilizing ontologies in anomaly detection in business processes, [24] presented an ontology-based process modeling to capture fraud in credit application business process, with the aid of Multi-Level Class Association Rule Learning (ML-CARL).

[25] also presented an anomaly detection framework in business processes via both process mining and fuzzy association rule learning. The fuzzy multi-attribute decision making is utilized to detect anomalies, and process mining is used to analyze the conformance between both the recorded event logs and the typical operational procedures of the business model.

Table 1. The main patterns of the PWO ontology

PWO entity	Pattern entity
Workflow	Plan (basic plan description, via basic plan)
WorkflowExecution	PlanExecution (basic plan execution, via basic plan)
Step	Task (task role, via control flow)
Action	Action (task execution and plan execution) TimeIndexedSituation (time-indexed situation)
hasStep	definesTask (basic plan description)
hasFirstStep	definesTask (basic plan description)
executes	satisfies (basic plan)
hasNextStep	directlyPrecedes (sequence)
hasPreviousStep	directlyFollows (sequence)
needs	isDefined in o describes (basic plan description)
produces	isExecuted in (o hasParticipant) (task execution and participation)

In [26], an Ontology-based Approach for Failure Classification in Predictive Maintenance Using Fuzzy C-means and SWRL Rules, in which the employed clustering techniques used to decide on the level of criticality of such failures based on historical data of machines, and ontologies use the results of those techniques for predicting both the time and criticality of such failures.

3 Proposed Approach

This section illustrates the proposed approach for modeling the business process and defining the SWRL rules for detecting and classifying the anomalous processes. As stated in Sect. 1, the proposed approach is composed of three steps, illustrated in Fig. 1.

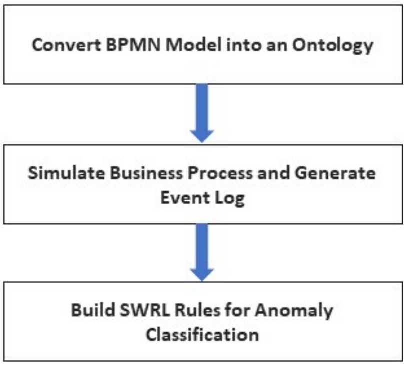

Fig. 1. Proposed approach

3.1 Convert the BPMN Model into an Ontology

For demonstration purpose in this paper, we focus on a generic business process for a procurement scenario illustrated in Fig. 2. (The real work is also performed on similar scenarios provided by our project industrial stakeholders). In this context, the class hierarchy of the constructed ontology is illustrated in Fig. 3, using the popular Ontology Editor Protégé 5.5.

To better represent and control the sequence of events in each process in our ontology, the following constraints must be fulfilled:

Constraint 1: Every process must have a clear start and end events.
This constraint will ensure that all process are consistent and conform to the business model.

Constraint 2: In each process, each event must have at least one connection to other events.

This constraint will ensure that a given process is built from connected events.

Constraint 3: No cyclic dependency (i.e. loops) between events within a process.
Otherwise, such a process will be classified as anomalous with one or more events reworked.

Constraint 4: To ensure simplicity of events within a business process, an event must have one successor and one predecessor.
In case of multiple successors and/or predecessors, inclusive or exclusive gateways (AND, XOR gates) must be specified either to join or split those events.

Table 2 describes both object and data properties defined for the Procurement Process Ontology.

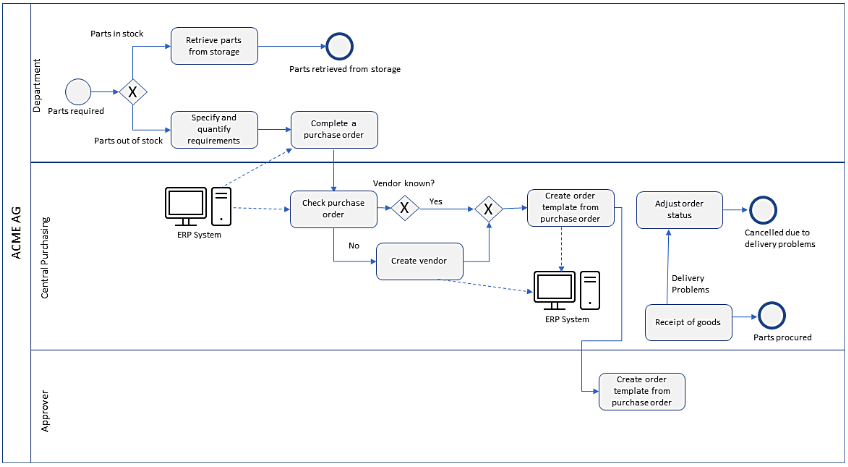

Fig. 2. Procurement business process

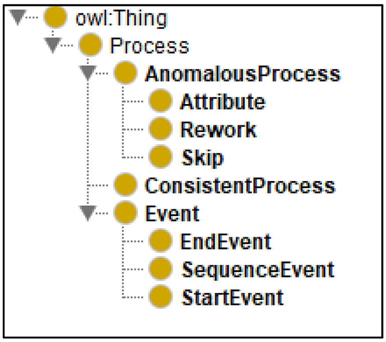

Fig. 3. Class hierarchy of the procurement ontology

Table 2. Asserted object and data properties for the procurement ontology

Property	Type	Description
beginsWith (P1, E1)	Object	Process P1 begins with start event E1
containedIn (SE1, P1)	Object	Sequence event SE1 is contained in Process P1
Contains (P2, E2)	Object	Process P2 contains sequence event E2
endsWith (P1, EE)	Object	Process P1 ends with end event EE
followedBy (E1, E2)	Object	Event E1 is followed by Event E2
PrecededBy (E2, E1)	Object	Event E2 is preceded by Event E1
hasEventName (E1, "ProcureParts")	Data	Event E1 is named "ProcureParts"
hasOwner (E1, "Department")	Data	Owner of Event E1 is "Department"
hasPName (P1, "ProcurementProcess")	Data	Process P1 is named "ProcurementProcess"
hasTimestamp (P1,"2021–01–26T21:08:18.849 + 03:00")	Data	Process P1 is timestamped with value of "2021–01–26T21:08:18.849 + 03:00"
pairsWith (E1,"Yes")	Data	Event E1 is associated with the yes part of the condition of XOR gateway

Anomaly Types:
The proposed model will classify the following types of anomalies in the workflow:

- ***Skip***: An event in the sequence was not executed.
- ***Rework:*** An event was executed more than once.
- ***Attribute:*** An event with incorrect attribute value.

Figure 4 Illustrates these types, compared to the normal workflow.

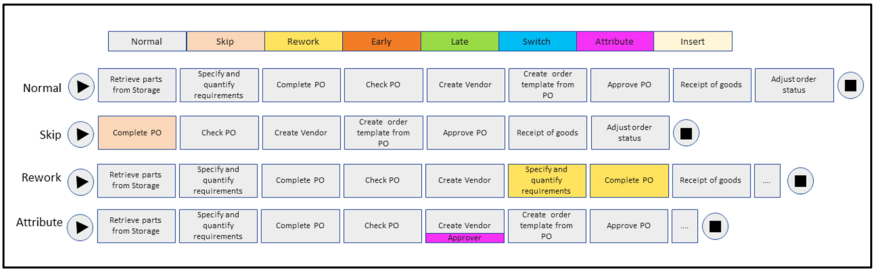

Fig. 4. Types of anomalies to detect and classify

3.2 Simulate Business Process and Generate Event Logs

For this purpose, we used ProM 6.10[1], that is a well-known Process Mining tool developed by Developed by Process Mining Group, Math and CS department, Eindhoven University of Technology, and has several capabilities related to simulation of business processes, as well as log generation capabilities. Table 3 provides a snapshot of a generated event log resulting from the simulation.

Table 3. Snapshot of a generated event log

Process ID	Activity	Timestamp
1	Parts required	2010–12–30T11:02:00.000 + 01:00
1	Retrieve parts from storage	2010–12–31T10:06:00.000 + 01:00
1	Parts retrieved from storage	2011–01–05T15:12:00.000 + 01:00
2	Parts required	2021–01–26T21:06:18.849 + 03:00
2	Specify quantify requirements	2021–01–26T21:12:18.849 + 03:00
2	Specify quantify requirements	2021–01–26T21:13:18.849 + 03:00
2	Complete PO	2021–01–27T21:23:03.707 + 03:00
2	Check PO	2021–01–27T21:25:03.707 + 03:00
2	…	….
3	Parts required	2021–01–30T22:18:32.555 + 03:00
3	Specify quantify requirements	2021–0–30T22:19:32.555 + 03:00
3	Complete PO	2021–01–31T22:28:32.555 + 03:00
3	Check PO	2021–02–01T22:14:41.262 + 03:00
3	Specify quantify requirements	2021–02–02T22:27:41.262 + 03:00
3	……	……
4	Retrieve parts from storage	2021–02–22T23:03:01.460 + 03:00
4	Parts retrieved from storage	2021–02–22T23:04:01.460 + 03:00
4	……	……
5	Parts required	2021–03–26T23:00:32.002 + 03:00
5	Retrieve parts from storage	2021–03–26T23:00:38.002 + 03:00
5	……	……

3.3 Build SWRL Rules for Anomaly Classification

In this sub-section, we present the constructed SWRL Rules that will be used for classifying consistent and anomalous processes, which are also based on the constraints discussed in Sect 3.1.

[1] http://www.promtools.org/doku.php?id=prom610.

The following two rules are used to classify reworked processes, rule (2) when a single processes is reworked, whereas rule (3) when there is a cyclic dependency between more than two processes:

Process(?P), StartEvent(?ST), beginsWith(?P, ?ST), followedBy(?ST, ?S), followedBy(?S, ?S), EndEvent(?EE), endsWith(?P, ?EE) -> Rework(?P) (2)

Process(?P), StartEvent(?ST), beginsWith(?P, ?ST), followedBy(?ST, ?S), followedBy(?S, ?S2), followedBy(?S2, ?S3), followedBy(?S3, ?S), EndEvent(?EE), endsWith(?P, ?EE) -> Rework(?P) (3)

The following rule is used to classify a skipped process:

Process(?P), StartEvent(?ST), beginsWith(?P, ?ST), hasEventName(?ST, ?Name), notEqual(?Name, "P4_PartsRequired"), EndEvent(?EE), endsWith(?P, ?EE) -> Skip(?P) (4)

Finally, the following rule is used to classify an anomalous process "Process 5" that has a wrong attribute value for the hasOwner data property, "Approver" instead of "Department":

Rule: Process(?P), StartEvent(?ST), beginsWith(?P, ?ST), followedBy(?ST, ?S), hasOwner(?S, ?Name), notEqual(?Name, "Department"^^xsd:string), EndEvent(?EE), endsWith(?P, ?EE) -> Attribute(?P) (5)

4 Results and Analysis

After the construction of rules to detect the abovementioned anomalies, we populated the ontology with five sample processes, extracted from log of Table 3. Each process has its own sequence of events, denoted by Px_EventName. Figure 5 illustrates the asserted individuals of processes and their corresponding events.

The next step will be running the Pellet[2] reasoner to classify those processes into one of the classes presented in the procurement ontology, with the aid of SWRL rules defined previously for this purpose. The following three use cases demonstrate the ability of our framework to classify the asserted business onto the corresponding classes in our ontology.

4.1 Scenario 1, Classifying a Consistent Process.

Table 4 summaries the Business Process "Process1" individual, asserted with the following data and object properties among its events, based on its presented event in the log of Table 3. Based on those properties, 'Process1' is classified as a Consistent Process, according to SWRL rule (1). The result of classification after running the reasoner is illustrated in Fig. 6.

[2] https://www.w3.org/2001/sw/wiki/Pellet.

Fig. 5. Individuals of processes 1 to 5, with their asserted events

Table 4. Properties of the 'Process1' Individual

Individual name	Property	Value	Class
Process1	beginsWith	P1_PartsRequired	'Start Event'
	endsWith	P1_PartsRetrieved	'End Event'
P1_PartsRequired	followedBy	P1_RetrievePartsFromStorage	'Sequence' Event
P1_RetrievePartsFromStorage	followedBy	P1_PartsRetrieved	'End Event'

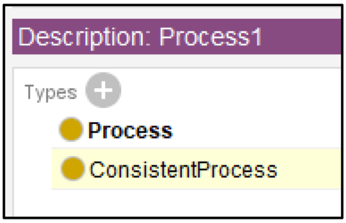

Fig. 6. Result of classifying ‘Process1’ individual

4.2 Scenario 2, Classifying a Process with Reworked Event

Table 5 summaries the Business Process “Process2” individual, asserted with the following data and object properties among its events, based on its presented event in the log of Table 3. Based on those properties, ‘Process2’ is classified as a Rework Process, according to SWRL rule (2), because the event ‘P2_Specify Quantify Requirements’ was executed twice. The result of classification after running the reasoner is illustrated in Fig. 7, in which ‘Process2’ was classified as a consistent business process (has a clear start and clear end events – constraints 1), and as a Rework process too, because of repeating the event ‘P2_Specify Quantify Requirements’.

Table 5. Properties of the ‘Process2’ individual

Individual name	Property	Value	Class
Process2	beginsWith	P2_PartsRequired	‘Start Event’
	endsWith	P2_PartsProcured	‘End Event’
P2_PartsRequired	followedBy	P2_Specify Quantity Requirements	‘Sequence’ Event
P2_Specify Quantity Requirements	followedBy	Specify Quantity Requirements	‘End Event’

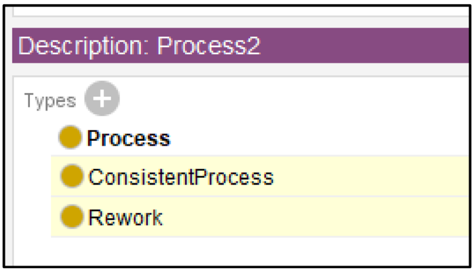

Fig. 7. Result of classifying ‘Process2’ individual

4.3 Scenario 3, Classifying a Process with Skipped Event

Table 6 summaries the Business Process "Process4" individual, asserted with the following data and object properties among its events, based on its presented event in the log of Table 3. Based on those properties, 'Process4' is classified as a Skip Process, according to SWRL rule (4), because it started with the sequence event "P4_RetrievePartsFromStorage" instead of the start event "P4_Parts_Required". The result of classification after running the reasoner is illustrated in Fig. 8, in which 'Process4' was classified as Skip Process, because it skipped the start event "P4_Parts_Required".

Table 6. Properties of the 'Process4' individual

Individual name	Property	Value	Class
Process4	beginsWith	P4_RetrievePartsFromStorage	'Sequence Event'
	endsWith	P4_PartsRetreived	'End Event'
P4_RetrievePartsFromStorage	hasEventName	"P4_RetrievePartsFromStorage"	string

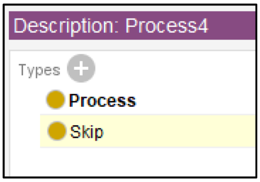

Fig. 8. Result of classifying 'Process4' individual

5 Conclusion

The major contribution of this research was modeling an example business process representing a procurement scenario, that was then used to classify business processes into consistent and/or anomalous (Skip/Rework or Attribute) processes accordingly. A generated event log from simulating the scenario was adopted to populate the ontology, with such processes and classify them successfully. In this work the constructed ontology serves as a knowledge base for discovered anomalies for future reporting, classification, and analysis. As a future work we aim at extending the ontology to be able to classify another type of anomalies such as:

- Early: An event was executed too early.
- Late: An event was executed too late.
- Insert: A random event was inserted to the workflow, and

- Switch: Two events swapped their order of execution.

We may also incorporate such framework as a layer in the architecture of the Blockchain-enabled Supply Chain Management System for anomaly classification. We may also incorporate deep learning techniques for anomaly detection in real world event logs, extracted from the Supply Chain Management Information System of the project stakeholders, which could also serve as another layer in the overall architecture.

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InnoCrowd, An AI Based Optimization of a Crowdsourced Product Development

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Abstract. The development of a new product can be accelerated by using an approach called crowdsourcing. The engineers compete and try their best to provide the related solution based on the given product requirement submitted in the online crowdsourcing platform. The one who has submitted the best solution get a financial reward. This approach is proven to be three time faster than the conventional one. However, the crowdsourcing process is usually not transparent to a new user. The risk for the execution of a new project for developing a new product is not easy to be calculated [1, 2]. We developed a method InnoCrowd to handle this problem and the new user could use during the planning of a new product development project. This system uses AI concepts to generate a knowledgebase representing histories of successful product development projects. The system uses the knowledge to determine qualitative and quantitative risks of a new project. This paper describes the new method, the InnoCrowd design, and results of a validation experiment based on data from a current crowdsourcing platform. Finally, we compare InnoCrowd to related methods and systems in terms of design and benefits.

Keywords: New product development · Artificial Intelligence · Knowledge management

1 Introduction

Howe has defined Crowdsourcing by 2006 [3]. Nowadays, crowdsourcing has gained popularity in several application areas because of significant cost and time savings [4]. Crowdsourcing covers quite a large range of application scopes, including simple tasks such as tagging a picture, medium tasks like programming a simple app, and even complex tasks such as designing and producing a vehicle [5]. Our work addresses primarily bigger projects, like the latter, a typical one for Local Motors. A traditional automobile manufacturer employs less than 5000 engineers to design a new car, but Local Motors depends on the support of more than 30.000 engineers (the crowd) for this purpose, as illustrated in Fig. 1. Engagement of more people can make the design process up to three

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https://doi.org/10.1007/978-3-030-94335-6_19

times faster and the manufacturing cost more than 10 times cheaper. Also, taking advantage of a greater variety of expertise and backgrounds tends to improve the innovation and quality of the product.

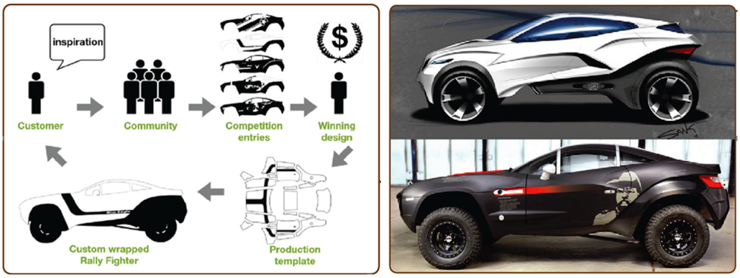

Fig. 1. Crowdsourced vehicle development in Local Motors [5]

Amazon Mechanical Turk, one of the best-known crowdsourcing platforms, offers micro tasks to the crowd, for example tagging images, and translating fragments of text. Top Coder offers low complex software tasks that together respond to user requirements. Similarly, Cad Crowd divides up new product design into smaller jobs. We used data from Cad Crowd experience to train our machine learning algorithm and for testing.

2 Problem in Industrial Business Use Cases

The difficulty of deciding whether to participate in a crowdsourcing competition increases with task complexity. Informal, purely manual procedures could be satisfactory only for simple projects. Determining the risk associated with complex projects requires more formal methods and tools, as reported in [1, 2, 6].

The crowdsourcing literature does not reveal any dominant theories or models [7]. Researchers have employed a wide range of techniques, including case studies, proofs-of-concept, design studies, usability studies, tool developments, and experiments. Findings tend to be ad-hoc and are sometimes conflicted. For instance, researchers differ on whether increasing payments tends to increase crowdsourcing output quality [8]. Crowdsourcing is an emerging research area with scattered knowledge.

In the following chapter we show the state of the art. The fourth chapter describes our development of methods for making decisions easier by making project risk more transparent. The fifth chapter presents results of the experiments. The sixth chapter discusses related works and enhancements to the state of the art through our contribution. The last section summarizes our current work.

3 State of the Art

Determining requirements for a system to assist in assessing the appropriateness of responding to a crowdsourced offer can be built around the goals for the system [7], using design patterns like reflection [8] or logical reasoning approaches such as constraint programming [9]. Both present limitations, such as rigidity and poorness of expression in the representation of a wide spectrum of requirements, and in the representation of evolving systems [10]. Several authors have tackled the problem from a requirements and knowledge reuse perspective [11], however, ad-hoc and manual practices persist [12]. Crowdsourcing has proved efficient for building a knowledgebase. The author in [13] built an enterprise ontology of business process crowdsourcing. It includes the main business processes, data entities, data attributes, and their hierarchy relationships, which were structured into a lightweight ontology. He made it more robust by adding decision-making relationships and business rules. Still, it lacks quantitative and precise effort estimation. Time and project cost are not explicitly estimated.

If we analyze deeper the existing works, there are two aspects of crowdsourcing that addressed, namely task management and crowd worker management. [14–16] developed algorithm for optimizing the work of the crowd. [14] introduced an analytics-based decision support methodology to guide decision making of crowd workers. The results imply that such kind of dynamic decision support for crowd workers is critical towards achieving an increased submission rate and reduced failure rate due to no or poor submissions. [15] developed a Bayesian-generative model to exploit "who knows what" for the workers in the crowdsourcing environment. The model provides a principle and natural framework for capturing the latent skills of workers. [16] formulated three steps for the crowd management. Step one includes important considerations that shape how a crowd is to be constructed. Step two outlines the capabilities firms need to develop to acquire and assimilate resources (e.g., knowledge, labor, funds) from the crowd. Step three outlines key decision areas that executives need to address to effectively engage crowds.

[17–19] addressed task management in their work. [17] developed a recommendation system that support to consider different types of crowdsourcing platforms, workers, and tasks in the evaluation. It has proven that even simple recommendation systems lead to improvements for most platform users. [18] used game-theoretic models to develop design principles for crowdsourcing contests and answer the questions: what types of tasks should be crowdsourced? Under what circumstances? He found out that when a single task is to be completed, crowdsourcing can lead to higher quality outcomes than directed assignment if the pool of players is diverse, but can lead to suboptimal outcomes when workers have similar abilities. [19] developed a domain knowledge to accurately model a worker's quality. He examined using knowledge base, e.g., Wikipedia and Freebase, to detect the domains of tasks and workers. He designed an Online Task Assignment algorithm, which judiciously and efficiently assigns tasks to appropriate workers.

Sample of works described above give an illustration on the limitation of the existing solution which concentrate only in two aspects, namely task and crowd management. We see a clear gap here because other aspects are still not covered in their work sufficiently. How about the financial aspect, the project cost. How about the timely effort, the project timeline. Minimally these two aspects are not addressed in their work.

We developed InnoCrowd to provide the necessary tools for the systematic reuse of requirements from project histories. It calculates risks while minimizing the necessary resources. The decision-making process is based on a domain ontology, which describes the system components and the metrics that guide their selection, according to user requirements. This framework also manages the high level requirements and dependencies to guide implementations.

4 Research Methodology

We use "Design Science" as our research methodology. We collect system requirements, define acceptance criteria, consider past knowledge to the related research projects in order to produce research contribution and not routine design.

As mentioned in the second chapter we take real productive data from the crowdsourcing platform CAD Crowd. Typical crowdsourcing task in product development area is given in text as requirement information and also images which represent rough visualization of the required product. In relation to this we have to consider both types of input data, namely text and image. If we consider only text as input data then the crowdsourcing project classification result might be not precise enough. Since we will use artificial intelligent for the classification task then it is very necessary to get as much as possible data necessary for the training and for the testing. Therefore the first requirement in our research methodology is how to fetch all related text and image data from the crowdsourcing platform effectively. The data fetching process needs to be semi automated so that it can be processed by only a single click. The task can be fulfilled by choosing and using an optimum web scrapper.

The second requirement is how to prepare the data before it is consumed by the tool of artificial intelligent. Not all the data gained from the fetching process is relevant for the classification task. If the irrelevant data is kept then it may lead to imprecise data classification. Here we can use text and image editor tools.

The third requirement is to get the optimum algorithm for the classification of text and image. In context of text processing there are several algorithms of Natural Language Processing (NLP). And for image processing there are also many alternatives from machine learning algorithm. This is to be explored in the experiment which will be reported in a specific chapter in this paper.

As the next step is the definition of the acceptance criteria. The most important acceptance criteria is the level of accuracy for the data classification result. We will try to reach the level of accuracy 90%. More than that we will consider time, cost, and quality as parameter for benchmarking with other relevant methods developed by scholars.

A comprehensive literature study is conducted for knowing state of the art and the gap to be fulfilled by our solution. It is shown by mentioning the past knowledge to each related sub aspect in this work.

5 Contribution: InnoCrowd Method

We developed a novel method for the generation of a knowledge database relevant to a specific crowdsourcing provider. Figure 2 shows an overview of InnoCrowd including system set up and system usage. The block “System set up” summarizes how we build the Decision Support System (DSS). Form definition point of view a DSS represents a point of view on the role of the computer in the management decision making process [14]. Decision support implies the use of computers to:

- Assist managers in their decision processes in semi structured tasks.
- Support, rather than replace, managerial judgement.
- Improve the effectiveness of decision making

It starts with the collection of data from the crowdsourcing provider, which consists of text files (product requirement from customer), images, project histories, and digital models (2D and 3D files of the product to be designed). The second step uses NLP and Deep Learning Neural Network (DLNN) to extract information. The third step embeds product classification in the Neural Network (after NN training and test). The last step establishes relationships between each product sub class and the project specific information relevant for a decision: product specification, related time and cost, and a description of the working team from the crowdsourcing provider’s project history.

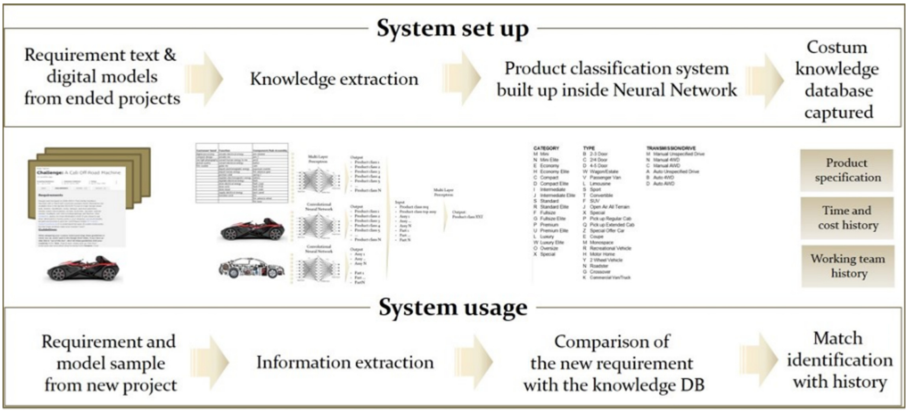

Fig. 2. InnoCrowd overview, system set up and system usage

The block “System usage” shows the way we use the DSS to decide on a new project. Requirements and model samples are input to the system. The second step is the extraction of relevant information from the given dataset (input in the previous step). In the third step, the DLNN classifies the new project by comparing it with others in the knowledgebase. The final step provides project-specific information relevant to a decision: product specification, related time and cost, and working team requirements. The user can then decide whether to apply for the new project.

We use DLNN for the automated recognition of the product design. For each step there is a special neural network trained for recognition. A deep learning neural network is known as the best analyzer/classifier of 2D pictures. It can process the data faster than a 3D model classifier [14].

The requirements are collected as free form text from the source system (crowdsourcing provider platform). Each relevant part of the text will be mapped to the related domain or application or adaptation layer. Then the Neural Network classifies the proposed product.

6 Experiment

The dataset for the experiment was extracted from the crowdsourcing platform CAD Crowd. More than 900 crowdsourcing projects are listed in the platform. More than 800 projects were finished and therefore could be used as input for our knowledge database in InnoCrowd. The dataset consists of text and images. We extracted the data with a web scraper. At the beginning we processed the text and image data separately in the data mining tool "Orange." Figure 3 shows the text processing procedure.

The data has to be preprocessed before being used in the classification system. The texts are grouped into several segments. We have found out that some segments are not relevant for the classification task. Therefore, we cut this from the dataset. We give specific group naming to some segment so that it gives more semantic meaning which is relevant for the classification task. Among others the group name "Dimension", "IT specification and "General specification". To the image data we also delete some images which are not necessary for the classification task. We concentrate on image analysis from the same perspective. It gives more accuracy when the image classification process is performed.

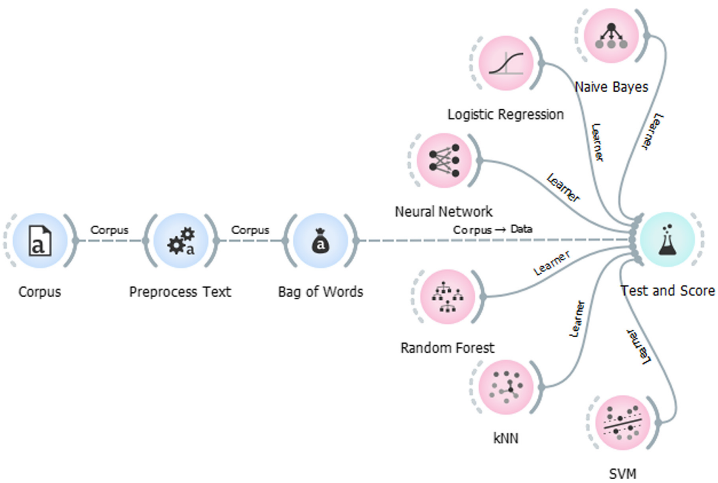

Fig. 3. Process chain for the text analysis

The process is initiated in the first step called "Corpus" which takes the text file in a specific data format. Therefore, it is necessary to convert the text file extracted from the web into this data format. The second step "Preprocess Text" is the step for handling parts of text that are not relevant for the data mining. For an example, commas, dots, low level words such as “and”, etc. The third step “Bag of Words” is the step where the words in each dataset are counted and then converted into numbers in order to make it calculatable and comparable during the data classification in the next step. The fourth step is the testing and scoring process by using several algorithms. As seen in the picture, six algorithms are evaluated in order to get the best classification result. These algorithms are: Neural Network, Logistic Regression, Naïve Bayes, Random Forest, kNN and Support Vector Machine.

This is the first experiment for comparing the performance of each algorithm. In the Fig. 4 (left side) we can see the result, the performance comparison between those algorithms. The most important result is given as the parameter called AUC which represents the grade of classification accuracy from each algorithm. Two best performance are achieved by Logistic Regresion (Accuracy: 0,657) and Neural Network (Accuracy = 0,653). Therefore, we limit the next experiments by using only these two algorithms.

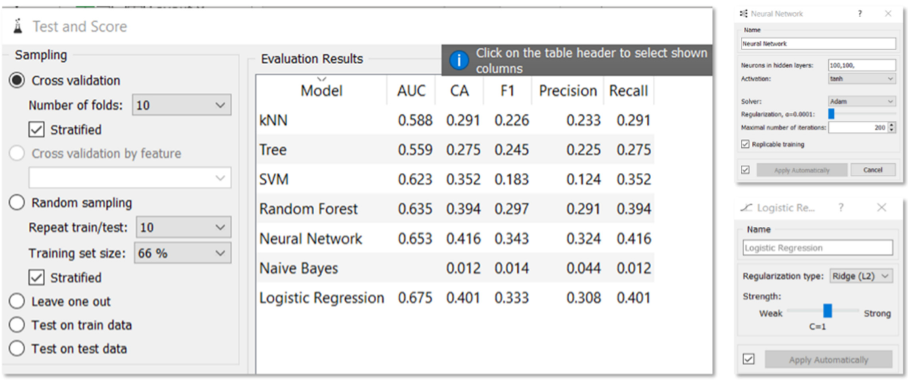

Fig. 4. Result of the text classification with several algorithms

On the right side of Fig. 4, we can see parameters of Neural Network and Logistic Regression that can be set to get more accurate results.

We carried out further experiments by manipulating each parameter. Roughly these are parameters that modified during the experiments:

- KNN layer:
  - number of layer: 3, 4 and 5
  - neuron number in layer: 50, 100, 150, 200
- Regularization: 0,01 0,02 0,05 0,1
- Max. nr of iterations: 100, 200, 300, 400

Manipulating the parameters during experiments revealed the best configuration of each algorithm.

These are the best parameters for the neural network:

- Neuron in hidden layer: 100,100
- Activation: tanh
- Solver: Adam
- Regularization: 0,01
- Max. nr of iterations: 200

Final best accuracy (AUC): 0,91

For Logistic Regression these are the parameters:

- Regularization type: Ridge
- Strength: C = 1

Final best accuracy (AUC): 0,90

The neural network had the best accuracy, so we adopted it.

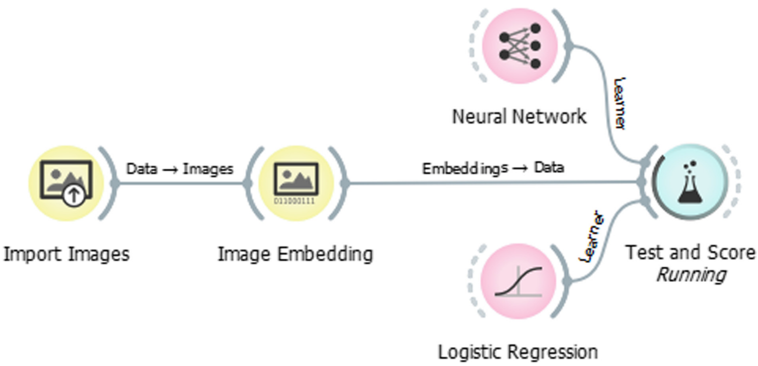

Fig. 5. Process chain for the image analysis

The second experiment was the processing of image files. Figure 5 shows the process chain. It starts with the module for importing the image. The second module embeds images and converts them into numbers according to the pixels inside the image. The third module evaluates each algorithm. This time we compared Neural Network and Logistic Regression. The neural network performed the best image classification, between 95% and 98% (Fig. 6).

The third experiment is the integration of the text and the image processing (Fig. 7). The process chain is integrated so that the system will give the final classification result. We used only the neural network, the best performer in previous experiments.

Fig. 6. Result of the image classification with deep learning Neural Network

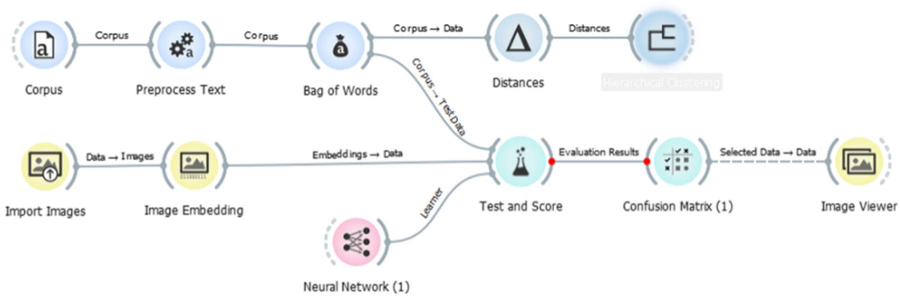

Fig. 7. Process chain for the integrated text and image analysis

We carried out further experiments by manipulating each parameter. Roughly these are parameters that modified during the experiments:

- KNN layer:
  - number of layer: 3, 4 and 5
  - neuron number in layer: 50, 60, 70, 80 90 100
- Regularization: 0,01 0,015 0,02 0,025
- Max. nr of iterations: 200, 230, 250, 270, 300, 330, 350

This experiment found the best result with the following parameters:
Neural network these are the parameters:

- Neuron in hidden layer: 80,90
- Activation: tanh
- Solver: Adam
- Regularization: 0,015
- Max. nr of iterations: 330

Final best accuracy (AUC): 0,90

This 90% accuracy is sufficient to significantly supporting decisions on product specification/requirement, project time and cost, and the working/crowd team.

7 Comparison with Related Work

As described in the chapter “State of the art” there are related works which can be seen as a decision support system for crowdsourcing. But they are focused on limited aspects, namely task management and crowd management. They don’t take into account other aspects such as project cost and project timeline. By considering this limitation we compare our solution with the solution given by [13] because it covers the same aspects as InnoCrow does. Figure 8 below shows the conceptual model of the solution developed by [13].

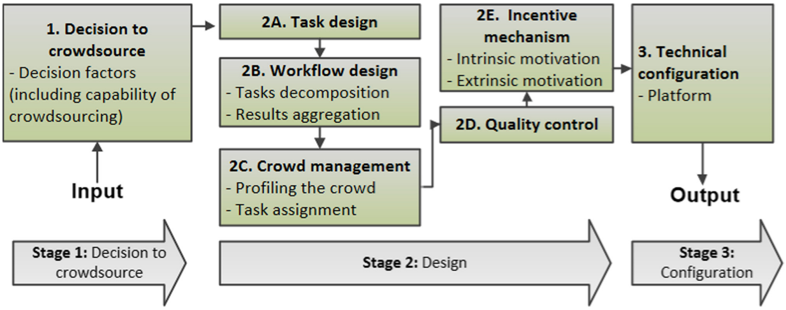

Fig. 8. Conceptual model developed in [13]

And for a comparison in the high level we show InnoCrowd’s conceptual model in the Fig. 9 below. The same aspect is that both concepts is that they are to be used as tool for a decision support in crowdsourcing project. In practice both solutions deal with the aspects task/product specification, cost management, as well crowd management. Solution of [13] takes quality control into account. Meanwhile InnoCrowd seals with time management.

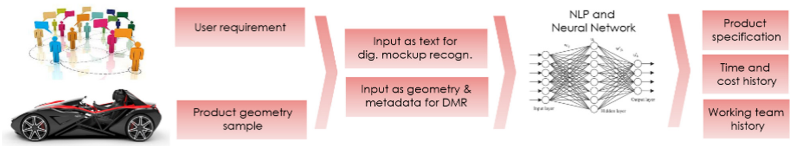

Fig. 9. InnoCrowd’s conceptual model

We found out that the biggest difference is related with the usage of the solution. In the solution of [13] everything is to be done step by step manually. Meanwhile InnoCrowd works automatically by giving input in form of initial product specification and initial possible product form as image file. The relevant output for decision is given automatically by the algorithm of InnoCrowd. This gives more advantage in term of easier usage and time necessary for making the decision.

Furthermore, we compare the both solution on three main aspects, namely time, cost and quality. The following is our estimation. InnoCrowd get 6 times "very good" and1 time "sufficient". Meanwhile solution of [13] get 2 times "good" and 5 times "acceptable". The comparison of average InnoCrowd vs Solution of [13] is 3,6 vs 2,3. It means InnoCrowd performs better that the solution of [13] (Fig. 10).

DSS tool	**InnoCrowd**	**Score**	**Solution [13]**	**Score**
Time				
Time to market	Only digital input necessary	++++	Need consulting	+++
Lead time	Automated evaluation process	++++	Through the questionair	++
Cost				
Prediction of project cost	Based on facts from DB	++++	Qualitative prediction	++
Tool investition cost	Need customizing on classes	+	Customizing only in high level	+++
Quality				
Quality of crowd workers	Very detailed record	++++	Qualitative evaluation	++
Quality of project mngmt	Transparant process	++++	Qualitative evaluation	++
Quality of input vs output	Enable improvement	++++	Only in high level	++

++++ = very good   +++ = good   ++ = acceptable   + = sufficient

Fig. 10. Solution comparison

8 Conclusion and Future Work

Methods for handling complex product is developed and embedded in the method for handling innovation creation process. As the whole it builds InnoCrowd. We verify the solution concept by using dataset from crowdsourcing platform CAD Crowd. The verification result on product requirement analysis (as free text file) gives a good classification result, namely in the accuracy level between 90% and 91%. Meanwhile the verification result on digital model analysis gives even a higher accuracy, between 95% and 98%. The overall performance when the text and image analysis are integrated is 90%. This result gives a clear view on the usability of InnoCrowd.

The comparison of InnoCrowd with other solution gives a clear result, that InnoCrowd performs better. The performance of InnoCrowd is "good", meanwhile the other solution is between "acceptable" and "good".

In relation with the usage of InnoCrowd as a decision support system then it is technically done by providing the user the information related to the previous project matched with the planned project. The user will have access to the information of the previous project cost, the time needed to finish the project and also the crowd workers who had work for similar task. These information give a clear transparency on the project risk, so that InnoCrowd can be used as an answer to the management when they want to crowdsource a product development project.

So far, we have developed the basic functionality of InnoCrowd. What we still have to develop in the future is the user usability so that the process chain starting from data fetching, data preprocessing, data classification and result presentation can be done in an integrated environment. And we still need to optimize the processing time as well as the accuracy of the algorithm.

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Applied Artificial Intelligence: Risk Mitigation Matters

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Abstract. Digital technology is the main driver of the transformation process that is already on its way and expected to take up speed. Science and engineering are challenged to realize the significant innovation potential while keeping an eye on economic and societal sustainability. Research methodology in science as well as development practice in engineering provide well-established approaches to risk management and mitigation relating to this technological transformation. Artificial intelligence, though, brings in new features to address which this chapter shall help to deal with. As such we take into view machine learning, automated decision making and autonomous systems, and data utilization. We look upon characteristic risks within the application lifecycle, and on functional, societal, and cybersecurity risks. We derive suggestions for an approach to proactive risk management addressing the lifecycle of Artificial Intelligence applications. Along with a preparatory section on terminological clarification regarding artificial intelligence, data, and risk this paper is intended to build awareness of risk mitigation matters and set the scene for the development of accountable risk management approaches.

Keywords: Artificial intelligence · Risk management · Risk mitigation · Data analytics · Machine learning · Automated decision making · Autonomous systems

1 Introduction

In the course of the Covid19 pandemic we could make, among others, two observations worth reinforcing. Firstly, when a not well understood danger - like the Sars-CoV-2-virus - disseminates out of control, the individual, societal, and economic cost can be tremendous, and reactive risk management becomes difficult whereas essential. Secondly, the development of proactive risk mitigation means – like Covid19 vaccines – is possible as a break-through innovation within record time, while regulation and well-established scientific methodology are in place calling for due procedures to follow that are aiming at the control of related risks. Both these observations strongly support the concept of proactive risk mitigation and management when it comes to the technological transformation digitization and artificial intelligence are introducing into our lives. This holds

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true even more if we consider that, other than in the case of Covid19, this transformation is not emerging out of the blue. We are well advised therefore not to neglect thorough reflection on appropriate ways to hedge potential risks that come along with the application of Artificial Intelligence (AI).

1.1 Digitization – Theoretical Considerations

Digitization, the numerical representation of analogue phenomena that can be observed – and measured – in the natural, technical, economic, or societal environment, can be taken as an approach to address the problem of complexity [15], i.e. to make complex things or situations manageable. In his 'theory of the digital society' Nassehi [15] distinguishes between the digital world and the analogue world. In the analogue world – the reality – data appear always in analogue context, continuously in time and space. In the digital world, however, any such context gets transformed into discrete data sets, where the discontinuity is being introduced via functional criteria, according to the specific purpose of observation, and realized via the measurement of related quantities. Result is the data world, the digital twin of reality[1]. While in the data world there is no generic connection of data, causation of and instruction for the analysis or processing of that data as well as their linking originate from the analogue world. This should be noted carefully as it implies a particular limitation to the perception of the concept of Artificial Intelligence, in the sense that any application of Artificial Intelligence in fact has a real-world, i.e. a human cause.

It is also worth noting that in his analysis of the digital society Nassehi takes the perspective of structural functionalism, where there are the two basic conditions of functioning and non-functioning. He analyzes the society as having been binary coded (e.g. science: true/false, law: right/wrong, economy: pay/no-pay) even well before the technologically understood binary pair of states functioning/non-functioning came into being. However, while the societal binary coding is widely accepted to depend on trust, technological binarity is considered being objective, hence more reliable, supporting the imagination as well as the requirement of full control. This is of importance for the way we address risk in the technological field, particularly with respect to Artificial Intelligence in the digital economy. Technically, an AI application must function according to its design, like a machine, where eventual malfunction can be detected easily. But inherent to Artificial Intelligence are the features of reasoning based upon the analysis of data, learning while in operation, and decision taking with full or partial autonomy. An AI application can work completely in line with its functional specification, the results, however, can be undesired, of doubtful validity, or even false. And that kind of, say 'misfunctioning', is anything else than easy to detect as it is being generated by highly complex algorithms. The need for appropriately extended approaches to the subject of risk in Artificial Intelligence thus becomes obvious.

[1] Nassehi uses the term "Verdoppelung" (doubling), which might be misleading, as the data world in fact is not equally as rich as the analogue world, given that it is the result of a functional reduction by which the non-functional features are omitted. The data world in fact is a reductive data model of reality that is determined by the choice oft he functional perspective and the quality of data gathered.

1.2 Artificial Intelligence – Regulative Context

The European Commission in their White Paper on Artificial Intelligence [5] apply an approach to risk in AI focusing on rights protection, safety, and liability[2]. This report distinguishes between AI systems of high and low risk, suggesting different regulative treatment of both categories. A quite detailed elaboration regarding the criteria for high-risk AI as well as the respective regulation of these has been published recently by the European Commission in their proposal of an Artificial Intelligence Act [3]. This proposed act comprises detailed requirements for high-risk AI systems including the obligation to implement risk management and data governance provisions. In any case, while regulation will be of large impact to the development of Artificial Intelligence, risk management beyond mere compliance with legislative rules has major value for the developers and operators of applied AI as it undoubtedly will affect the acceptance, hence successful uptake of such technology.

The view of policy-making institutions like the European Commission, whose purpose, among others, is to set the rules which frame the technological and economic progress for societal benefit, is kind of a view from the outside - where there is also the inside view of those who develop and run AI applications, and the third side view of those being affected, the users. No doubt it is of interest to any of these to see risk issues be thoroughly addressed in advance. Even more so if the suggested voluntary labeling of AI applications (cf. [4, 5]) gets implemented as a means of quality certification. The term coined in this regard is Trustworthy Artificial Intelligence.

Starting point for the generation of trust in Artificial Intelligence are the ethics guidelines elaborated by the High-Level Expert Group appointed by the European Commission, laid down in their report [9, 10]. Seven topics have been identified there and are taken up in [5] as key requirements:

- Human agency and oversight
- Technical robustness and safety
- Privacy and data governance
- Transparency
- Diversity, non-discrimination and fairness
- Societal and environmental well-being
- Accountability

It is crucial, though, to get to operationalization of these requirements, as authors like Stix [16] have pointed out, claiming the necessity to develop actionable principles which are missing so far. Attempts to operationalize these requirements in the application of Artificial Intelligence should include appropriate procedures to assess, monitor, and mitigate risk. This calls for proactive risk management.

[2] "The main risks related to the use of Artificial Intelligence concern the application of rules designed to protect fundamental rights (including personal data and privacy protection and non-discrimination), as well as safety and liability-related issues" [5, p. 10].

2 Terminological Clarification

In [14] we briefly reflected on the meaning of the term Artificial Intelligence as compared to Human Intelligence. Simply put, the difference is the absence of mental processes in AI systems. They work with empirical or statistical data as their input, process these by algorithms, and generate correlation-based results of certain probability. However, there is a wide range of conceptual attributes used when talk is about Artificial Intelligence. The extremes are smart machines – whatever smart may mean there – at the low end, and AI systems with an own legal or even ethical status at the high end. Likewise, the terms data and information often get mixed up in this context, taking data as a kind of a natural resource while ignoring they come into existence only by functional reduction of reality. And similar confusion as to risk and its management can be observed in the public discourse. In this chapter we lay out the meaning of the terms as we apply them subsequently.

2.1 Artificial Intelligence is Unconscious Intelligence

In whatever form applications of Artificial Intelligence appear, they are utilizing software as their very kernel. They are programs, designed to simulate the analogue reality. The question is, do they reach as far as to make the difference between reality and simulation vanishing, which would justify the perception of AI systems being intelligent. Not few protagonists would subscribe to this, basically arguing that if no difference can be observed, there is no difference, or, a little weaker, the difference is no longer relevant. The opposite position is drawing on Artificial Intelligence as unconscious intelligence. Fuchs in [8] presents well elaborated principal considerations distinguishing human from artificial intelligence which in essence are summarized as persons are not programs, and programs are not persons [8, p. 35: 'Personen sind keine Programme. Programme sind keine Personen.']. Besides living vs. not-living, consciousness vs. unconsciousness, and subjectivity vs. no-subjectivity he names self-causation vs. external initiation and reflexivity (understanding) vs. input-output-transformation as the criteria which distinguish human from artificial intelligence.

The latter two are of practical relevance for applied Artificial Intelligence[3]. Although an AI system can, based on the data input from the exterior and processed by interior algorithms, well initiate some action making the system look as if it causes the action, this still is result of an input-output-transformation following the rules put in externally (and on functional purpose), which the system itself cannot reflect upon, but only execute. Think of autonomous vehicles as an example. The system thus has no responsibility for what it is executing. Responsibility, and in the operational sense liability, can only be ascribed to the ones having designed the rules and those having specified the purpose. That is where transparency, accountability, and human agency and oversight come into play, key requirements of the European Commission for trustworthy Artificial Intelligence.

[3] Their theoretical relevance would be pointed out if we spoke of Algorithmic Intelligence instead of Artificial Intelligence.

2.2 Data and Information

Reduction of complexity through digitization, Nassehi's doubling of the reality to generate the data world by means of functional reduction, digital simulation of analogue processes, or the instantiation of analogue phenomena in digital twins are all bound to generate data. Applied Artificial Intelligence, including data analytics, are making use of that data. Algorithmic processing then results in action, e.g. in robotics, or in decisions, e.g. in autonomous systems, or in derived data sets for subsequent processing, e.g. in embedded systems. The procedural pattern is input-output-transformation of data. The functional effect, though, is the generation and utilization of information, be that the movement of a robot, executing a decision, or detecting a correlation. Only this functional effect is to be held as valuable outcome of the data transformation. The mere transformation itself has no effect unless it feeds into a connection with the environment, be that physical, literal, or logical. To make sense, the data world needs to come into exchange with the real world[4] (cf. [15]).

The question now is whether this exchange is genuinely of technical nature, i.e. is nothing else than the transportation of data on the physical layer. Janich in [12] has presented a well elaborated investigation showing the problems of such a perception. He breaks the question down to the analysis of the conditions for successful communication, the pre-requisite of senseful interaction. These conditions comprise necessarily a process of mutual understanding, and this process is what turns data into information. He lets open whether it is possible to simulate this process technically. It seems to be clear, though, that such simulation could only work on a finite set of functional determinants. Through functional reduction (cf. [15]) such a finite set can be created. But without it, not even the simulation of mutual understanding is possible.

Resuming these considerations, we note that transporting data from one point to another does not imply equal information at both points exists. Thorough use of the terms data and information thus is recommended. In the context of Artificial Intelligence, taking data as the raw material should not mislead to taking it as some natural resource. Instead, informed approaches are needed to generate data from reality, e.g. functional reduction, and informed processes are necessary for their utilization, e.g. intentional algorithms. These informed approaches and processes are human made. A detailed investigation on these processes has been presented in [13].

In essence, applied Artificial Intelligence rests on human causation. And it implies human caused as well as inherent risks.

2.3 Risk Management

The management of risks is a well-established element in business, science, and technology. In the finance industry comprehensive regulative obligations for risk assessment and monitoring govern day-to-day operation. Research as well as application in medicine and pharmacology rest upon pertinent methodological regimes for the control of undesired effects in diagnostics and treatment. Almost any technological field is ruled by

4 An approach to deal with this in data business and applied AI is to make use of metadata providing contextual enrichment of raw data.

norms, standards, and regulative precautions aiming to enable interoperability and the mitigation of risks connected with their appliances. All but surprising risk management becomes an issue for Artificial Intelligence, too. There are features of AI, however, which raise the need to look upon specifics to consider there. They concern the evaluation of risks difficult or even impossible to anticipate, since AI systems are explicitly expected to generate outcomes not fully determined.

The terms risk, risk management etc. have many specifications. For our purpose in this text those suggested by the International Standards Organization can be used as common ground. We are referring to the publicly available definitions in [11].

Risk there is the effect of uncertainty on objectives of an organization. It is subject to assessment by an overall process including the identification, analysis, and evaluation of risks. Coordinated activities to control and direct an organization regarding risk build risk management. This is governed by criteria of risk to be set in advance. These comprise tangible and intangible uncertainties, measurement of likelihood and consequences, and combination of multiple risks. The issue of the identification of risks, i.e. recognizing and describing them, is particularly relevant in the case of applied AI and poses problems, because often it can be done ex post only. The same applies to risk analysis, i.e. the comprehension of the nature, characteristic, and level of risks. Risk evaluation, finally, is based upon these preparative steps and leads to decide on implementing options for addressing risk, i.e. risk treatment (Fig. 1).

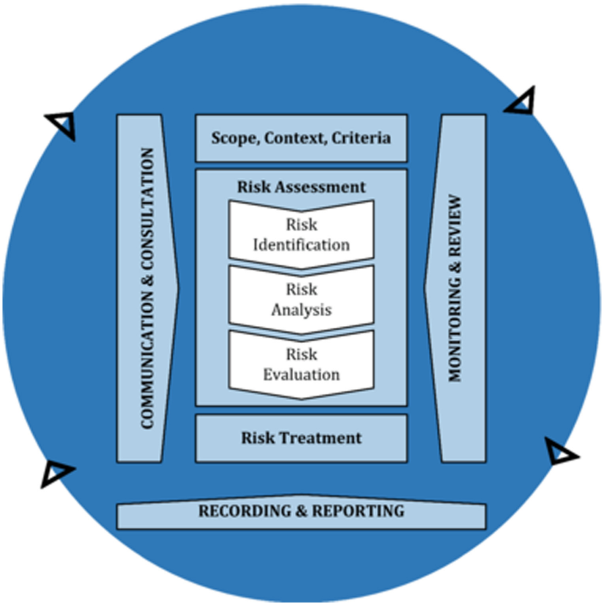

Fig. 1. Risk management process[5]

[5] Source: https://www.iso.org/obp/graphics/std/iso_std_iso_31000_ed-2_v1_en/fig_4.png. Reproduced with permission DIN Deutsches Institut für Normung e. V.

If there is uncertainty, planning becomes hard. The outcome of a technical application that is functionally closed, e.g. a machine, can in general be forecast even as to cases of malfunctioning. The uncertainty here comes down to possible malfunctioning. Empirical analysis of its operation will enable the assessment of the probability of malfunctioning. Applied AI systems, however, are considered functionally open to certain extent. Not only malfunctioning, but also what we have called misfunctioning are sources of uncertainty. This affects both the tasks of risk identification and analysis. An appropriate comprehension of the functional openness of AI applications therefore is needed. We address this in the following section.

3 Applied Artificial Intelligence

The distinction between applied AI and "smart" computing is not easy to make. In first order, it can be related to the level of openness, i.e. how far processing outcomes are not completely determined by processing algorithms. This may vary largely, depending on functional features implemented in an AI application such as Machine Learning, Automated Decision Making, and Data Utilization. Here is a brief characterization of these features.

3.1 Machine Learning

A machine is said to be learning when algorithms use empirical data sets for the detection of certain structures or relations within these data by an iterative process, where a subsequent iteration generates an improved representation of the pattern of structures/relations as compared to the previous iteration in a probabilistic sense, with improvement being calculated using stochastic models. When such a learning process is implemented in an application, it can operate (cf. Bartneck et al. [1]).

- unsupervised, which basically is to explore clusters (like the position of specific marks in e.g. analysis of images), or
- supervised, meaning the iteration process uses a classifier for a target category generating a classification of the data set with respect to that category (think of facial recognition) - this classifier is to be trained by test data, or by
- reinforcement, where iteration is to proceed towards a desired goal (think of the movement of an autonomous vehicle) by feeding in and using additional data, e.g. delivered by sensors.

In essence, in machine learning proceeding to the next step depends on a probabilistic calculus. Selection is made by comparison according to higher similarity. It works in an environment that is functionally modelled and digitized. Modelling and digitization imply the used data sets being finite, even though highly complex, and providing reduced representation, as compared to reality. However, within this limitation, machine learning as part of an AI system enables a certain form of autonomous functioning or auto-control. The outcomes of such AI systems (the classification of a facial image according to specified attributes, the driving or flying course of an autonomous vehicle, etc.) are not necessarily straightforward. There is still room left for variance. They are open, although in a limited sense, including the possibility of misfunctioning.

3.2 Automated Decision Making and Autonomous Systems

Machine learning is an essential prerequisite for autonomous systems, as Wahlster [18] pointed out. In the industrial context, such systems combine Artificial Intelligence, involving machine learning for auto-controlled decision making, and interaction with the environment through sensors and actuators. Sensors observe the environment and measure relevant parameters to feed them into internal processing for the purpose of deciding upon subsequent operation. Actuators perform resulting actions.

Autonomous systems are expected to operate goal-oriented in a basically open, while limited, space of possible action. This is evident in the case of, e.g., an autopilot of an aircraft, or a robot in a manufacturing shopfloor. And they are bound to become part of AI applications in the medical sector, supporting e.g. diagnostics, or in the finance industry, e.g. as robo-advisors for investments. Common to all these are interaction with the exterior, governed by the flow of data, and the intentional establishment of an internal experience base built from empirical data gathered through operation. Quality of data thus becomes fundamental, as does the functional fit of the algorithms being employed.

Misfunctioning, in the sense of the generation of undesirable outcomes although there are no functional or data faults, is an inherent issue with any system that involves automated decision making. Wahlster [18] describes an approach to resolve this by introducing human supervision for non-standard events occurring during operation. Such semi-autonomous systems need well-organized mechanisms for the exchange and transfer of control between human agent and the automated system. They comply with the principle of human agency and oversight suggested by the European Commission as a key requirement to trustworthy Artificial Intelligence.

3.3 Data Utilization and Uncertainty

Data used as input to AI systems typically are subject to a processing cycle aiming to secure appropriate data quality. A useful illustration of data transformation along the lifecycle of an AI system is shown in Fig. 2.

Fig. 2. Data transformation along AI lifecycle development stages[6]

The basic steps in this process are initial data collection, data pre-processing including cleaning and transformation into a numerical data set, reduction to a functionally

[6] Source: [6]. Permission granted.

relevant data set, and training of the AI system according to a machine learning model (see Sect. 3.1 above) to generate the augmented data set.

As mentioned in Sect. 2.3, one expectation related to an Artificial Intelligence application is that it shall generate results which are reliable, as they are based upon objective data and imply no human bias. However, as pointed out in Sect. 3.1 above, the machine learning algorithms involved use probabilistic calculation. Judgements in the iterative learning process are made under uncertainty. The problems of judging under uncertainty have been established since long, going back to the work of Tversky and Kahneman [17]. In our context here, particular attention relates to the issues of representativeness and bias of input data used for judging. Tversky and Kahneman showed that they can substantially affect the reliability of judgement. This applies not only to judgement made by a human, but likewise to judgement as an inherent function in machine learning. For that reason, a trained AI application in general is subject to subsequent testing and evaluation.

It should be noted, however, that this leads to the question of quality and representativeness of testing resp. evaluation datasets. There are basically two approaches to address this issue, usage of empirical datasets, or standardized ones that get agreed in advance. While the first one is applicable ex post observing the operation of a system, the latter requires ex ante specification. The frequent claim of Artificial Intelligence is, while being based on objective data instead of subjectively estimated evaluation, to reduce or even avoid sources of flaw of this kind. It deserves thorough consideration yet in any case. Various examples have been reported where AI applications, e.g. for the recognition of specific patterns like mood or emotion in face images or videos, let show significant bias or incoherence when tested with real life datasets.

4 Risk Categories

Along with the entering of digital business models into the economic and societal ecosystem over the past years, implications showed up which gave reason to public debate about risks involved. It is not in the scope of this text to discuss these in detail. We note here, though, that digitization appears to bring about more than just technical risks, in particular societal risks and those related to cybersecurity. Artificial Intelligence will add specifics which we are concentrating on, as they are expected to affect the acceptance of respective applications, hence their business potential. The subsequent considerations are the result of initial reflections, but we do not claim they represent the complete picture. Our first attention is given to the lifecycle aspect of applied AI.

4.1 Risk Along the Application Lifecycle

When the features of machine learning and/or autonomous operation are included in an application, it will become dependent on an empirical experience base introduced during design and implementation, while this is bound to develop during operation. The application is subject to changing their base of operation, meaning its mode of operation and even the outcomes may change. These changes and any risks they might imply cannot in any case be taken care of in advance “by design”.

This is not just hypothetical, in fact there are examples. It occurred when a chatbot for writing comments in a chatroom under auto-control, i.e. without being surveyed by a reflecting human actor, ran out of the range of what is being the accepted way of communicating publicly. While it was rather testing than a released application, it revealed, however, the limitation of auto-controlled machine learning. This raises the need for risk considerations being applied not only to the design of AI systems, but also to subsequent phases of its lifecycle. Risk responses should be thought of proactively for the development as well as the operational phase.

4.2 Technical Risks

Like any technical device, an AI application can function or not. Malfunction is an inherent risk. There are ways to its anticipation by implementing appropriate response means in advance. Engineering in general, and software engineering in particular, are used to cover this kind of risk management approach. Sources of risk can be false input, failures in output, and model flaws. The standard way is to address them during design and development by implementing precautional procedures. For the operational mode, maintenance and repair are the routines of choice. Taking it as an applied AI example close to the low end, the cases of fatal problems with automated operation control in aircraft in the recent past turned out to be a combination of false input and an inappropriate software procedure in the system.

In the case of applied AI of more general nature, an additional type of risk can be named, we call it misfunction. It can be result of deficient, while not false input, caused by e.g. insufficient data quality. A facial recognition application can produce false identification because the image data fed in are lacking precision or accuracy. Misfunction can also be the effect of an algorithmic flaw. Algorithms used may be designed such that even in error-free operation they can lead to biased evaluations in the end, although input data are not deficient in the sense above but bear characteristic features which in the process of algorithmic classification generate inappropriate tracks. Examples have been reported a. o. in the field of criminal disposition investigation.

As third type of risk we consider emerging phenomena. Think of the chatbot example mentioned above. Neither an issue of false or deficient data input or output, nor the result of an algorithmic or model flaw, that application of AI featuring machine learning and autonomous operation in a real-life environment produced outcome which was unforeseeable, while not intended. It just emerged. Obviously, this kind of risk is utmost difficult to deal with, during development as well as operation of an AI system. In terms of risk management, here is a major challenge.

4.3 Societal Risks

The easiest-to-grasp risks in this category are those related to regulation including legislation. Providers of AI applications must comply with regulative rules. Breaching them is an obvious business risk. Their potential violation is a risk for the society and individual users concerned. As there is no uniform regulative regime in place internationally, addressing this risk type requires much effort regarding the design of the system architecture during development and operation.

The technical risk of misfunction goes hand in hand with the societal risk of undesired implications. Frequently debated is the danger of bias in the context of AI applied to assess personal attributes. This may concern mainly individuals. Of broader societal impact yet are implications caused by model design which rests on personalization. Examples are echo-chambers in the field of social media or news services constraining the availability of information to a person, thus bearing the potential of e.g. political manipulation. The occurrence of such effects has been brought about by various studies. With respect to the commercial sector, the implications of personalization through filter-bubbles are widely discussed. Arguments draw on the non-transparency to users which increases the information asymmetry between suppliers and consumers and thus affects market efficiency.

A major societal risk category then relates to the connectedness e.g. of digitized infrastructures. Thinking of smart metering in the sector of public energy utilities, where intelligent management is expected to contribute to efficiency improvements to the supply and use of energy, the embedding of AI applications into complex grids of devices poses the risk of potential flaws propagating through the network, thus endangering resilience. As soon as such digital networks get equipped with embedded AI components, the functional openness of these components becomes a source of risk.

The fourth type of risk with societal relevance we take into view is the very basic phenomenon of ethical dilemma. In the context of the autonomous car a reoccurring subject of debate is if and how an artificial system can be designed to operate when it comes to decide between alternatives that both result in damage to a human. While there is good reason to doubt that a satisfying general resolution to this dilemma can be found, the need to address it in practical situations cannot be denied. Apparently, it shows up as a problem with any autonomously operating physical AI application. Catastrophic external events, though not very likely, can happen, and the way an artificial system is designed to deal with them will be a major issue of acceptance[7].

Within the purpose of this text, we put focus on these four risk types. A wider political view is provided in [7]. That report is supposed to support further elaboration of the societal risk category.

4.4 Cybersecurity

Cybersecurity has been gaining increasing relevance in the past decades. Adversarial attacks on the IT systems of public authorities, companies, institutions in science or public infrastructure are being reported in ever growing numbers. Criminal, political, or economic interest appear to be the drivers. With Artificial Intelligence on the rise, it is safe to expect growth will continue. The threat is twofold. AI technology can

[7] Machine ethicists have been discussing that kind of problems since long. In his comprehensive reflections on Limitations and Risks of Machine Ethics, Brundage [2] in essence concludes that "…there is more to successful ethical behaviour than having a good algorithm" (ibd., p. 268). He draws upon, a. o., two lines of argument: knowledge limitation (real-life ethical decision-making is heuristic, because it is impossible to consider the whole space of possibilities) and computational limitation (computing the implications in a given situation can be intractable because of the number of agents, the time horizon, or the actions involved).

provide novel instruments for intentional attack. And AI systems in operation will be of particularly high interest to attack as they are largely non-transparent and, at the same time, of high economic or strategic value. This risk category therefore deserves to be considered separately, although there is much overlapping with the technical and the societal categories. Even more so, as there is still a significant lack of awareness.

The European Union Agency for Cybersecurity ENISA recently presented their report on AI Cybersecurity Challenges [6]. This illustration of the threat landscape for Artificial Intelligence can be taken as a point of reference for risk management activities in applied AI. Within the threat modelling methodology provided there the identification of risks is key, in terms of threat and vulnerability. Our focus in this text is on three risk types: attack, accident, and outage. Other than most of the risk types considered in Sects. 4.2 and 4.3, they typically have external causes. Any approach to risk mitigation therefore must include thorough reflection upon the environment an AI application shall operate in.

Further to the considerations in [6], we draw attention to a few specific aspects. With respect to attack by external action or accident by environmental impact especially the interaction of an AI system with the exterior, be it logical or physical, is of concern. Logical program interfaces as well as physical sensors and actuators need to be included in the process of risk identification (and of course then in risk management activities). In fact, this must be done with bi-directional perspective, i.e. inbound and outbound. Not only can a threat be imported into an AI application, but also can one be unintendedly exported to its environment, as far as the application operates autonomously or involves automated decision making.

Likewise, the potential impact of an autonomous system on its environment in the case of physical failure like loss of power can become dangerous. In a system of coupled autonomous units the management of which rests upon communication between the units, the outage of one can result in severe problems for the entire system. Such kind of risk is known in the context of connected systems in general, but it is of significantly higher impact when there are autonomous units operating.

5 Toward Actionable Risk Management

The reflections described so far make us suggest a path to the development of actionable risk management in applied AI which starts from the risk identification matrix in Fig. 3.

As a recommendation, the development and operation of an AI application should in general comprise an exercise to build awareness of the risks involved. And especially if that risks are estimated to be of high likelihood or represent a large damage potential. Categories and types of risks shown in the table should be assessed as to their relevance in the phase of system development or operation or both as first step. Then the specification of the risks as such – events to be avoided – relating to their source can be defined more specifically. Actors involved can be identified, as well as logical or physical procedures, and coupling interfaces. Final step should deal with exploring possible responses and their introduction into the development process, resp. their preparation for the operative lifecycle.

Risk category	Risk type	Source	Response Development	Response Operation
Technical				
	Malfunction	False input or output failure		
		Model flaw		
	Misfunction	Deficient input		
		Algorithm flaw		
	Emerging phenomena	Model design		
Societal				
	Regulative breach	System architecture		
	Undesired implications	Model design		
	Flaw propagation	Embeddedness		
	Ethical dilemma	Catastrophic event		
Cybersecurity				
	Attack	External action		
	Accident	Environmental impact		
	Outage	Physical failure		

Fig. 3. Risk identification matrix.

Apparently, this approach is neither exhaustive nor complete in fitting with the manifold of AI applications that may come up in the future. It is rather the utilization of what has been put up during past efforts to realize the potential of AI in science, technology, economy, and administration. Yet we are convinced that there is significant rationale for the introduction of proactive risk mitigation to this field beyond regulative obligation. It can help to direct future progress toward what is beneficial for business, society, and individuals. It can become a decisive enabler for the building of trust in AI. And it will not downgrade the innovative potential AI can bring to the digital transformation as it supports the acceptance of applied AI. Like with any transformation, scepticism and even resistance are being encountered and must be overcome. Openminded consideration of chances and risks, of opportunities and constraints pave the way to affirmative uptake. And avoidance of potential damage and the related cost at last contribute to the profitability of businesses involved.

The three pillars of the digital transformation – Data, Artificial Intelligence, and Robotics – are subject to risk considerations each to a different extent and under specific perspectives. This will surely extend further with increasing implementation of applied Artificial Intelligence. The realization of its potential rests upon the technical excellence employed. Proactive risk mitigation can significantly contribute to this excellence. This paper describes a starting point for the development of actionable risk management. Further work shall be dedicated to the empirical elaboration and exemplification of the approach. This will include the collection and investigation of AI use cases from different fields of application. Based upon these, a Risk Management Framework will be suggested by filling the gaps in Fig. 3 and further operationalizing the approach. Furthermore, it is intended to establish a Risk Management Library and in the longer run a Risk Management Experience base that can be used as a reference for the development of new systems of applied Artificial Intelligence.

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Smart Contracts Implementation Based on Bidirectional Encoder Representations from Transformers

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Abstract. The distribution and immutability properties of blockchains made it possible to use them in various fields, such as Supply Chain, finance and health. The automation of the creation and execution of transactions in a blockchain in a decentralized and transparent manner is realized through Smart Contracts programming codes. This paper presents the implementation of Smart Contracts in specific manufacturing Supply Chains and discusses their life cycle and impact on the Supply Chain management. The presented application deals with the possibility of transforming natural language contracts of a given Supply Chain to automated Smart Contracts that makes the Supply Chain management faster and safer. A first solution is proposed based on Bidirectional Encoder Representations from Transformers (BERT) model and limited to the implementation of Smart Contracts of the Supply Chain legal contracts. Also described here is the ways of extracting contract elements from legal contracts by applying the BERT Deep Learning method on annotated contract dataset of a corpus of 13000 annotations over 510 contracts.

Keywords: Blockchain · Smart Contract · Supply chain · BERT · NLP

1 Introduction

Blockchain has become one of the emerging research fields after the success of the first crypto currency, the Bitcoin[1] in 2009. After a decade, blockchain is now in its voyage in various fields in addition to cryptocurrencies such as insurance [1], Health [2], Supply Chain [3, 4], Internet of Things [5], Building Information Modeling [6] etc. It can be defined as a shared and immutable ledger for transaction and control of goods and services of the Supply Chain. The main attraction of blockchain is its ability to automate the secure, transparent, and flexible business transactions.

Smart Contracts are the backbone of blockchain that control the transaction with rules that are to be satisfied for proceeding the transactions. They are the pieces of software

[1] https://bitcoin.org/bitcoin.pdf.

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that has written rules to be executed automatically to update the state of the block chain in a systematic way. They are powerful tools for creating decentralized applications without any third-party support.

This paper discusses the concepts of Smart Contracts and the use of Smart Contracts in manufacturing Supply Chain. Such Supply Chain involves the management of lots of legal contracts in various steps and between all the partners. The handling and management of such numerous contracts manually over the lifecycle of the products is in general tedious and time consuming. The automation of such contracts and their handling is a necessity nowadays and their conversion into Smart Contracts is one of the possible solutions in a decentralized and secure context due to the cryptographic handling within their supporting blockchain. The paper addresses two parts. First, the ongoing automation of entity extraction (clauses identification) from supply chain related legal contracts. This step needs the creation of annotated contract dataset and implementation of an appropriate NLP technique for entity recognition and extraction. The main challenge in this field is the unavailability of annotated contract dataset, especially in the supply chain domain. Since contracts are considered as highly confidential, for security reasons, most of the law firms and contract management companies do not make the dataset public. To create a dataset, a large number of contracts need to be manually annotated. This is very tedious and time-consuming work that needs thorough knowledge of the contract structure and content. A new annotated contract dataset called Contract Understanding Atticus Dataset (CUAD), is made public for the first time by a contract management project called the Atticus Project[2]. This dataset contains all type of legal contracts and provides a good input start for our research. This dataset is prepared as Question Answering task of NLP. The proposed model is implemented using Question Answering model of Hugging Face Transformers library [16]. Bidirectional Encoder Representations from Transformers (BERT) model is used for identifying the underlying clauses. The task is being experimented using python as a programming platform. The second part of the research is the automation of smart contract creation using the extracted clauses. This research will be a promising enhancement in the domain of blockchain to supply chain in terms of money, time, and effort.

Globally, the main issues addressed in this research are:

- Creation of supply chain related annotated dataset for this research. This includes selection of important contract clauses that is necessary for creation of an appropriate Smart Contracts.
- Selection of best NLP techniques to be used for extraction of these clauses.
- How to automate the creation of Smart Contract from the extracted clauses with efficiency.

2 Lifecycle of Smart Contracts

Smart Contracts are the scripts in a blockchain which help the automation of trading and transaction in a decentralized network. The idea of Smart Contract, first introduced

[2] https://www.atticusprojectai.org/.

by Nick Szabo [8], explains how to execute a contract securely between two parties without the need of a third party. Smart Contracts have a simple if-then-else structure that is embedded in to the blockchain. The rules written in Smart Contracts are executed when the predefined conditions are verified and met. This can be anything like releasing of funds, issuing of tickets, registering a vehicle, sending notifications etc. Once the Smart Contract has been deployed, the transaction cannot be changed. Only the people participating in transaction can see and access the result. A Smart Contract has mainly three functions [9].

- Agreement between the parties. The contractual agreements between the parties are transformed to executable code. The transaction denotes the fulfillment of contractual obligation. The code evaluates the condition for fulfillment. This code is then stored in the blockchain.
- Precondition validation. Validation of whether the preconditions of the Smart Contract are met or not is done by the participating nodes.
- Execution of Smart Contact. If the preconditions are satisfied, the next step is the execution of Smart Contract. The participating nodes perform the transaction which is reflected throughout the blockchain.

2.1 Smart Contract- Life Cycle

The life cycle of Smart Contract is composed of the following phases [7]:

- Creation
- Deployment and Freezing
- Execution
- Finalization

These phases are shown in the Fig. 1 hereunder:

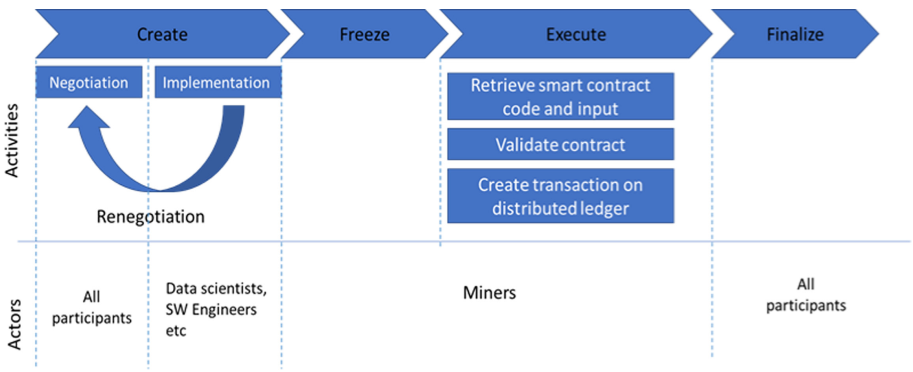

Fig. 1. Life cycle of a Smart Contract [7]

Creation of Smart Contract. In this phase, parties involved in the transaction must agree on the terms and obligations of the contract. This negotiation phase is very similar to actual agreement negotiation. After the agreement on obligations, the contract must be turned in to code. This is the implementation phase. Implementation of the Smart Contract can be done in many high-level languages. One most used language is Solidity [10].

Now participants must agree to the coded version of the Smart Contract. After the agreement, the Smart Contract will be included in a distributed ledger. Thus it gets published in the blockchain. At this stage, all participants will receive the contract. After all nodes agree to this Smart Contract, it will start execution. In case any error occurs in the contract, reverting to previous state is not possible as Smart Contracts are decentralized. So, when an error occurs, a new contract needs to be created.

Deployment and Freezing of Smart Contract. After the submission of Smart Contracts to a blockchain, their validation depends on the majority of confirmations by the participants. At this freezing phase, any transaction made to the wallet addresses is frozen and nodes are in control of checking if the preconditions are met or not for validating the Smart Contract.

Execution of Smart Contract. After the preconditions are met, Smart Contract is now ready for execution by the nodes. During execution, many new transactions are added, and the current states are being updated throughout a distributed ledger and these are validated through consensus protocol.

Finalization. After the validation of transactions and states by consensus protocol, all the prior committed digital assets that were frozen, get transferred. And thus, the validated transactions confirm that the contract is fulfilled.

2.2 Contracts Automation for Supply Chain Management

Supply Chain management is well known as a long and complex process. The Supply Chain includes all the activities from design and manufacturing through shipping to delivery of the products to customers. This may involve lots of supplier and customer chains [11]. As the structure becomes complex, the risk and efforts involved also become high. The complex structure of a Supply Chain is represented in Fig. 2.

Smart Contracts can contribute to simplify this complex process by improving visibility and tracking. The participants can decide and negotiate over the agreements and the decentralized nature of Smart Contract may help them to avoid dispute and track the smooth movements of goods and services with transparency.

Supply Chain management is one of the largest domains that deals with large number of legal contracts at a time. The life cycle of a Supply Chain product deals with management of different types of contracts. Contracts are legal documents signed by two or more parties that clearly explain the rights and duties of participants for the execution of any activities in the Supply Chain. The participants must be careful in following the clauses and activity durations defined in the contracts as this may lead to financial losses and disputes in future.

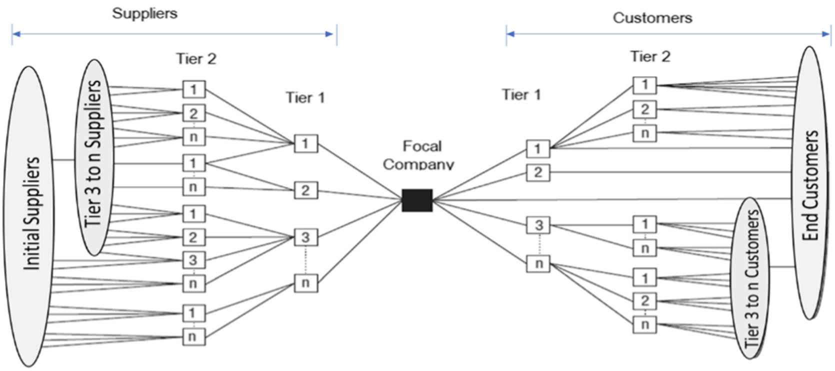

Fig. 2. Supply Chain network structure [11]

Usually, contract management is done manually by the legal authorities and staffs. This process is highly error prone, expensive and time consuming. Automation of contract management can solve many of the problems faced by current manual contract management system.

Since Supply Chain process involves handling a lot of contracts, the introduction of automated contract management in this domain can help a lot in speeding up the process and avoiding unwanted financial losses. Automation helps to get rid of the loopholes and manual mistakes that may arise during the manual contract management and thereby provides transparency on the contents.

The introduction of blockchain to the Supply Chain domain further increases the possibility of automation of contracts. The contract automation and conversion of contracts to Smart Contracts can help to make the contractual obligations to be handled more professionally in blockchain. Smart Contracts, as discussed before, have a decentralized nature and are more secure. The idea of contract management through Smart Contracts for blockchain will make the Supply Chain management simpler and faster.

The main process in contract automation involves extraction of key entities from the contract. This can be done by performing Named Entity Recognition (NER) on the contract dataset. NER is a subset of Natural Language Processing (NLP) that deals with recognition of main entities from the given text [19].

There are various Machine Learning and Deep Learning methods for performing NER. Many pre-trained NER applications such as Stanford NER[3], SpaCy[4] etc. are also available. The problem of using pre-trained NER models for contract element extraction is that these are trained to identify general named entities such as person, place, date etc. In the case of contracts, these have specific structure and usage. Hence, pre-trained NER models perform poorly for such domain specific dataset [18].

Domain specific NER needs the model to be trained in domain specific datasets. There are various domain specific NER systems in existence, such as in medical fields and in different languages. The problem with contracts and other legal data is that there are not

3 http://nlp.stanford.edu/software/CRF-NER.shtml.
4 http://spacy.io.

much publicly available annotated datasets. Some researchers, such as Ilias Chalkidis et al. [12] proposed NER on contract dataset. They created a benchmark dataset of 3500 contracts by manually annotating them with 11 types of labels. In addition, they also used 75,000 unlabeled contracts for the purpose of word embedding. They introduced various extraction methods to extract labels from the dataset. But because of the security issue, they provided the dataset only in encoded format[5]. They have implemented various methods from Machine Learning methods such as SVM and Logistic Regression [12] to the Deep Learning methods such as LSTM, Bi-LSTM with Conditional Random Field (CRF) [13].

Another recent project by Hendrycks et al. [14] has developed an annotated dataset named Contract Understanding Atticus Dataset (CUAD) on various legal contracts with the help of law students. The main advantage of CUAD is that it is publicly available. The project developers annotated 41 unique labels from the dataset. This is a great step for supporting researchers in this area. They used the question answering task of NLP for identifying key entities from the contract. This is achieved by using transformer models. For implementing this model, they modelled the dataset as Question Answering task such as SQuAD 2.0. i.e., for each label in the contract, the substring which specifies that label is highlighted. This dataset and model is tried in our proposed method.

Most researches related to contract management automation till now are in the area of legal contracts mainly to help the contract analysis job easier for the lawyers. Our research on contract management automation in supply chain domain for smart contract creation is first ever of its kind. This will help the supply chain industry with the blockchain technology, to act smarter and faster.

3 Supply Ledger Use Case

Within the Supply Ledger project[6] on the design and implementation of a blockchain platform for a railways manufacturing Supply Chain we are currently developing the automation of contract entity extraction using transformers and transferring of the automated contracts to Smart Contracts. In an initial work we have used a Petri-Net-based formalism to model the smart contract workflow in the supply-chain context [15]. We focus currently on the specific part of contracting workflow, based on the CUAD dataset described in [14]. This dataset contains various legal agreements from the Electronic Data Gathering, Analysis, and Retrieval System (EDGAR) by the US Securities and Exchange Commission (SEC). Though for the proposed work, we need only the Supply Chain related contracts; we are considering the whole set as initial experiment and for methods training purpose. The corpus contains 13000 annotations over 510 contracts, with 41 categories or unique labels in this dataset. Figure 3 picturises the dataset. Table 1 shows some of the categories and descriptions given by CUAD.

[5] http://nlp.cs.aueb.gr/.

[6] https://www.supplyledger.qa/.

Fig. 3. CUAD Dataset description

Table 1. Some of the categories and their description given in CUAD

Category	Description
Document name	Name of the contract
Parties	Two or more parties who signed the contract
Agreement date	Date of the contract
Effective date	On what date is the contract effective?
Expiration date	On what date will the contract's initial term expire?
Renewal term	What is the renewal term after the initial term expires?
Notice to terminate renewal	What is the notice period required to terminate renewal?
Anti-assignment	Is consent or notice required if the contract is assigned to a third party?
Governing law	Which state/country's law governs the interpretation of the contract?

Question Answering model of Hugging Face Transformers library [16] has been used for implementing the model as in CUAD [14]. For each category it treats the label as a question and the answer is the category name with short description. Clauses or entities are extracted using BERT, experimented using python as a programming platform. The overall structure of the model is shown in Fig. 4.

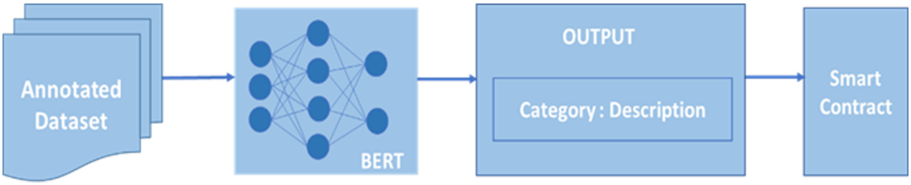

Fig. 4. Proposed architecture

3.1 More on BERT

BERT is a transformer based deep-learning technique for NLP tasks [17, 20]. It is designed to pre-train unlabelled text for bidirectional representation of the data by conditioning both left and right contexts. The pre-trained BERT model has been fine-tuned for downstream functions, to be used in a wide range of applications. The BERT model architecture is shown in Fig. 5.

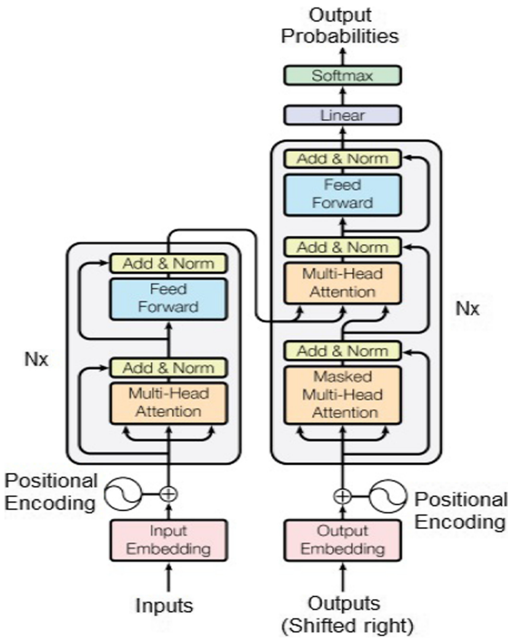

Fig. 5. BERT Model [20]

It is a multi-layer bidirectional encoder architecture. The main attraction of BERT is the self-attention layer. Attention mechanism decides which word has more contextual contribution to the current word. BERT has shown promising results on eleven NLP tasks such as NER and question answering and NER.

There are mainly two steps involved in BERT:

- Pre-training: The model is pre-trained over large number of unlabelled data for different NLP tasks. The pre-training includes two unsupervised tasks.
  - Masked Language Models: In masked representation of pre-training, BERT masks 15% of input tokens at random and predicts the masked tokens from the unmasked tokens.
  - Next Sentence Prediction: This task is aimed to learn relationships between the sentences.
- Fine tuning: The model is initialized with pre-trained parameters and fine-tuned for specific tasks over these parameters. The self-attention mechanism encodes bidirectional cross attention between two sentences. For each task, a specific input-output is plugged in to BERT and then it is fine-tuned with the corresponding parameters. For token level tasks, such as question answering and NER, the tokens are fed into the output layer. For every sequence in BERT, the first token is a special classification token called [CLS]. For classification tasks, the [CLS] token is fed into the output layer. The pre-training and fine tuning is shown in Fig. 6.

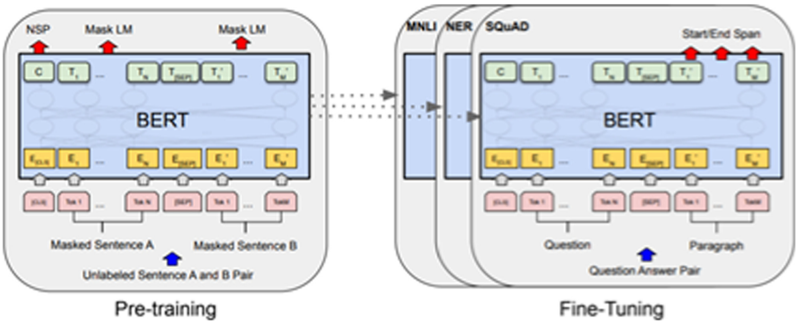

Fig. 6. BERT pre-training and finetuning[7]

4 Result and Discussion

At the current stage, the design and implementation of the initial steps of global platform is finalized. Contract annotations based on NLP techniques is a tedious but necessary work for the accuracy of our results. The CUAD dataset that is being used now, contains contracts from all legal domains. As an initial experiment, the entire dataset is used as a whole. While proceeding forward, a minor filtering process has to be performed on the dataset for the selection of only supply chain related contracts. The next step is the finalization of pre-training and fine tuning of BERT on the comprehensive annotated dataset and test it on the contracts provided by the Supply Ledger project's stakeholders.

[7] https://arxiv.org/abs/2009.04968.

An initial implementation of BERT for the CUAD dataset has been tried. Figure 7 shows the precision-recall curve obtained for BERT implementation using CUAD dataset. This experiment is carried out as a Question Answering task based on the CUAD dataset structure.

The research is in its initial phase and further experiment with NER on the contract dataset is planned to compare the performance of Question Answering Task and NER for opting best method.

The main attraction of Transformer models such as BERT is that the processing of inputs is not sequential. As the name indicates, BERT reads the inputs bidirectionally, i.e., the reading of entire sequence is performed at once. This feature allows them to parallelize and scale the processing compared to other models. Thus, Transformers can learn the context of the text deeper, and hence, the perform much better compared to other deep learning techniques. This is the reason behind the selection of BERT model for this research.

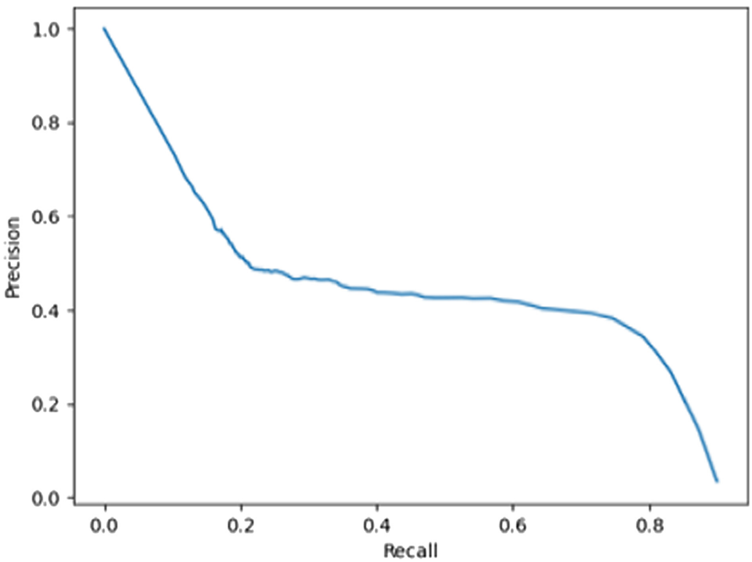

Fig. 7. Precision-recall curve

Next phase of the research is the implementation of Smart Contracts based on the best results obtained from the entity identification and extraction. This will allow the SCM to recommend best Smart Contract template for supply chain related natural language contracts and thus make the entire job easier, cheap, and efficient.

5 Conclusion

Smart Contracts are an essential part for blockchain based Supply Chains. These are computer programs that are executed automatically when preconditions are verified.

This paper has discussed the characteristics and lifecycle of Smart Contracts and their importance for modern Supply Chain management. The conversion of normal contracts in Supply Chain to Smart Contracts makes the execution of blockchain based Supply Chains more efficient and safer. For contract automation process, entity extraction technique is designed and implemented from annotated contracts dataset using Bidirectional Encoder Representations from Transformers (BERT) approach. The CUAD dataset of 510 different contracts is used in this research and the clauses are identified using the Question Answering task of NLP. We are planning further implementation using NER task on the contract dataset and compare the result to opt the better method. Our next focus is on conversion of the contracts to Smart Contracts based on the extracted clauses. The automated selection and recommendation of best Smart Contract template corresponding to a particular supply chain contract will make the block chain process much easier and cost effective.

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Blockchain-Based Manufacturing Supply Chain Management Using HyperLedger Fabric

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Abstract. Production of goods has reached record numbers in the last decades as it became more efficient and effective than ever before due to the automation and digitalization of the production process. This gave customers more choice and the delivery process became faster and more satisfying. However, supply chain management remains a bottleneck due to the limitations of the supply chain management systems which suffer from poor traceability, product tampering, lack of timely information sharing, and delays. These issues can be addressed by the blockchain as a digital platform with features like immutability, transparency, and decentralization of information. In this paper, we propose a case study for improving the manufacturing supply chain management through a blockchain-based solution. The proposed system would provide a more transparent supply chain with improved product traceability because of the tamper-proof and decentralized nature of blockchains.

Keywords: Blockchain · Manufacturing · Supply chain · Transparency · Traceability · HyperLedger Fabric

1 Introduction

To reach the hands of the consumer, a product often goes through a long chain of participants which might include suppliers, manufacturers, transporters, distributors, retailers, and storage companies. Billions of products are manufactured daily through this complex supply chain that could stretch across continents starting from raw materials such as cocoa beans in the Ivory Coast to the hands of a customer in Japan in the form of a nicely packaged chocolate bar [1].

The supply chain participants combine their efforts to design, produce, market, and deliver the final product. This long journey from an idea to a final product is in most cases not visible in a holistic way for a single viewer. Each actor in the manufacturing

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supply chain of a product uses his private information system and the information is exchanged between the actors if necessary either through system integration, manual paperwork, or informal channels such as emails [23]. This would create fragmented silos of systems that are under the control of the supply chain actors with minimal traceability and visibility capabilities. This leads to several issues that include but not limited to data error and discrepancy, information tampering, delay, and lack of real-time information sharing in the supply chain. These issues cause significant risk in terms of reputation and environment which could impact any brand's profitability, equity, and operational capabilities [2].

Additional consequences of these issues are unethical labour environmental damage, end of life wastes and counterfeit products. Another consequence of the defragmentation of the systems and their databases is the difficulty of tracking the origins of the products as the supply chain is stretched and the product travels through a vast network of different parties. Information of where and when the product is manufactured is often obscure. This effect is compounded by the fact that most companies relocate their manufacturing facilities to developing countries [3]. Although recent technologies such as Internet of Things (IoT) devices and wireless sensor networks have started to be used to improve visibility and tracking [4], there remains a major issue in the supply chain which is lack of trust.

The information that is shared between parties in the supply chain either in a central database or in one-to-one information exchange is not trusted. Any party can tamper with the data. Having a centralized information source in a monolithic system without strong protection is a major flaw in the network and any individual or organization who have access to the database can tamper or falsify information to gain an advantage. These actions would result in a complete loss of trust between parties which would often lead them to fall back to more traditional and manual transaction processing [5].

This problem of centralized non-trusted information sources happened to have been solved in another completely different domain which is the digital currencies where information is shared by distributing it between the parties in a decentralized network of nodes. Any further modification for the data once it is committed and distributed between the nodes is not allowed. This is the essence of the blockchain technology which have turned out to be a revolutionary idea that is touching almost all domains. This immutability feature improves traceability, visibility, and most importantly restores trust in the supply chain information systems [6].

In this paper, we propose a decentralized blockchain-based system that implements a manufacturing supply chain use case as opposed to a traditional information system with an RDBMS database. The Fabric Ledger is selected as the suitable platform for the domain for reasons that will be discussed later, and the resulting solution is compared to a non-blockchain based solution in terms of functionality and performance. The goal of the system is to prove that such a system is feasible to implement as a blockchain and investigate the advantages and disadvantage of such a system.

The remainder of this paper is structured as follows: In Sect. 2, we present a state-of-the-art overview of related works on blockchain-based manufacturing supply chain management applications. In Sect. 3, we cover the impact of blockchains on manufacturing systems and the Product Lifecycle Management (PLM). The next section provides an overview of the system. Section 5 covers implementation aspects of the system including its evaluation. We draw our conclusion in Sect. 6 highlighting a set of future challenges.

2 Related Work

Various studies on the effects and applications of the blockchain technology in many fields have been conducted. We have focused on the research conducted on blockchain applications in Manufacturing supply chains.

Fu et al. [7] presented a solution for the emission trading schema that is based on blockchains for Industry 4.0 and an innovative emission link system that is capable of reducing emissions. Li et al. [8] proposed a blockchain-based framework that crosses enterprise boundaries for a high level of sharing services and knowledge in the manufacturing supply chain. They believe that because of blockchain, the manufacturing networks are going to move from traditional networked manufacturing to open manufacturing. Yin et al. [9] developed a secure blockchain-based machine-to-machine communication network to address the problem of securing the communication between the different machines in a cyber-physical system. To fulfil the requirement of checking the authenticity of components in additive manufacturing, Kennedy et al. [10] proposed an anti-counterfeiting method that is based on blockchains.

Lin et al. [11] proposed a framework that is composed of hierarchical four tangible layers and is designed to integrate vertically the inter-organizational value networks, manufacturing factories, engineering value chain, etc. They also developed a secure blockchain-based system for mutual authentication to enforce more fine-grained policies of access control. Lee et al. [12] presented a service for custom manufacturing with a peer-to-peer (P2P) network for customers and manufacturing as a blockchain-based IoT architecture. The architecture is composed of a manufacturer rating classification, a reputation assessment method, and a malicious evaluator identification. To improve the traceability of the components and products manufactured, Westerkamp et al. [13] proposed a blockchain-based method for generating non-fungible digital tokens for the products. Yu et al. [14] proposed a Blockchain-based framework (BSM) to support Cyber-Physical Systems.

The manufacturing industry is going through substantial changes as we are moving to the era of Industry 4.0, and smart manufacturing is becoming a reality through emerging technologies such as blockchains, Internet of Things (IoT), cloud manufacturing (CM), and artificial intelligence (AI). Manufacturing giants such as BMW and Ford are adopting blockchain technology to improve the efficiency of their supply chains and attain business innovation. Leading technology companies and innovative start-ups collaborated to create the Trusted IoT Alliance which aims to develop the necessary standards to integrate blockchains and IoT. The main goal of the standard is to develop smart contract interfaces that enable the exchange of data between blockchain-enabled systems. The alliance efforts are focused on using blockchains for the trusted identification of hardware and documentation immutability.

To encourage the adoption of blockchains by the industry, the cloud-based Blockchain as a service (BaaS) was proposed by various vendors. Businesses can use this cloud-based solution to develop, host, and use their blockchain applications which include their smarts contracts through a blockchain infrastructure that is developed by a vendor. It provides tools that simplify the management and deployment at scale. Similar to the increasing trend of Software-as-a-service (SaaS) where access to the software is granted on a subscription-basis, BaaS enables businesses to tap into a blockchain network using its configuration without having to invest in developing their blockchain infrastructure and without requiring inhouse expertise in the subject especially for resource-constrained enterprises [15].

The Mobility Open Blockchain Initiative (MOBI) is an initiative formed by giant automotive companies such as General Motors (GM), Ford, and BMW to help in making automobiles safer, more affordable, and accessible using blockchain technology. To give new cars a digital entity, MOBI specified the first blockchain-based car identity standard. This enables the tracking of significant events during the lifetime of the car. The blockchain digital identity can also be used to exchange information between cars such as location, speed, travel direction, driver behavior, and even driver intention predictions [16].

3 Blockchains Impact on Manufacturing Systems and Product Lifecycle Management (PLM)

The impact of blockchains on manufacturing supply chains can be seen from two perspectives: the manufacturing systems perspective and the product management lifecycle perspective [17]. From the perspective of manufacturing systems, blockchains can be considered as an enabling driver for existing information systems in the manufacturing domain such as the manufacturing execution systems (MES) and the traditional enterprise resource planning (ERP) (Fig. 1 – vertical axis). In an industrial workshop, the blockchain can act as an indexing server for tracking manufacturing parts to speed up manufacturing automation. At the higher level of enterprise, blockchains can enable distributed manufacturers to create a trusted environment that self-manages the service transactions and interconnection between them over a transparent and decentralized credit mechanism. In this setting, smart contracts improve the efficiency of the manufacturing process by automatically executing planning and scheduling processes. Also, due to the tamer-resistant nature of blockchains, data such as order information and transaction history can be exchanged safely between manufacturing nodes for a more convenient product traceability.

On the other hand, and from the perspective of product management, the lifecycle activities (starting from concept generating all the way to the final stage of recycling & remanufacturing) as shown in (Fig. 1 – horizontal axis) are increasing in complexity. This is mainly due the increase of stakeholders, socialized resources, and advanced technologies that are involved in the lifecycle of the product. Moreover, the challenge of managing and exchanging product information is increasing because of the requirements of security, intellectual property protection, and other trust issues.

Blockchains can be the tool that would provide the community of lifecycle management (designers, manufacturers, suppliers, etc.) with a unified and shared database. This database is the medium by which the community share product information, enable untrusted manufacturers to freely change requirements and capabilities, and eventually make deals. Blockchains allows manufacturers to search for more efficient approaches to connect with each other and with the end customers as well. With blockchains, decisions on these aspects can be taken by consensus algorithms and smart contracts instead of management boards. Likewise, the process of making deals in product life management, which includes bidding, payment, resources management, usage tracking, and final services can be automated through smart contracts with the input from IoT devices for instance.

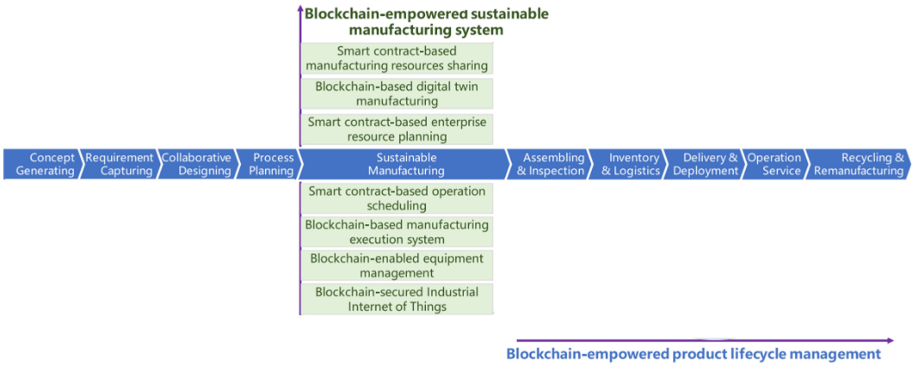

Fig. 1. A bi-dimensional impact of blockchains on manufacturing [17]

In manufacturing, the systems managing the supply chain consists of several entities such as people, knowledge, physical items, contracts, processes, and transactions that enables suppliers to provide products to customers. Manufacturing supply chain systems are typically large which makes it challenging to get a complete picture of all the transactions in the supply chain [18]. Information is usually scattered in multiple systems and sometimes it is duplicated in multiples locations with no warranties for data consistency. The final consumer who is an individual or a company typical will have only very limited access to the overall supply chain information [19]. In most cases, the reason for this is the suppliers who treat this information as a commodity which results in a low level of transparency. Consequently, the tractability of transactions depends on the trust between the different actors of the system.

The traceability and transparency issues in the manufacturing supply chain can be addressed using blockchain technology through controlled user access, decentralized data storage and most importantly immutable data records. In the next section we present a blockchain-based system for the manufacturing domain. We explain the actors in the supply chain network, how they interact with each other through the blockchain and how smart contracts are used to control and govern their interactions. Finally, we cover how data privacy between groups of supply chain actors is achieved and how a token-based model is used for financial transactions in the blockchain.

4 Blockchain-Based Manufacturing Supply Chain System

An overview of the proposed blockchain-based supply chain system for manufacturing is shown in Fig. 2.

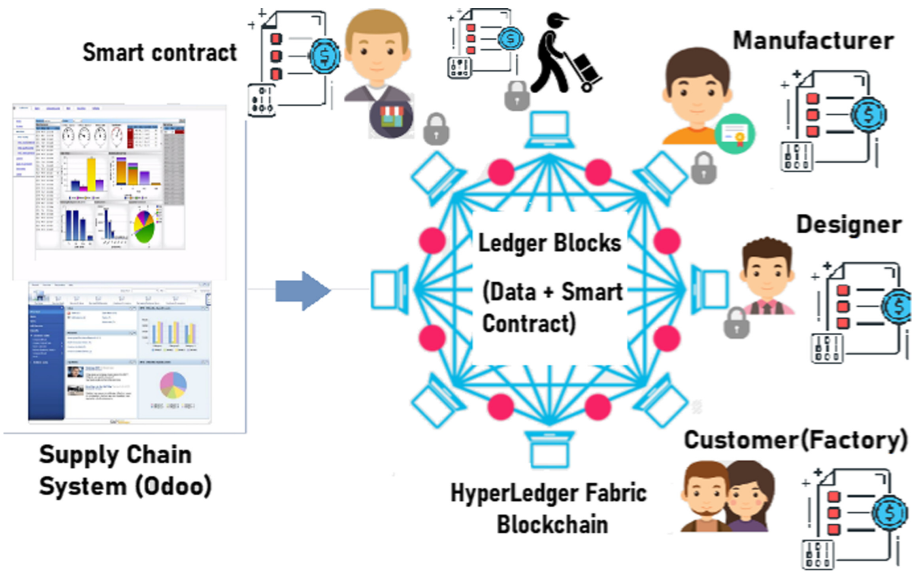

Fig. 2. Supply chain system for manufacturing blockchain

The central component of the system is the decentralized blockchain where each actor has a complete copy of the information. All the data collection, storage, and management of the product lifecycle are performed in the blockchain. Throughout the life cycle of a product, its ownership is potentially transferred between the actors of the supply chain, for instance, customers, designers, retailers, suppliers, producers, manufacturers, and distributors. These actors play an important role to fulfil the goals of the system (traceability and transparency) as they supply the product information during each phase of its lifecycle. Each product has a distinctive digital profile that is updated constantly as it moves through the supply chain. This provides a real-time view of its status in the blockchain and consequently in the supply chain. To link the digital profile with the physical product, an information tag needs to be attached to the product. This tag could be an RFID, QR, or barcode. This tag is considered as the digital cryptographic identifier that is linked with the digital profile which is the virtual identity of the product in the network. The use case developed to evaluate the system involves a customer who needs to design a factory machine.

Case Study Scenario

The scenario of the case study consists of the following actors:

- *Customer:* a food factory that needs a new machine to improve its efficiency and increase its production.
- *Designer:* a design firm specialized in industrial machines design.
- *Manufacturer:* bespoke machine manufacturing company.
- *Supplier:* raw materials supplier.
- *Transporter:* goods transportation company.

The supply chain starts with a food factory that has an increase in demand and needs to increase its production. It formulates its requirements in a document and sends it to several design companies for quotations. Design companies then evaluate the financial standing of the customer and upon satisfying a certain rating, they prepare the design and send it to the customer. If the customer accepts a design, the typical transactions between him and the designer take place (Quotation, invoice, etc.). Once the design is finished, it is delivered to the customer who will in turn send it to a manufacturer with the same interaction patterns. The presentation of the case study focused mainly on the interaction between the customer and the designer where the following aspects are highlighted:

- The smart contracts representing the different actors in the blockchain such as the customer, designer, and manufacturer.
- The smart contracts representing the transactions between actors such as the one representing the relation between the customer and designer.
- The representation of the domain entities such as design and quotation.
- Asset transfer in the blockchain for instance transferring the ownership of the design from the designer to the customer and vice versa.
- Create and transfer fungible tokens using an account-based model for payment aspects.
- Establishing private channels between groups of actors in the blockchain.

The system has been implemented using the Hyperledger Fabric platform as the most suitable of the problem domain where the access to the blockchain is not open to the public besides other features that will be highlighted in the next section.

HyperLedger Fabric

The system was implemented using the Hyperledger Fabric platform which is one of the blockchain projects within Hyperledger. Like other blockchain technologies, it has a ledger and smart contracts [20]. The following are the main characteristics of Fabric:

Privacy Features

Unlike most other blockchain systems, Hyperledger is a private and permissioned blockchain allowing only known and registered entities to participate in the network. Members of the network gain access through a trusted Membership Service Provider (MSP). This property of the Hyperledger makes it suitable for the supply chain management domain where access is only open for the SC members and not open for the public. The pluggable architecture of Hyperledger Fabric allows some parts to be exchanged such as the data formats, the consensus mechanism, and MSPs.

Another requirement in the supply chain domain is the need for privacy between certain actors in the SC. For instance, some participants in the network might be competitors and they do not want their all transactions to be visible to everyone in the network. Some of these transactions could be a special price for client that should not be known to the competitors. The solution to this requirement is through channels that allow a group of participants to have their exclusive shared ledger of transactions [21].

Shared Ledger Data Store
The ledger subsystem of the Hyperledger Fabric is a combination of two main components: the world state and the transaction log. Each node in the network has a copy of the ledger. The world state component is a snapshot of the ledger at any given point in time. The transaction log is a record of all the transactions that took place in the blockchain and led us to the current world state. The default data store for the world state is a LevelDB key-value which can be replaced by another data store. As for the transaction log store, it is not pluggable as it only persists the before and after values of the ledger database.

Smart Contracts
Smart contracts in Fabric are written using chaincode which can be implemented in several programming languages. Currently, Go, Node.js, and Java chaincodes are supported. Chain code can be called by external applications that are outside the blockchain boundary to interact with the ledger. The most common interaction scenario is the interaction between the chain code and the world state component of the ledger to query for data.

5 Implementation

For the proof-of-concept implementation, we used JavaScript as the implementation language for smart contact and hosted the HyperLedger Fabric on Linux as it uses Docker extensively which is recommended to run on Linux to avoid technical issues. The different aspects of the implementation are presented in the next sections.

5.1 Domain Entities

The use case consists of the domain concepts such as design, design request, quotation, invoice, receipt, etc. So how are these concepts created in the blockchain? All concepts in the blockchain are inherited from a class called *State* predefined in Fabric (Fig. 3). It has a unique key and a lifecycle current state of the concept where the key and current state are determined by the specific subclass. The class has also helper functionality to convert to and from the JSON format. An example domain concept in the system is the *IndustrialDesign* concept. To define it, we inherit from the *State* class and add the entity-specific properties. The *currentState* and *currentFeeState* are defined as enumerated values. The *createInstance* method is used to generate instances of the entity.

Domain entities are typically initiated in smart contracts either to create a new instance such as a new Invoice or retrieved as an existing instance from the database for further processing. The definition of entities can be nested, for instance, the *Invoice* is composed of a list of *LineItems* with is also defined in the same manner by extending the *State* class.

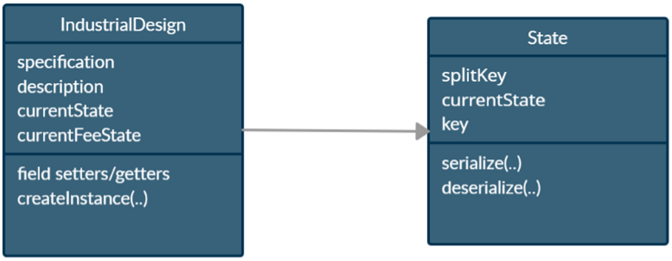

Fig. 3. Concept representation in fabric

5.2 Smart Contracts

Smart contracts in the blockchain are used in our case study to represent two concepts: the actors in the system such as the customer and the relation between actors such as the relation between the customer and the designer. All smart contracts inherit from the *Contract* class as shown in (Fig. 4). The smart contracts for the actors in the system contain mainly the Create, Read, Update, Delete (CRUD) operations.

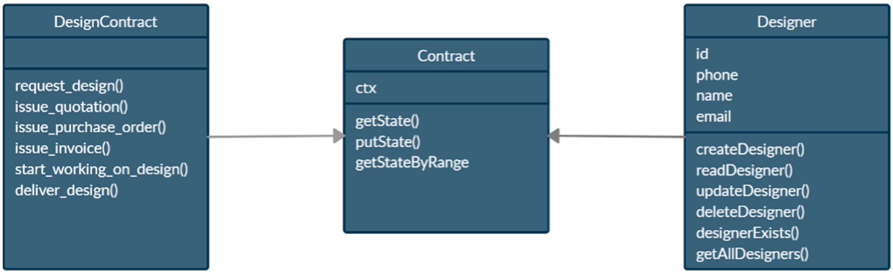

Fig. 4. Smart contracts in fabric

All the *Designer* methods take as a first argument a *ctx* variable that represents the blockchain context. This variable is used to manipulate the entity in the blockchain for instance to store a *Designer* in the blockchain we invoke the *ctx.putState()* method. The relation between actors of the system is governed by smart contracts which are defined in Fabric as a regular class where the methods of the class represent the contract clauses that should be honored (Fig. 4). For instance, the relation between the *Customer* and the *Design* is defined in the *DesignContract* class as follows:

Smart Contract 1: Request an IndustrialDesign from a Designer

```
Input: ctx, requester, designer, design_code, spec, description, requestDate

Retrieve the customer(requester)
Create design request(requester, designer, design_code, spec, de-scription, request-
Date)

If customer_credit_rating > 3 then
   Set design state(ACCEPTED)
end
else
   Set design state(REJECTED)
end
Store the design(contract_id, design)
```

As with entities, the smart contract functions also require the passing of the blockchain context variable *ctx* to access the blockchain database. Another example is the *design delivery* smart contract which is defined as follows:

Smart Contract 2: Deliver the design to the Customer

```
Input: ctx, contract_id

design ← retrieve the design contract(contract_id)
job_days ← get the difference between the request date and today(contract_id)
fees_reduction = Update fees based on delay(contract_id, job_days);
design.fees = fees + fees_reduction

store_the_design(contract_id, design)
```

This design delivery smart contract calculates the delay in the delivery of the design and based on that update the agreed-upon fees. If there is no delay, the *Designer* will be paid full fees, otherwise, his fee will be deducted according to the length of the delay.

5.3 Asset Transfer

Transferring assets between supply chain members in the blockchain is just a matter of changing an attribute in an entity to represent the owner. The *pay design fees* smart contract changes the owner of the design from the designer to the customer after settling the payment as follows:

Smart Contract 3: Pay design fees

```
Input: ctx, contract_id, customer_id
financial transaction logic [Details in Smart Contract 4]

design ← retrieve the design contract(contract_id)
design.owner = customer_id

store_the_design(contract_id, design)
```

5.4 Financial Transactions

The financial transactions between supply chain members are implemented using the ERC-20 account-based model [22]. A smart contract can either create or transfer fungible tokens using an account-based model. In this model, there is an account for each participant that holds a balance of tokens. A *mint* transaction creates tokens in an account, while a *transfer* transaction debits the caller's account and credits another account. To test the model, we allowed all the participant to call the *mint* function to create a certain limited amount in their account. The smart contract *mint* function takes the client certificate as the client identity through an API and credits their account with the requested number of tokens. To transfer money to another account, a *transfer* function is called to transfer the requested tokens to the account of the recipient. The recipient should provide their client ID to the sender to complete the transfer. The following is an example of a financial interaction between the *Customer* and the *Designer* where the customer calls the *mint* function to generate 7000 tokens then transfer 300 to the *Designer*:

Smart Contract 4: Transfer money

```
1   Input: ctx, designer_id, customer_id

    mint(customer_id, 7000)
2   customer_balance ← get available mints (customer_id)   // output: 7000
3   designer_balance ← get available mints (designer_id)   // output: 0

4   accountId = get account id(designer_id)
    transfer from customer to designer(customer_id, accountId, 300);

5   customer_balance ← get available mints (customer_id)   // output: 6700
6   designer_balance ← get available mints (designer_id)   // output: 300
```

5.5 Private Channel Transactions

Hyperledger Fabric uses an immutable ledger for each channel in addition to the chaincode that manipulates the state of assets. This ledger can either be visible to all the network participant or can be limited to a specific subset of participants. In the latter case, participants will have their segregated transactions and ledger. To balance between total transparency in the network and the needed privacy between subgroups of participants, we created dedicated channels for subsets of participants and authorized them to use their private data. We further obfuscated the data by encrypting the values in the chaincode using the AES cryptographic algorithm before sending it to the ordering service which will append it to a block in the ledger. The encrypted data in the ledger can only be decrypted using the user key that was used to encrypt the data.

5.6 Evaluation and Discussion

To evaluate our proof-of-concept, we developed a test client that simulates the complete use case of manufacturing a machine by engaging all the actors that are required to complete the use case. In terms of functionality and when compared to a traditional information system, we did not find any difficulty in implementing the features required by the use case as the programming languages used to implement the smart contracts are Turing-complete languages and do not have any limitations. Also, the supported peer databases LevelDB and CouchDB are satisfactory for most business applications. The LevelDB stores chaincode data as simple key-value pairs and CouchDB which is the alternative state database supports rich queries and chaincode data values are modeled as JSON.

To test the performance of the blockchain network, we calculated the average time it takes to complete a single business transaction. The average delay from the first smart contract invocation requesting a design and the last call which settles the financial payment after delivering the design was around 7 s where the single call takes between 0.5 and 2 s. This time is slightly higher than a traditional Java application storing similar information in a MySQL database where the single call to manipulate the database take an average of 100 and 200 ms. However, the reaped benefits from implementing the solution as a blockchain could outweigh the performance penalty of the blockchain complexity in many business domains. By design, our system as a blockchain solution has achieved all the benefits of the blockchain technology namely: immutability, durability, and transparency. These features as discussed are the solution to many of the manufacturing supply chain challenges such as the lack traceability and transparency. However, to enable blockchains to be applied to more industrial systems, more research is required in the performance area to close the gap between blockchain-based systems and traditional information systems.

6 Conclusion

Blockchain technology went beyond its original intended purpose as a cryptocurrency platform to become a major disruptive technology for numerous business fields and an interesting topic for academic research due to its attractive characteristics. Technology enthusiasts claim that it has the potential to completely transform our contemporary cultural, economic, legal, and political landscape. In this paper, we reviewed the impact of blockchain technology on the manufacturing supply management and how it could solve the various shortcomings of the current information systems used in the domain. Then presented a blockchain-based system implemented using one of the leading private blockchain platforms, the Hyperledger Fabric. We highlighted the main characteristics of Fabric that make it suitable for applications in this domain. As an example scenario, we proposed a hypothetical vision of a manufacturing supply chain of a factory designing a new machine. The business transactions between the customer and the designer were the conveyer that demonstrated how the main features of the chosen platform were used to create a solution that demonstrated the benefits of using blockchains to achieve transparency and traceability. The system protects information from public access and provides privacy for subgroups of the supply chain participants. While blockchain platforms provide several benefits, their main known downside is their performance limitations compared to traditional storage systems such as RDBMS databases. In future, we will focus on exploring more features of blockchain platforms that apply to the supply chain management domain and perform a comparative study of the performance of the different available blockchain platforms.

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Comparative Evaluation of Product and Service Solutions in the Context of Product-Service Systems and Technical Inheritance

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Abstract. With the increase of Product-service systems being implemented, it is necessary to evaluate whether a function should be provided as part of the physical product or as a service. Therefore, it is required to evaluate which of the possible solutions is objectively better. For these 3 major factors have to be evaluated and be put into a comparative relation. The three major factors considered are requirement fulfillment, cost and ecological impact. The calculation for comparative scores that describe the relative quality of each solution for these three values is explained. The separate scores are aggregated into to one score on which the solutions are compared to find the best solution. The method is then used in a case study. Which focuses on an electronic object carrier sorting system, for which a new product generation is planned. This is achieved by following the process of technical inheritance in combination with the method proposed here to evaluate the different possible solutions.

Keywords: Product-service system · Product development · Technical inheritance

1 Introduction

The number of publications with Product-service systems (PSS) as a subject matter has been increasing rapidly over the last years [1]. Where it is usually defined as a combination of products and service to fulfil customer needs [2]. Although not many companies market their products as PSS there are indicators that suggest that the adoption of PSS has become much more widespread. In order to stay competitive and to insure more regular cash flow many companies a transforming their business models to either contain services or offer their products as services instead [3].

PSS contain at least one product and one service component and their combination is used to fulfil customer needs. The services in a PSS can take many form and can be a supplementary offering or can be a core part of the product function. This means that not all customer requirements have to be realized in a product. But instead it is possible to realize them through a service that can fulfil the same requirement. For example,

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product reliability can be fulfilled trough ensuring that the technical components of a product meet the reliability requirements. Alternatively, the overall reliability of the product could be achieved by including a maintenance service that ensures the specified reliability requirements are met. With this a product is transformed into a PSS, which leads to new decisions during the product development process which have to be made. During the design of conventional products decisions have to be made on which design alternative is best to fulfil the product requirements. This is a field has been thoroughly explored and resulted in many methods such as *Decision matrix analysis, Technical-economic assessment* and *Cost-utility analysis* [4–6]. But these methods do not consider the comparison of technical components against service components as possible solutions to fulfil the product requirements. Therefore, it is necessary to find a structured approach that allows for the evaluation of technical against service solutions in an objective manner. Which leads to the question this paper tries to answer: "How does a methodical approach for evaluating technical against service solutions in PSS on their suitability for requirement fulfilment have to look?".

2 Research Background

2.1 Product Service Systems

Product-Service Systems have been defined as the combination of products and services that jointly fulfil a customer need [2, 7, 8]. To which degree the customer need is fulfilled by product or service components is flexible. But if either one is used alone it is no longer a PSS. When discussing PSS the product component is considered to be tangible content. This tangible content is represented in the form of physical artifacts. While the service component of the PSS is considered to be intangible. Which means that the services are produced and consumed simultaneously [2].

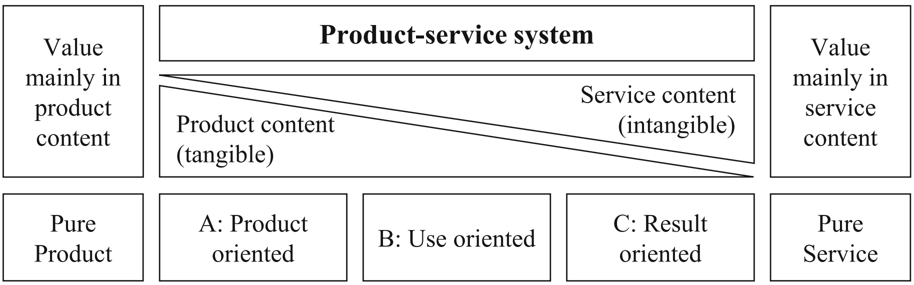

Fig. 1. PSS classification [2]

It is possible to classify PSS into three major groups based on their level of service integration [2, 9]. These three distinct groups are shown in Fig. 1 and referred to as product oriented, use oriented and result oriented. In the product-oriented category there is still a transfer of ownership between the PSS operator and the customer and the services are only supplementary. Use oriented PSS are where the traditional sale of products is no longer an objective and the product ownership remains with the PSS operator. The product is then made available to customers for limited times. Third is the category of result-oriented PSS in which only a result is agreed upon and not a predetermined product that will be used to achieved said result [2]. While other researcher occasionally classify PSS in a different manner they usually aim to increase the precision of the different classes. For example, Tan has described PSS as a combination of seven strategic characteristics that can take different form depending on the PSS [10]. Alternatively, Mont has [11]. Ultimately it is possible to reassign these subcategories back to the categories proposed by Tukker and since the degree of granularity is sufficient for this paper this is the understanding of the term PSS which this paper refers too.

2.2 The Concept of Technical Inheritance

Technical Inheritance is defined as a transfer of assembled and verified information frobe able to make a conclusion regarding them development, production and application to the next product generation [12, 13]. Based on collected and verified information components are adapted and optimized for the next generation. Deduced from evolutionary mechanisms from nature mechanisms for the evolution of technical products are adapted and determined (Fig. 2).

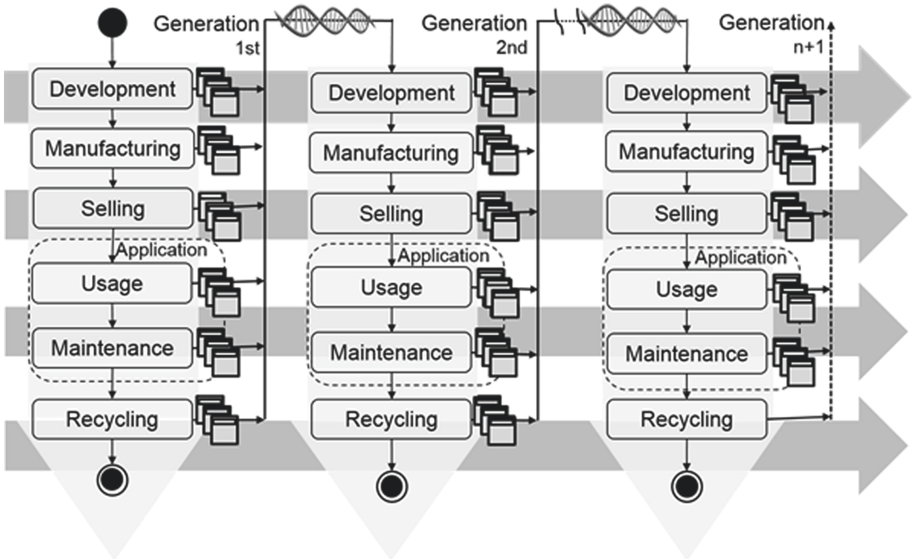

Fig. 2. Transfer of life cycle data [12]

The proceeding of an intergenerational development includes four steps. First, the needed life cycle information have to be identified. Second, the monitoring strategy has to be implemented. Third, a Data Mining method has to be realized and finally the information has to be transferred back to the development for a new product generation [14]. Within the product development the life cycle information is analysed and requirements for the new product generation are defined [15]. If a requirement is implemented as a new technical solution or as a service a decision matrix is used.

2.3 Methods for Evaluation

The assessment of complex decision problems requires a systematic use of principles, such as weighting, aggregating or scoring, based on criteria, functions and algorithms [16]. In applying these principles, errors within the evaluation must be minimized by checking objectivity, plausibility and sensitivity to evaluate criteria with equal evaluation standards and allow constraints for robust decision processes [6, 17]. Depending on the quality of these decisions, the "pair-wise comparison", the "technical-economic evaluation" and the "utility analysis" offer different methods to capture the complexity and the implementation time.

Decision Matrix Analysis/Pairwise Comparison. The "pairwise comparison" or "decision matrix analysis" allows a decision to be made on a comparison of different alternatives with low input [4, 18]. All considered alternatives X_i are listed in a decision matrix as lines and all available evaluation criteria C_J as columns. The evaluation of these criteria can be analysed column by column according to the "best" alternative [4], allowing a ranking of all alternatives based on the preferences to be created (cf. Fig. 3) [6, 18].

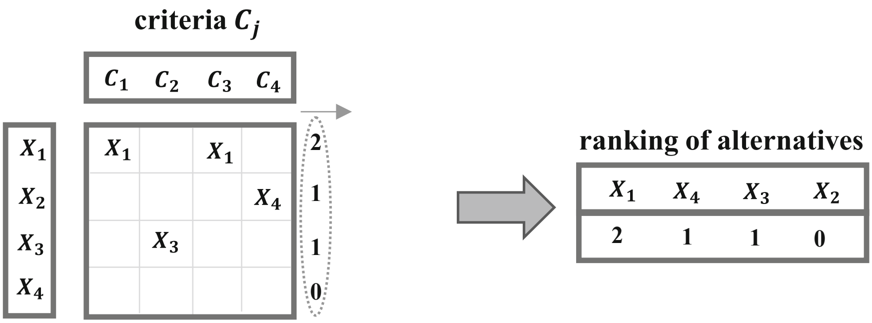

Fig. 3. Decision matrix according to Alabool et al. [4]

The method is limited in its objectivity, as the outputs correlate directly with the subjective perceptions of the user. In addition, the use of a decision matrix for complex problems is very time-consuming and limited in terms of illustrating multi-criteria interactions [4]. An improvement of this method is the "analytic hierarchy process" (AHP), as a weighting is integrated to select the preferred alternative which has a direct influence on the resulting hierarchy of alternatives [16, 19].

Technical-Economic Assessment. The "technical-economic evaluation" according to the VDI 2225 for "technical-economic design of complete technical products" is used for decision-making by a systematic classification of available alternatives [5, 6]. In contrast to the AHP, unordered criteria are listed at the beginning of the assessment and indicators are allocated to represent the fulfilment of these criteria for the alternatives concerned. In addition, the various criteria are weighted against one another to be able to prioritise these [6, 18].

The technical valence x describes the weighted average value for all criteria of the alternatives considered [5]. Analogously, the economic valence y is composed by the ratio of the ideal and the actual manufacturing costs for the respective alternatives [5]. In addition to the economic and technical valence, the total valence is defined as the "strength" s and shown graphically (cf. Fig. 4) [5, 6, 18].

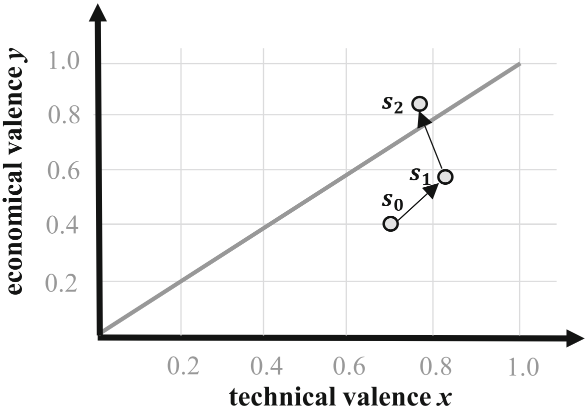

Fig. 4. Strength diagram according to VDI2225

This method, which requires a lot of time to implement, is a systematic and transparent approach for evaluating complex decision problems and, in comparison to pairwise comparisons, enables a higher quality of the results [6, 18].

Cost-Utility Analysis. Dealing with complex decision tasks requires a clear method for evaluating a large number of different evaluation criteria and determining the relative value of a considered alternative [6]. These assessment criteria are hierarchically ordered in form of a system of objectives according to their complexity as well as the intended objective areas for rating the relevance of the defined sub-objectives of lower order in the total context. This resulting decision tree comprises nodes as well as order-specific values [20].

For weighting the different evaluation criteria, values between 0 and 1 are used, which always add up to 1 in their order [20]. Within this weighting, a distinction can be made between ordering and knot weightings. As the order weighting is the product of all position-specific knot weights in ascending order, the calculation of these knot weights has priority [6].

Following this calculation, characteristics are determined for the various alternatives and links to the considered assessment criteria are created, which depend on the fulfilment of these criteria and is deposited with values of an ascending scale [6]. As the resulting total utility value and the result of the assessment, the values are multi-plied with the weightings and summed up in accordance of the relevant assessment criteria [6].

Ecological Impact. To be able to make a conclusion regarding the ecological impact related to the comparison of a technical material product solution and an immaterial service component, the definition is not standardised [21]. Regardless of the chosen categories and indicators for impact assessment, a consistent functional unit must be defined first, on the basis of which the comparison is made [22]. One possibility is the assessment of resource productivity, which can be applied to both products and services by means of various raw material indicators, such as the cumulative energy analysis (CEA) [23]. According to the ecoinvent database, the CEA considers the following factors [24]:

- wind, renewable energy resources, kinetic;
- water, renewable energy resources, potential;
- solar, renewable energy resources, conventional;
- primary forest, non-renewable energy resources;
- nuclear, non-renewable energy resources;
- geothermal, renewable energy resources;
- fossil, non-renewable energy resources;
- biomass, renewable energy resources.

The CEA is an easy-to-use screening indicator that can be seen as an introductory method to conventional life cycle assessment that calculates MJ equivalents as its result [24].

3 Defining Requirements

As shown in Sect. 2 when comparing different solutions in the product design process it is necessary to consider the costs of the design alternatives, since a product that is financially not viable cannot survive long term in a competitive market. Furthermore, it is necessary to evaluate how well the different alternatives fulfil the customer requirements, because if a product does not sufficiently fulfil customer requirements it will not be bought. In addition to these two factors that are both imperative for the overall success of a product the ecological impact of products has come more into the focus of product developers in recent years. Therefore, the developed method must contain an evaluation of the fulfilment of customer requirements, costs of the product and also allow for an ecological evaluation. Additionally, an option to prioritize theses three factors when evaluating the alternatives would be advantageous to ensure that the method can be customized if business strategies or market forces lead to a higher importance of a given factor. Established methods such as those presented in Sect. 2 are focused on evaluation of these factors independent of each other and given no explicit recommendation which solution should be chosen based on the results for the individual factors. Furthermore, the evaluation of requirement fulfilment focuses either on a comparative evaluation solely based on which one is better or on an evaluation based on requirement fulfilment with certain degrees of fulfilment. The developed method should therefore be able to show which solution is better in fulfilling a requirement and to which degree. Additionally, methods for the calculation of ecological impact are not designed to be utilized for the use with services. Which highlights the necessity that a method is developed that is also applicable to services and products to allow cross comparability.

4 Method

As described in Sect. 3 the method for comparing service and product solution against one another needs to take into account three different areas fulfilment of the requirements, cost of the solution and its ecological impact. But before these are compare it is important to first determine if a service solution is even possible. This means that it must be feasible to realize a technical requirement through a service. Additionally, it has to be verified that the customer allows the provider access to the product in order to provide the service. Furthermore, it has to be ensured that there are no legal restrictions that would prohibit the provider from fulfilling the requirement as a service. Once it is ensured that none of these causes would impede the implementation of a service solution the first task in Fig. 5 has been performed and the yes path is followed. If any of the causes impede the implementation the requirement cannot be fulfilled trough a service and no comparisons in accordance with this method is necessary.

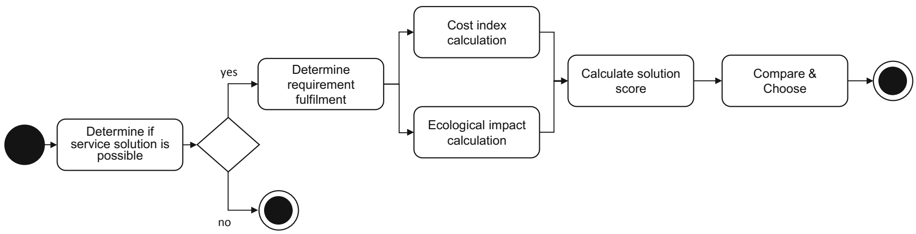

Fig. 5. Method for comparison of product and service solutions

The next step is to determine how well the different solutions full fill the requirements that the component has to satisfy. For this we will use an adapted and combined version of the technical valence and the decision matrix analysis. The first step is to create a list of a requirements the solution has to satisfy which will subsequently be scored comparatively. The requirements are separated into requirements that have to be fulfilled in order to achieve the desired function and optional requirements which also contain possible benefits. When the scoring is performed the scoring is always done as a comparison between both solutions. There are four different results that are possible one solution is substantially better than the other solution. One solution is slightly better than the other solution. Both solutions fulfil the requirement equally. Lastly one solution fulfils a requirement the other one does not, this should only be the case for optional requirements.

To determine the requirement fulfilment of both solution a matrix is created as shown in Table 1. If a solution is substantially better, it gets a 2 and the other solution a 0. If

Table 1. Requirement fulfilment matrix

	Solution 1	Solution 2
Requirement 1	2	0
Requirement 2	0	1
Requirement 3	0	0
Optional requirement	–	0
Result	0,66	0,25

a solution is slightly better than the other solution it gets a 1 and the other solution a 0. Should both solutions satisfy the requirement equally both get a 0. In the case of optional requirements that are only fulfilled by one solution the solution that does not fulfil it gets a 0 for that requirement and the other one is left blank. To calculate the requirement fulfilment all individual evaluations for each solution are summed up and divided by the count of non-blank evaluations. These higher results is the solution that better fulfils the requirements.

After that it is necessary to determine the costs that are generated by either solution. When doing this it is important to consider all costs that will occur during the life time of the product, since service costs are likely to occur more regularly during the entire product life cycle and product cost are mostly incurred during the initial creation of the product. This means all initial capital expenditures necessary to set-up the solution are combined with all the costs that will be incurred during the operation of the product and are relevant to the solution. The solution with the larger sum is the one with the higher costs and therefore less desirable. Following that the ecological impact of both solutions has to be determined. For this the CEA introduced in Sect. 2 can be used.

Now these three results are normalized and combined into one solution score. In order to make the individual values combinable they have to be normalized into one common range. For the requirements fulfilment we assign the best possible solution which is equal 2 to the number one 1 and the worst possible solution to 0. Therefore the results have to be divided by 2. For the cost we have to set the cheaper result to the number 1 as the best possible score. In order to reflect how much better the solution is we take the cheaper solution divided by the more expensive solution. Which results in the score value for the more expensive solution. Then the solution form the CEA has to be normalized to get the eco score that can be input into the solution score. This can be done following the same logic as for the cost index.

Lastly we can fill in the values into the Eq. 1 with representing the requirement fulfilment the cost index and the eco score.

$$s = \tau * r + \gamma * c + \varepsilon * e \tag{1}$$

As shown in Eq. 1 the individual comparison results can be adjusted with a factor, and respectively which can be used to change the significance of either of the individual scores. If all scores are equally important, they can be just set to one. But if either of the score should be more or less important than the other, they all should be between zero and one. But the sum of all three should be one. Also, it is important that the factors remain constant during the comparison of two solutions. The solution scores are than compared and the solution with the highest solution score is the solution that should be chosen.

5 Case Study: Electronic Sorting System

For the case study a sorting system for object carriers is chosen as a demonstrator. The sorting system, depicted in Fig. 6, is used in a medical environment of a hospital pathology, where object carriers were sorted manually by a number from 1 to 1000. To relieve the laboratory staff, the sorting system was developed and manufactured by the Institute of Product Development. The object carrier is taken by a pneumatic gripper from one of four separators and is transported by a room portal to 1 of 1000 slots regarding its scanned number. Object carriers with no number are placed in a waste area. The movements and the usage of the room portal can be detected and saved on an external storage medium [25].

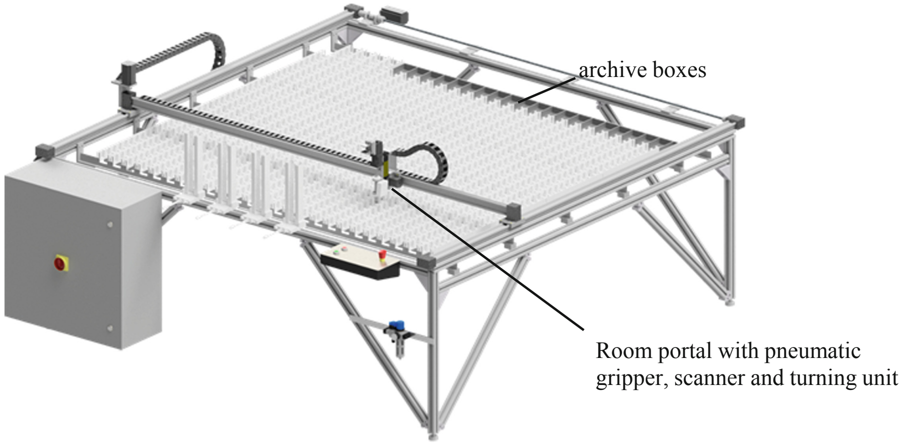

Fig. 6. Sorting system for object carriers at a pathology

The sorting system requirements are defined by the customers and the Institute of Product Development. Fixed requirements defined by the customers must be fulfilled by the product development. The following requirements are only an extract from the total list of requirements:

1. The sorting system must handle 2000 object carriers per day non-destructively;
2. The sorting system provide have 1000 slots;
3. The object carrier are taken out of the sorting system by laboratory staff into archive boxes.

These requirements from the customer are taken to the product development without knowing if the quantities are hold true during usage. Therefore, the Technical Inheritance is necessary to collect data and information about the usage and to concretize the requirements of the next product generation. Consequently, the usage phase is monitored and analysed.

5.1 Requirements for Second Generation of Sorting System

During the usage of the sorting system all information about the movements, usage and all failures are digital detected and saved. The evaluation of the saved information takes place by an automated tool written in the programming language python. The results shown the actual usage of the sorting system and can be compared to the initial requirements. The comparison has shown that the old requirements can be concretized and new information and requirements are added by the costumer. The pathologists examine the tissue samples on the object carriers on two days a week at the same room, where the sorting system stands. Because of the need of complete silence the sorting system or an outstanding person is not allowed to work during this time. Also an outstanding person is not allowed in the room during the examination due to privacy reasons of the patients. The following requirements are only an extract from the total list of requirements for the second generation:

1. The sorting system must handle 670 object carriers per day non-destructively;
2. The sorting system must have 400 slots;
3. The object carrier are taken out of the sorting system into archive boxes without the interaction of the laboratory staff
4. The object carrier should be able to be archived at any time of day;
5. The object carrier should be able to be archived without any additional noises;
6. No additional space should be needed;
7. The error quote should be by less than 1%.

These requirements must be taken into account in developing a new generation of the sorting system.

5.2 Designs for the Second Generation

The second generation needs to full fill the requirement that the object carrier are taken out of the sorting system into archive boxes without interaction of the laboratory staff. Based on the new requirements for the second generation two different designs are created. The first solution does not change the design of the first generation, but adds a service to take out the object carrier out of the sorting system into the archive boxes. The second solution changes the design of the first generation with additional technical components to fulfil the requirements.

The solution with an additional service contains a service employee, who comes three days a week to the pathology to takes all sorted object carrier into an archive box by hand. The sorting system does not need to be changed or build new, but is used as it is. The employee with an hourly wage of 75 € drives 120 km in total from the service central to the pathology and back with an initial combustion car. On site, the service employee needs 15 min to prepare the equipment. He/she needs 30 min additionally to take all object carriers out of the sorting system and put them into the archives boxes.

The second solution takes the design of the first generation as a starting point, because not everything needs to be designed completely new. Only the areas for new requirements need be adapted by a technical solution. For the technical solution the original design is kept and only the room portal with the scanner and pneumatic gripper are changed, see Fig. 7. Additional to the first design an electronic turning unit is installed. After every object carrier is sorted into the according slot the turning unit turns the grippers by 180°. That leads to the fact, that the second pneumatic gripper for object carrier stacks is taken to the first slot of sorted object carriers and takes the whole stack of one slot. The room portal takes the stakes to the back of the sorting field, where the archive boxes are installed. The swivel unit flips the second pneumatic gripper vertical by 180°, so the stack is placed in the archive boxes standing vertical. The technical solution archives the object carrier at the end of every day or as soon as the order for archiving is given. Because of the installed archive boxes within the sorting system, the dimensions are larger than for the first generation.

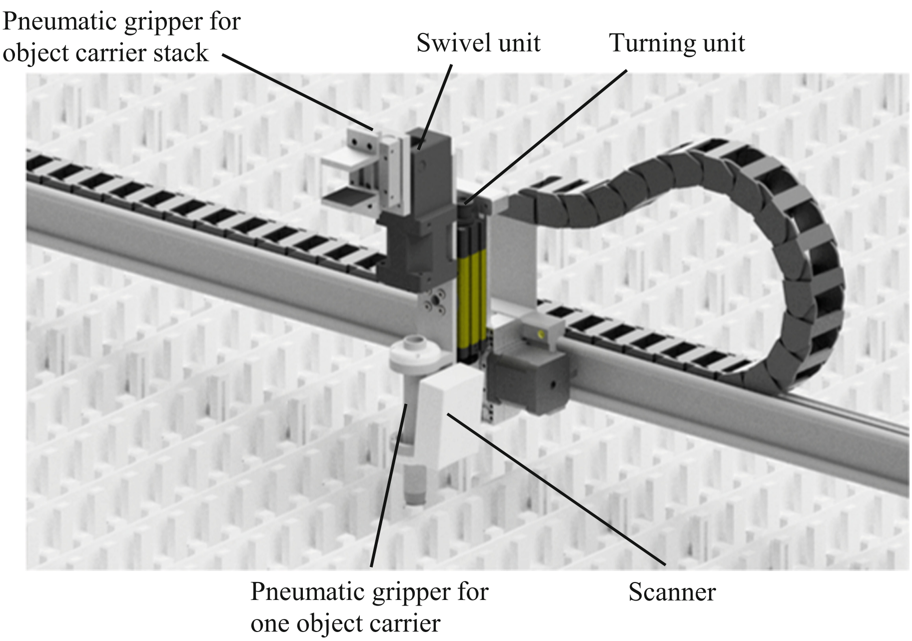

Fig. 7. Technical solution for sorting the object carrier stacks into archive boxes

5.3 Comparison of Service and Product Solution

Both solutions need to be compared to decide which solution should be developed for the second generation. Therefore, the method presented in Sect. 3 is used in for this case study.

Before the solutions are compare it is important to first determine if a service solution is even possible. The customer allows the provider access to the sorting system, however just on three days a week. Within these three days are no further legal restriction as long no patient information are shared with the service employee. The technical solution does not save or monitor any information about patients and can be used any time during a day. That leads to the fact, that a service solution is possible and can be compared with the technical solution.

The next step is to determine how well the different solutions full fill the requirements that the component has to satisfy. The requirements are listed above and are scored comparatively. Both solutions must fulfil the requirement that the object carriers are taken into the archive boxes without the laboratory staff. In addition, the object carrier should be archived at any daytime, which can provide the technical solution. The service solution cannot guarantee that the service employee is always available during the complete day. That leads to the result, that the technical solution fulfils this requirement better. The technical solution brings more pneumatic moving parts, which bring additional noises. The service solution is not completely silence but does not bring additional noises through pneumatic parts. This leads to a slightly better result for the service solution. The technical solution does need additional space for the archive boxes, which are installed into the sorting system. Only the service solution fulfils this requirement and gets a 0 and the technical solution is left blank. The requirements about an error quote by 1% is better fulfilled by the technical solution, because a service employee can be a bigger source of errors (Table 2).

Table 2. Requirement fulfillment matrix for service and product solution

	Technical solution	Service solution
Object carrier are taken into archive boxes without staff	0	0
The object carrier should be able to be archived at any time of day	2	0
The object carrier should be able to be archived without any additional noises	0	1
No additional space required	0	–
Error quote less than 1%	2	0
Result	0,8	0,25

Next it is necessary to determine the costs that are generated by either solution. The lifetime of both solutions amounts to five years. For both solutions every 3 month a maintenance is needed. The maintenance costs for the service solution amounts to 1000

€ per maintenance and the technical solution amounts to 1250 €, because of the additional mechanical and pneumatic parts. Over five years the mechanical solution generates 25.000 € maintenance costs, but the service solution generates 20.000 € maintenance costs. Additional to the maintenance costs come the initial costs for the technical solutions, which are 730 €. In total the technical solutions cost over five years 25.730 €. The service solution has also additional cost, which are caused by the service employee. The service employee with an hourly wage of 75 € comes 3 days a week in every week in 52 weeks during the year. Every year the service employee causes 8.775 € of cost per year and 43.875 € over five years. In addition, with the 20.000 € maintenance costs the service solution causes 63.875 € over five years.

The ecological impact needs to be determined by the cumulative energy analysis (CEA). Both solutions do not need to build a new sorting system but are using the existing one. The technical solution adds mechanical and pneumatic parts, which cause an additional power consumption of 0,1 kWh per day. The one-time installation of the parts results in a CEA of 46,64 MJ-Ep. During a working day the new parts causes 12,93 MJ-Ep. The employee drives 120 km in total from the service central to the pathology and back with an initial combustion car. On site, the service employee needs 45 min to prepare the equipment and to take all object carriers out of the sorting system and put them into the archives boxes. This results in a CEA of 593,61 MJ-Eq. for one day for the service solution.

Now these three results of the technical and service solution are normalized and combined into one solution score. For the requirements fulfilment we assign the best possible solution which is 2 to the number one 1 and the worst possible solution to 0. Therefore, the results have to be divided by 2. The score *r* for the requirement fulfilment is 0,4 for the technical result and 0,125 for the service solution. For the cost we have to set the cheaper result of the technical solution to the number 1 as the best possible score. In order to reflect how much better the solution is we take the 25.730 € of the technical solution divided by the 63.875 € of the service solution, which results in a score *c* of 1 for the technical solution and 0,4 of the service solutions. The ecological impact *e* is calculated the same way as the cost index, which results in a score of 1 for the technical solution and a score of 0,1 for the service solution. The factors, and are defined as 1, because all scores are equally important.

According to the Eq. (1) the Solution Score s = 2,4 for the technical solution and s = 0,652 for the service solution (Table 3).

Table 3. Solution score

	Technical solution	Service solution
Requirement fulfilment [r]	0,4	0,125
Cost index [s]	1	0,4
ecological impact [e]	1	0,1
Solution score [s]	2,4	0,625

Due to the Solution Score the technical solution is chosen for the further development.

6 Conclusion and Outlook

The goal of the paper to develop a method that can be used to compare technical and service solutions against each other and identify the preferable solution has been achieved. Which is demonstrated by the application of the developed method in the case study. The method considers three major factors in the comparative evaluation of product and service solutions. While the case study considers all factors are equally important an adjustment of any of the factors would have been easily possible. Furthermore, the used case study provides insight in how the proposed method can be integrated into the framework of technical inheritance. Additionally, this also shows how the data necessary for the calculation of the solution score can be obtained if a previous system generation already exists.

Even though the method considers the three most important factors it should be noted that the expansion of the proposed method is possible and should be the focus of further research. One of these additional factors would be the time to market which would not only impact the development costs of a product, but a shorter time to market can be an advantage in a competitive market. Furthermore, it would be prudent to expand the evaluation from a single PSS to PSS fleets. This is necessary to account for the fact that practical applications of PSS are rarely restricted to only a single PSS. For this a combination of the method shown here and the approaches discussed in [26], could be a path towards a solution taking both considerations into account. Additionally, it could be worthwhile to explore how multi criteria decision methodologies can be utilized to better model the relevance of the different criteria and their interaction.

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Sequencing Through a Global Decision Instance Based on a Neural Network

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Abstract. An existing concept for sequence planning in production planning and control was extended by a global decision instance based on neural networks. Therefore, information regarding the state of the production and available orders were normalized and analyzed by one agent. In contrast to a partially observable Markow Decision Problem one single agent was allowed and used to process all available information. Feasibility and problems were examined and compared with a concept for decentralized decisions. The implementation consists of two parts, which continuously interact with each other. One part is a simulation of a job shop, including multiple machines. The other parts tackle the Markow Decision Problem with the use of double Q reinforcement learning in order to estimate the best sequence at any given time. Later, problems due to scaling and comparisons to the usage of multiple agents are given.

Keywords: Sequence planning · Artificial intelligence · Neural network

1 Introduction

A continuous trend in industry is the attempt to reduce the total time to market of a new product. While both production planning and design try to support that goal, their impact relies heavily on each other. The decisions made in the design phase have a huge impact on the reduction potentials in the production planning. Therefore, it is necessary to give the design departments via PLM tools ways to estimate the impact of decisions in later stages of the product life cycle. The first step in creating such tools is to automate decisions that are currently done manually within the production planning.

At the same time, production systems are evolving into Cyber-Physical Systems that are in constant exchange with central servers and with each other. Large amounts of data are available that provide information about the status of resources, such as production machines or logistic vehicles, as well as about the progress of orders within the production systems.

New technologies and application scenarios also create new challenges. One challenge that can only be solved by the complete networking of production systems and products is the dynamic creation of sequence planning based on the current situation. In manufacturing companies, this is still done manually and by using simple priority

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rules [1]. One approach to solve this problem is using multi-agent systems. Deep neural networks are used, which receive information about the state of the production and can then influence the sequence. These networks are called agents. A distinction can be made between approaches in which a single agent coordinates the entire production and approaches in which several agents are used for different production sections.

A further distinction must be made between the optimization target. Sequencing can be optimized either for the shortest possible production time or for maximum delivery reliability. Existing research often refers to the shortest possible production time, which means that there is a wide range of approaches. In the case of the most exact delivery reliability possible, which in the context of a just-in-time industry has to take a higher priority, the amount of research is smaller. This is due to the fact since no absolute mathematical models are available in this case. In this paper, we consider sequencing as a Markow Decision Problem. To solve this problem, neural networks are used to insert a global decision instance into the process. The goal is to achieve the highest possible delivery reliability rather than the lowest possible lead-time.

This paper will therefore start with a brief introduction into sequence planning and machine learning. Both technologies are the foundation of the later concept and implementation. After this literature review, the concept is presented. Fundamentally, the concept is separated in two distinct parts. Both parts interact with each other, as the results of either are the input of the other. Right after the concept an overview of the implementation is given. The technologies used within the prototype are shown, so that the reader can develop a more detailed understanding of the approach. In the end a summary concludes the findings and the current limitations of the approach.

2 Literature

2.1 Sequence Planning

Sequencing is concerned with finding an optimal arrangement for a given number of orders and a given number of machines. But optimality is subject to the selected goal. In the theoretical consideration of sequence planning, three assumptions are usually made [2]:

- A machine can only process one order at a time
  - Consequently, a single order can contain more than one product. In this case, all products must always be treated as a single entity from a sequencing perspective.
- After processing an order, a machine is immediately available for a new order.
  - Set-up times and maintenance work must be recorded in the processing time of an order in each processing step.
  - Planned maintenance work can be included in a schedule by a separate order.
- An order can never be processed by two machines at the same time

– Machines working in cooperation with each other are represented by a single machine within the simulation.

In almost all problem definitions, several orders are accepted. However, the problems can be differentiated by the number of machines included. If there is only one machine in the planning, it is called a single machine model. This solution of a single machine problem can be solved mathematically and is therefore widespread. In industry, this problem only occurs on machines that represent a bottleneck in production.

More complex are models with multiple independent machines. In such a problem, each job must be processed by a different number of machines in any order. Problems of this type are NP-hard and thus no longer mathematically solvable as complexity increases. Here, different heuristics are used to create approximations.

A further distinction is made between flow shops and job shops. In flow shops, each job must be processed once on each machine. The processing sequence on the machines is the same for all orders and there is a storage area with infinite capacity in front of each machine, so that any number of orders can wait there to be processed. The difference in a job shop is that the order of processing is defined individually for each order and not a processing sequence is fixed for all orders.

Whereas in the past the utilization of operating resources was the most important optimization criteria in production planning and control, today delivery reliability and a short delivery time are the decisive target variables [3]. In practice, sequence rules, also called priority rules, are still the most common method for determining the processing sequence of orders:

– First In - First Out
– Earliest plan start date
– Earliest plan end date
– Least remaining slip
– Earliest Due Date
– Shortest operation time

More detailed information on these rules is provided by HERMANN and SWAMIDASS [4, 5].

2.2 Reinforcement Learning

Reinforcement learning is the most general form of machine learning. There is no historical data available at the beginning of the problem to which the methods of supervised or unsupervised learning could be applied. Thus, part of the task is to develop a basic strategy. One form of implementing reinforcement learning is a Markow Decision Problem. Here, a machine learning based agent interacts with the environment [10].

The interaction possibilities are defined by the influence possibilities provided by the environment, also called action space. The agent regularly receives information from the environment about the current situation, the observation space and possibly a reward for his actions. These can be positive or negative. The goal of the agent during a run is to maximize the achieved reward. Over the course of many simulations, called episodes, the different situations, the possible actions and the rewards are put into context so that situations are valued accordingly (Fig. 1).

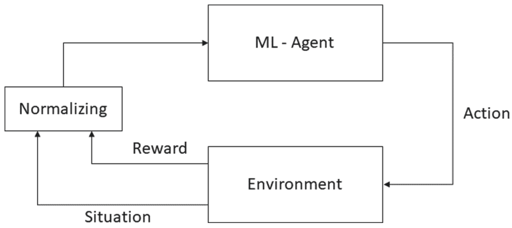

Fig. 1. Setup for reinforcement learning

Within a Markow Decision Problem all Situation an agent encounters are stored within a graph. The different possible actions an agent can perform in the situations lead to transitions through the graph. Specific actions within a situation deterministically lead to a transition into a specific other situation, which means that situations can be put into context to each other. Since the overall goal of the agent is to achieve situations in which high rewards are obtained or low rewards are avoided, different situations can be valued differently. Even if they do not explicitly contain a reward, but only enable the transition to such. This transfer of rewards is achieved by different algorithms, in the context of this paper mainly double Q-learning is to be mentioned. Two images of the situation space are used to compute the rewards of each situation. One of the two images does not yet take into account all episodes. The estimated reward of an action is stored as the Q-Value [11].

It is often inefficient or even impossible to store the action values Q for each state. In problems with a large number of state dimensions, this can quickly exhaust the computer's memory. Storing many individual values also has the disadvantage that when a state is reached for the first time, no estimate can yet be made about its action value. Neural networks allow a more efficient approach here. Artificial neural networks have a similar structure to the human brain. Artificial neural networks were first described in the form of the so-called perceptron by Frank Rosenblatt in 1958. The work was based on the function of a human eye with its biological neurons [12].

An artificial neural network consists of neurons and weighted connections between them. The neurons are typically arranged in columns, so called layers, and follow a Feed Forward approach. Feed Forward in this context means that connections only ever go from one layer to the next and no connection goes from one layer back to a previous layer. If all neurons of one layer are connected to all neurons of the following layer, it is called a densely connected network. The agent uses a deep, densely connected neural network, a network with multiple layers, to reduce the amount of memory required and to increase processing speed. The training is done in episodes. Meaning one or multiple simulations are run and then the results are processed in batches. After each episode, the weights within the neural network are adjusted to allow the network to approximate the correct decisions.

3 Concept

The concept can be divided into two parts, as shown in Fig. 3. First, there is the sequencing simulation that the agent must serve. Previous work in the field of sequencing has shown that it is necessary to create a separate simulation. Prototypical implementations with the software Anylogic could show that these cannot fulfil all requirements for the application. During the training of the neuronal network a large number of runs are simulated. While existing software can easily represent very large production runs in great depth, it is not optimized for high throughput.

A simplified UML diagram of the simulation setup is shown in Fig. 2. The training of neural networks for even simple problems requires that the production is run through completely several hundred times. With increasing problem size, the amount of necessary runs also increases, which is not the central design criterion for industrial simulation software.

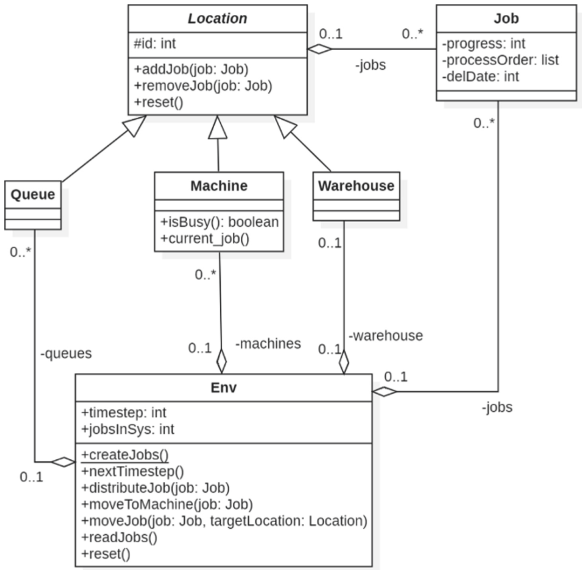

Fig. 2. UML-class diagram of the job shop simulation

The creation of simulation underlies several design decisions. These decisions are described and justified in the following. In order to go beyond the state of the art in the context of sequence planning, it is necessary to simulate several machines simultaneously. This is the only way to deal with a multi-machine problem.

The simulation has to be able to represent a real workshop production. A distinction can be made between a flow shop application and a job shop application. Within a flow shop, the individual production steps between all orders are arranged in an identical sequence. This means that the sequence of machines that has to process an order is fixed. This case is close to most real applications, since most products require a fixed sequence of processing steps. A job shop on the other hand allows swapping the sequence within the different jobs. This increases the complexity of the solution space, but at the same time allows more interaction possibilities. Modelling as a job shop problem is more general and can be simplified to a flow shop simulation. The jobs in the simulation must be processed in an individually stored order on the machines in the simulation. Therefore, the job shop approach was chosen for the simulation.

Another feature of simulation and a special feature when considering sequencing is the possibility of not manufacturing on a machine. As already mentioned in the state of the art, most sequencing problems optimize for the fastest possible processing of orders.

However, as will be explained later, the goal of the systems is to fulfil the orders as timely as possible. Therefore, it is necessary that the individual machines can also simulate waiting.

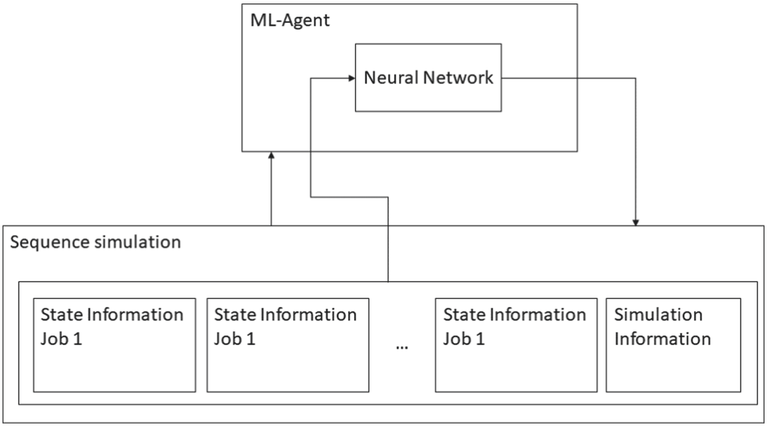

Fig. 3. Schematic of information flow between machine learning - Agent and simulation

The created concept for the optimization of sequence planning by a global machine learning agent is outlined in Fig. 3. The machine learning agent interacts with the sequence simulation via an interface, which provides information about the status of all orders. In addition, the machine learning agent receives a reward for each action, which can be used to adjust the weights of the neural network. Earlier works deal with the use of local machine learning agents, and the results were not sufficient. Therefore, the approach of a global agent is used here. A comparison of the two approaches is discussed in the abstract.

The concept is divided into two parts based on the components of a Markow Decision Problem. The sequence simulation must represent a workshop production. The environment thus consists of the basic building blocks of a workshop production. The workshop production consists of machines, each of which has a queue. In a queue are orders, which must be processed in the next step at the assigned machine. In order to be able to make this assignment, the processing sequence must be stored for each order. In addition, the progress within the sequence simulation must be saved for each order. Since finished orders should neither be stored in a queue nor in a machine, an additional storage is necessary for complete orders.

4 Implementation

The implementation is based on the programming language C++ and Python. Tensorflow 2 with the Keras API was used as the basis for the neural networks.

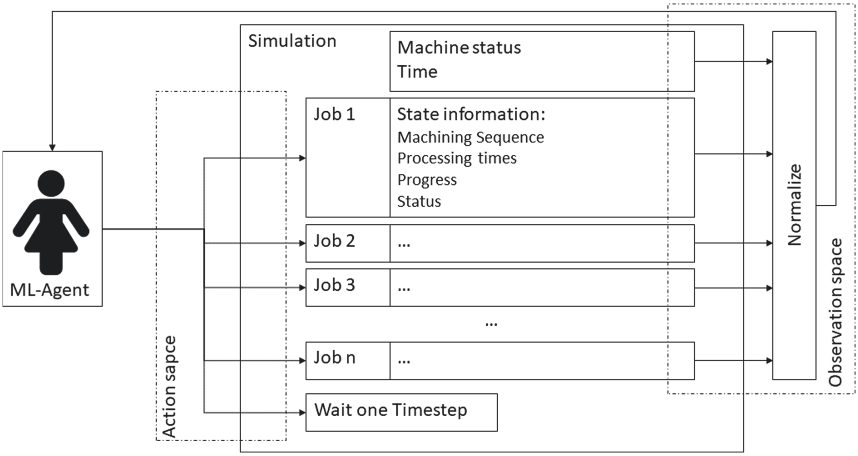

Fig. 4. Implementation of an machine learning - Agent for sequence planning

Figure 4 shows the relationship between the machine learning agent and the simulation and what information is exchanged between these. All actions that the agent can trigger are summarized under the action space. The information that the agent receives from the simulation is called observation space. The entire simulation does not take place in real time, but is an iterative cycle between simulation and machine learning agent. The simulation is divided into single time steps and after each time step a response of the machine learning -agent is expected.

The response of the agent is limited by the action space. The agent can select a task to be processed. Alternatively, the agent can decide to wait a time step. This option is necessary because situations can arise in which waiting is the most strategically sensible action in order to maximize the long-term reward.

Since the output of the simulation is to be used directly as input for a neural network, it makes sense that all values have a similar order of magnitude. For this, the value range [0, 1] is suitable, to which the values are linearly scaled in each case. For this purpose, they are normalized by their maximum value. This value is constant over all episodes and is based on a maximum value analysis. For the information of the time step, therefore, the highest possible value for the episode length must always be selected and not the random value, which originates from this uniform distribution and determines the maximum length of the episode.

The simulation state is to be completely described by an array. 2 * number of machines + 3 numerical values are required per job. For each machine an order has the information, which processing step it is and how long the order must be processed at this machine. The information about the processing time on a machine is divided by the largest possible time step in an episode, so that the value is always < 1. The information about the progress of each job is contained in the state-describing array. In addition, it is indicated for each job whether it is currently being processed or not. Finally, the current time step of the simulation is contained in the state array. This array is passed onto the agent as the observation array.

Many simulations must be performed as part of the training. The respective runs are referred to as episodes. An episode ends when all orders have been completed or the maximum number of time steps in an episode has been exceeded. After an episode has been completely run through, the weights within the neural network are adjusted according to the described double Q-learning.

The core of this adaptation is the reward that the machine learning agent can accumulate in the course of an episode. Here, the form of the reward is crucial. The stated goal is to achieve the most accurate delivery fidelity possible. Thus, other than a total time as short as possible, the reward function must also include penalties if an order is completed too early. Here, bell functions have established themselves in order to achieve an exact result.

However, bell functions based on e-functions produce very low values far outside the target value. Since the simulations can run for a relatively long time, this leads to the phenomenon that especially at the beginning of the training hardly any training progress is achieved, since the reward function does not have a significant slope. This is due to the small differences in the function values, which disappear completely due to rounding errors. Therefore, in addition to the traditional bell function, an overlay with a linear function was used. This superposition could only enable the training when the number of simulation steps increased.

The reward function used is therefore as follows for orders that are completed close to their actual target time:

$$R = \propto * e^{\frac{-(C-d)^2}{K}} + (1 - \propto) * \frac{C}{d} \tag{1}$$

For orders where C > d, the reward changes, resulting in a linear decrease as the deviation continues to increase:

$$R = \propto * e^{\frac{-(C-d)^2}{K}} + (1 - \propto) * \left(2 - \frac{C}{d}\right) \tag{2}$$

- C: Delivery date of an order
- d: Finishing date of an order
- K: Factor for manipulating the width of the bell function
- α: Factor for the balance between bell function and linear part

Figure 3 shows that the machine learning agent is based on a neural network for decision making. To implement the machine learning agent, an algorithm that uses double Q-learning is implemented in Python. The algorithm is based on an implementation by Andy Thomas [6]. The training of the transitions takes place offline, the transitions are first stored and used at another time to approximate over the neural networks. This requires storing a transition and retrieving a certain number of transitions from memory.

As illustrated in the explanation of double Q-learning, the agent actually works with two neural networks. Both networks are fully connected feed-forward networks with hidden layers and an output layer. One network serves as the target network and the second one as the primary network. In each time step, the weights of the primary network are adjusted as suggested by Lillicrap [7]:

$$\theta^{Q_{Target}} \leftarrow \tau * \theta^{Q_{primary}} + (1 - \tau) * \theta^{Q_{Target}} \tag{3}$$

Double Q-learning was chosen because this approach is advantageous when there is a state action space that is too large to be completely traversed and at the same time there is no pre-trained system. These characteristics are present in this case [8].

5 Conclusion

To test the system, simulations were first performed with one machine and one job. With this setup, the machine learning agent was able to converge quickly and the basic functionality could be proven. Figure 5 shows that the neural network does not change further after 600 episodes.

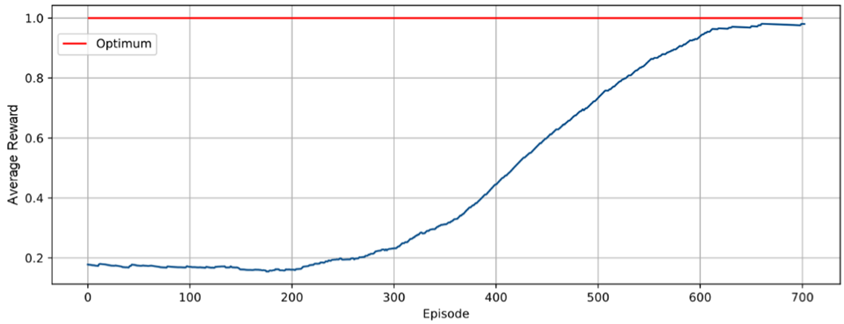

Fig. 5. Average reward with one machine and one job

In the next step, the scope of the simulation was expanded. The number of machines and the number of orders were each increased by one. Two effects occurred. As expected, the training time required to reach a stable state increased. The time required tripled. As can be seen in Fig. 6, however, uniform training no longer takes place. These are local optima, which are approximated by the system structure. An example of this can be observed around episode 720. Experiments with different parameters regarding the ratio of how greedy the agent should act could show that a convergence to an optimal solution is not guaranteed.

Similarly, not every configuration could be guaranteed to maintain a steady state near the optimum, but as can also be seen in this iteration, fluctuations occur around the target value. Further tests regarding the scaling of time and the stability will be conducted in further research.

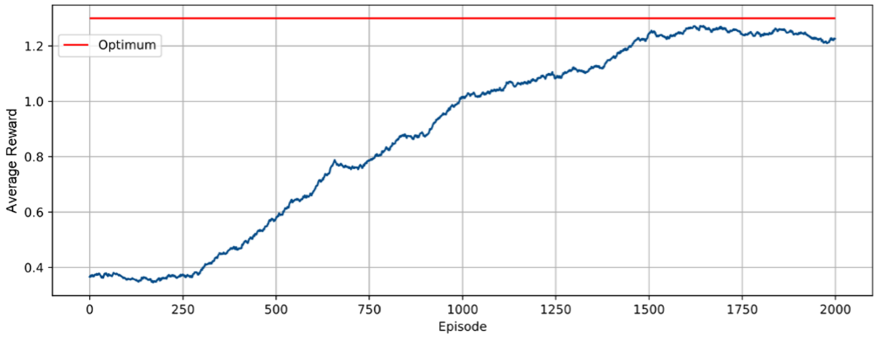

Fig. 6. Average reward with two machines and two jobs

The structure of the implementation further results in an asymmetric network. This can be recognized by the fact that the order of jobs and how these are put down within the observation space, has an influence on the processing. By a rotation of the same orders, the same net can produce different processing orders.

In order to give a final conclusion, a comparison to other disciplines is necessary. The concept is in competition with systems that use priority rules. Furthermore, there is a variation of the concept described here where machine learning agents are not used globally, but locally. Earlier research has shown that it is not generally possible to create convergence of the individual agents in a local application, but that they are in a permanent competition with each other [9].

From this point of view, the concept shows that it is basically possible to implement sequencing by means of a global agent. In contrast to a distribution of the machine learning agent to the individual machines, all orders in the system can be considered. It can be taken into account that an already delayed order, which is currently still being processed on a machine, must be released for processing immediately. This advantage of a global machine learning agent is not only compared to a concept with split machine learning agents, but also to the use of priority rules. Rules such as the least remaining slip rule can only eliminate delays if the machine used for processing is not currently processing another order and processing has already been completed for the delayed order in the previous step.

However, this advantage is also the biggest disadvantage for a global machine learning agent compared to the use of multiple machine learning agents, each of which has a smaller observation space. Accordingly, a global machine learning agent scales poorly with the number of orders, which is expressed by an unstable training.

The Just in Time manufacturing-like option of not releasing an order and waiting for a time step makes the job shop problem many times more complex. Many transitions occur in which no evaluation of the current state of the sequence simulation can be given, so the machine learning agent must wait for a reward until an order is released for the last processing step. This leads to a delayed adaptation of the neural networks. While specific solutions can be implemented here to evaluate orders differently, these are not generally applicable options. Instead, it is necessary to analyse the orders separately in order to reward the agent for every processing step.

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PLM Maturity, PLM Implementation and Adoption within Industry 4.0

Enabling Collaborative Lifecycle Engineering of Smart Products and Services by an Adaptive Innovation Infrastructure

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Abstract. Due to the continuously rising digitalization of traditional products towards smart product-service systems, there is a considerable need for new methods, processes and IT tools in future product development. As well as for collaboration and integration of various stakeholders in engineering in particular. This contribution aims at analyzing and addressing the challenges in collaborative lifecycle engineering of smart products and services considering the entire product lifecycle. With a focus on cross-discipline collaboration an adaptive innovation infrastructure for lifecycle engineering a innovative research transfer infrastructure in Kaiserslautern has been developed in order to support a variety of heterogeneous target groups in industry and education. Focusing on hybrid prototypes along the engineering 4.0 lifecycles, the scenario of racing car within the engineering 4.0 lab infrastructure serves as an example for a cross-discipline engineering scenario.

Keywords: Smart product engineering · Collaborative smart product and service engineering · Engineering 4.0 lab

1 Challenges in Collaborative Smart Product and Service Engineering

In the age of digitalization and information technical integration of products, processes and services the engineering complexity is rising dramatically while the corresponding potential for support by virtual engineering methods and technologies is increasing disruptively too. This means fundamentally new opportunities for product development and engineering, but also a strong need for integrated information and model management including all engineering disciplines involved. This is true not only for traditional product development phases but for the entire lifecycle of Smart Product-Service Systems (SPSS), beginning in early cross-discipline innovation phases, including the product use and reconfiguration and the end of life of SPSS components. In parallel companies have to integrate new value network partners as well as additional stakeholders in their engineering processes and to shorten innovation cycles in order to be able to meet current customer needs in line with the market [1].

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Besides a multitude on converging software and hardware innovations (e.g. in the field of artificial intelligence, cloud computing, embedded chips, mobile devices and 5G) the Internet of Everything (IoE) serves as a core enabler for SPSS. SPSS are defined as intelligent multidisciplinary products capable to communicate and interact with their environment and other smart products by using product-related, internet-based services offered in data driven business models [2, 3].

The transition from traditional mono-disciplinary and mechatronic products to-wards connected SPSS can be observed in almost all industrial sectors. Examples in the consumer industry (e.g. smart phones using app stores), in the machinery and plant industry (e.g. predictive maintenance and remote assistance services) and in the automotive industry (e.g. mobility and assistance services and platforms) show the disruptive potential of this transition impressively.

Considering the more and more dominating share of SPSS in the revenue of industrial companies, there is a strong need to enable collaborative engineering processes, methods and IT tools to meet the challenges determined by SPSS.

Beginning in early innovation phases the requirement engineering of SPSS has to integrate existing and potential use cases from customers and value network partners covering the whole SPSS lifecycle with a special focus on the use and reconfiguration. This also includes requirement development facilities gained by the analysis of product and service use data gathered in Internet of Things (IoT) platforms using industrial data analytics methods [4, 5].

According to enhanced V-model approaches like [6–10] cross-disciplinary functional and logical SPSS models integrating SPSS shares of the engineering disciplines mechanical, electric/electronic, software, service and business model engineering as well as the co-creation by customers and partners build the core of early product development phases. Here overall SPSS architecture models including all initial components of a well-defined system of interests have to be considered. This includes also the connectivity, communication capabilities and product and service related plat-forms and ecosystem components. By a partitioning process of these cross-discipline SPSS models consistent discipline specific engineering shares as well as technical interfaces have to be defined. Here agile collaboration of SPSS system architects and discipline-specific knowledge provided by business model architects, methodical and virtual mechanical engineers, electrical engineers, software engineers, service engineers and user experience experts are essential prerequisite. The methodical approach and the result can vary fundamentally depending on the concrete SPSS focus, the customer and market priorities and the company specific constraints.

The partial models of a SPSS developed in the respective engineering disciplines using a specific set of engineering methods and IT tools have to be validated within the corresponding discipline context and in an integrated context comprising a set of interdisciplinary SPSS components and environment components. As a basis for the validation the concept of the digital product twin provides a set of digital SPSS models which is specified according to specific use cases (e.g. validation use cases) and according to a concrete SPSS lifecycle phase [7, 11, 12].

The concept of the SPSS instance specific product twins serves as a core for the production planning in the context of the digital factory approach and as a basis for the tracking, preventive maintenance and reconfiguration of SPSS during its use phase. Thus, the current state and configuration structure of each SPSS instance is permanently known by the SPSS provider and linked with the sensor data captured by the SPSS over the operating time.

The relevance of the digital twins for this purposes in industrial companies is also analyzed in studies like [13]. Here 92% of the respondents for instance stated that they were concerned with the concept of the digital twin because they see the influence and opportunities of the concept on digitization projects. Of those surveyed, 36% had already launched initiatives and 50% said they would launch initial pilot projects in the next twelve months. However, more than 50% of respondents still indicated that a transfer to ongoing operations is not expected until the next three years. There is significant relevance of the concept of the digital twin in a cross-company ecosystem solution. Just under 80 per-cent of respondents still indicated that use is internal to the company. According to respondents, internal use will change to cross-enterprise use in the next five years (77% of respondents) [13].

2 Collaborative Engineering Infrastructure Concept for Smart Product-Service Systems

The main vision to meet the mentioned challenges is to establish a highly adaptive infrastructure for the engineering of future SPSS in order to systematically support the knowledge transfer in the field of digitalization and the associated transformation of business processes and to create their own innovative engineering ecosystem. Enabling companies to serve customer requirements in the future with new business models as well as smart products and services in a most innovative way. As outlined in chapter 1, products in the future will have significantly more complexity (e.g. high amount of partial models) than traditional products, for example. And the many different partial models in particular will have to be considered holistically in terms of information technology using an integrative approach in order to keep the complexity in the engineering phases manageable. Due to the increasing servitization within the SPSS and their individual functionalities, however, there are also considerably more interfaces, for example to other surrounding ecosystems and industries (e.g. system of systems) and this throughout all life phases of a SPSS, not only in the classic usage phases as past products were usually classified.

The engineering 4.0 lifecycle, as shown in Fig. 1, describes a multi-stage process from requirements development, interdisciplinary product design, discipline-specific design, product integration and validation, production and product logistics to the operation and reconfiguration of SPSS. The process is also bidirectional, which means that all partial models are linked with each other in terms of information technology and feedback from the various phases along the life cycle is available in an integrated form. On the basis of this guiding process, cross-disciplinary requirements such as those to the infrastructure were derived on the basis of well-founded analyses in order to provide adequate support for the engineering of SPSS. One of the main focuses here was on the consistent integration of all partial models within the engineering 4.0 lifecycle. Furthermore a conceptual framework for a future collaborative engineering infrastructure was developed (as shown in Fig. 2) based on the identified challenges as described in chapter 1 and the expertise of the participating professors from various disciplines. In addition to the information technology coverage of the partial models along the engineering 4.0 lifecycle, for example, the aspects of the corresponding lifecycle phases regarding a comprehensive knowledge transfer from and to the industry were also included in the conception of the framework.

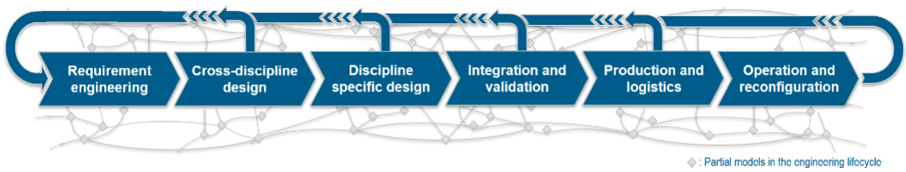

Fig. 1. Engineering 4.0 lifecycle for SPSS

On the one hand, this includes direct exchange with industry for example, through use-cases and best practices from specific industry applications. On the other hand also the transfer of knowledge to industry from the research activities of the various partners and stakeholders along the engineering 4.0 lifecycle. Furthermore, a distinction is made between different levels of knowledge transfer (demand-oriented transfer): Beginner, enthusiast, expert. In addition, the depth of content can be scaled again depending on the industrial purpose or educational purpose. E.g. trainees (e.g. pupils, students) will be enabled to get to know and be able to use appropriate engineering methods and processes already during their training. The focus here is not only on the direct acquisition of knowledge, but also on the development of further competencies in the engineering field, such as the development of associated soft skills. In order to be able to build up and transfer this knowledge, the infrastructure concept is thus combined with a corresponding heterogeneity of different experts and partners (e.g. chairs, institutes, key software partners, etc.) as also corresponding laboratories (e.g. a design thinking tank laboratory and a mobile engineering lab) are integrated into a virtual collaboration concept in order to achieve the highest possible coverage of all relevant disciplines for the engineering of future innovative SPSS. However, it is not always possible to develop the innovation potential of the disciplines and experts involved in a collaborative manner and to leverage it in the most comprehensive manner possible. To address this in the context of the engineering 4.0 lifecycle and the corresponding conceptual framework for a collaborative and adaptive engineering infrastructure, a highly dynamic interior concept was designed on the basis of studies on innovative working methods and future office space concepts. A so-called engineering 4.0 lab (e4lab) [14] was set up for this purpose based on the derived requirements from the analysis described above.

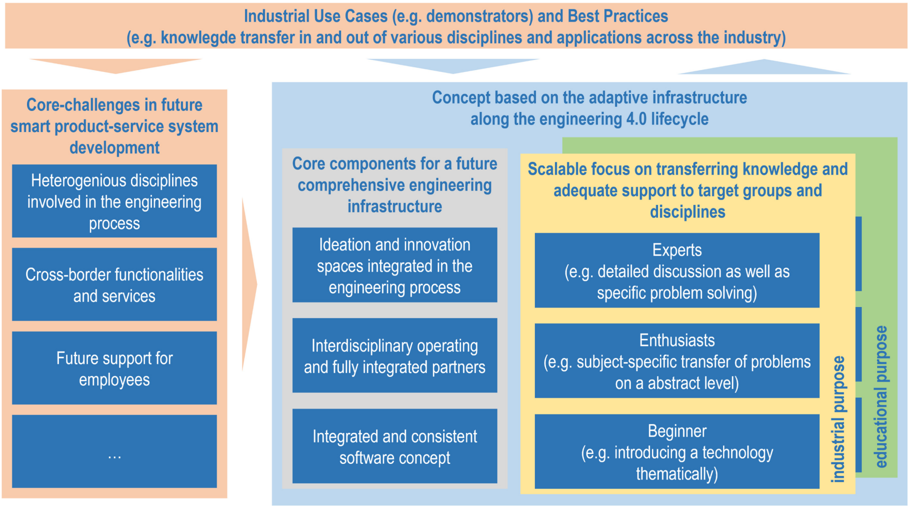

Fig. 2. Conceptual framework for a collaborative engineering infrastructure

The engineering 4.0 lab is operated by 9 professors with 20 scientists and covers the engineering 4.0 lifecycle holistically in terms of information-technology as well as specialized departmental with the participating professors, as shown in the Fig. 3 on the upper half. This concept divides the engineering 4.0 lab area into three consecutive areas: Innovation and Ideation Area (as shown in Fig. 3); Educational and Software-based training Area; Elaboration and Reconfiguration Area.

The innovation and ideation area is the central hub in the infrastructure of the e4lab. This is where the exchange of content between the various stakeholders mainly takes place. The setup and the fully flexible structure allows for a complete redesign of the space within a few minutes. In this way it is possible to react adequately to the needs of the respective partners in order to maximize the quality of the according knowledge transfer. Another special feature is the integrated design thinking area, which can also be virtually connected to a specialized design thinking tank laboratory for expert workshops and used collaboratively. In order to facilitate companies' entry into the transfer process, various physical and virtual demonstrators and use cases have been set up and mapped in the innovation area along the engineering 4.0 lifecycle (various partial models) and linked with each other. The e4lab software concept also plays a key role here. Together with the strategic partner Siemens Industry Software GmbH [15], a holistic software concept was designed and set up along the engineering 4.0 lifecycle in order to achieve consistency across all partial models and partners within the entire e4lab infrastructure and areas. In the Educational and Software-based training Area, there is also the possibility to work in detail on focused problems referring to the software ecosystem and partial models used and to evaluate various solution areas. Here, the main focus is on scalable transfer at the content level in order to be able to work out the required solutions in a target-group-oriented manner. This includes, for example, general training on various individual software components in use as well as specific software concepts for concrete applications from industrial use cases.

Fig. 3. Innovation and Ideation Area of the engineering 4.0 lab Kaiserslautern

The third area, the Elaboration and Reconfiguration area, is primarily used for building and testing the physical demonstrator scenarios. Here, it is possible in particular to build up and test the challenges of future SPSS, specifically for the scenario intended and thus to validate it before it finds its way into the corresponding innovation area. This means that a scenario can be updated promptly as soon as new aspects arise from research or from the industry itself. As also ensuring all demonstrators and partial models along the engineering 4.0 lifecycle are always up to date and conducive to innovation, in order to be able to ensure the highest possible innovative potential in the transfer of knowledge as well as in collaborative work within SPSS engineering in the future. In addition, in pandemic times like these, where aspects such as travel restrictions and social distancing are in the foreground making it difficult for some companies to access transfer offerings, the e4lab has been successively expanded to include specific aspects such as virtual collaboration workshops, virtualization of physical demonstrator scenarios, virtual tours, etc., in order to cover not only the stationary infrastructure of the engineering 4.0 lab, but also to make it easily accessible and thus available to various target groups on a virtual and on-demand basis. The engineering 4.0 lab now also has a virtual innovation and collaboration ecosystem in the form of a digital twin of the engineering 4.0 lab that complements the stationary offerings.

3 Smart Product-Service System Based Hybrid Prototypes as an Exemplary Engineering Lifecycle Use Case

One area of application from engineering, which creates a constructive, agile and at the same time cooperative framework distributed over the complete engineering 4.0 lifecycle, is the combination of initially SPSS-dependent but equally discipline-dependent combined know-how for the creation of prototypes. Through this, the complex SPSS and especially their integrated sub systems can be virtually tested to be developed and enhanced in a most efficiently and data-driven manner in terms of information technology.

The comprehensive SPSS prototyping considers the holistic integrated engineering lifecycle management of heterogenous systems (e.g. further described in [8–11]) and promotes, among other things, the parallelization of the interdisciplinary development steps by applying agile engineering methods for example. Cross-disciplinary relevant partial development processes can be considered together with downstream process steps at an early stage as a result innovation cycles can be shortened. Thus the functional SPSS prototypes can be designed in a collaborative way by incorporating all relevant product information from e.g. mechanics, electric/electronics, software as well as product-relevant and product-specific external dependencies as covert by the involved professors and scientists along the engineering 4.0 lifecycle supported by the adaptive innovation infrastructure of the e4lab. Depending on the existing physical, virtual and/or simulated sub systems, these can be applied throughout the entire product lifecycle according to the needs and requirements. In terms of the SPSS lifecycle, prototypes continue to develop in line with the maturity of the SPSS. Thus, in the early phases of SPSS development, mostly purely virtual or simulated models are initially designed. For example, to be visualized initially by using virtual reality (VR) methods and techniques. In the Phase initial design reviews can be carried out and first functions of the later physical, smart product or service can be simulated and further tested in different use case specific scenarios. Be able to be expanded in the further development, when the first physical prototypes have already been produced. The amount of virtual components is increasingly being replaced by physical components and developed in an iterative way into a hybrid prototype. The so-called hybrid prototype is in this case a prototype consisting both, virtual and physical systems and components which can be realized via augmented reality (AR) and mixed reality (MR) methods and techniques. Even before the complete physical implementation, hybrid models of the SPSS can be created and multimodally simulated and validated in their actual functionality and interaction with the intended context or environment. Joint interaction with these prototypes creates intuitive and immersive working environments in which specialists experience a comprehensive understanding of complex interrelationships of the SPSS in close cooperation with each other. These methods and tools promote the merging and combining of the knowledge required for product understanding across the entire value chain.

Using exemplary partial models of the KaRaT e.V. [16] racing car, the cross-lifecycle design of processes, methods and IT tool chains for the engineering of SPSS is to be further described and thus the continuous information technology networking in the engineering 4.0 lifecycle is to be demonstrated as shown in Fig. 4. The phase of requirements engineering at the beginning of the engineering 4.0 lifecycle must already be designed cooperatively and iteratively along the involved stakeholders and partners in order to be able to determine, analyze and define the systems requirements. In this context, a essential step is to provide the results in downstream processes or partial models and their validation to be fed back in order to adapt the feedback in the corresponding requirements models. Based on the requirements models, the interdisciplinary product design can be implemented in the first purely virtual prototypes in one of the subsequent partial models. The racing vehicle is now initially created based on abstract parameters (e.g. geometric information, safety restrictions etc.) and is available virtually, for example in virtual reality applications, for design reviews or construction space estimations. So the system model is used to validate design requirements or initial system behavior or functionalities in the early phase of the SPSS development. Likewise, variants of the racing car can be compared with each other and serve as the basis for further decisions.

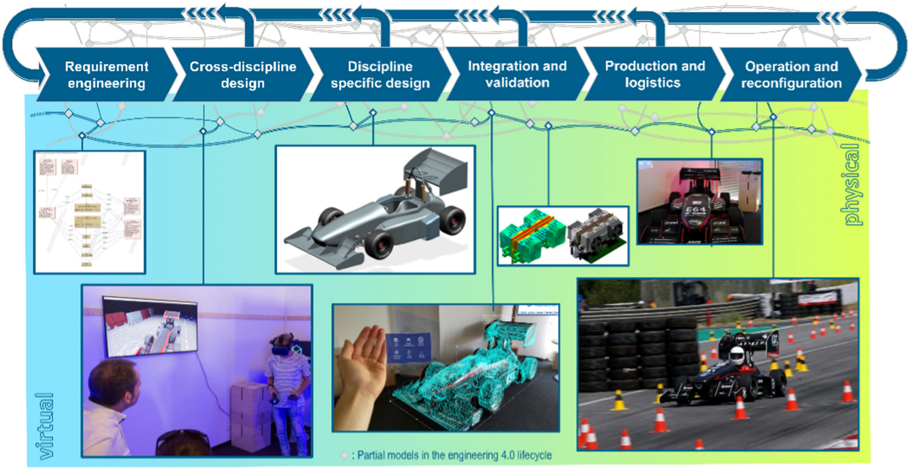

Fig. 4. Exemplary prototypes across the engineering 4.0 lifecycle based on the design Use-Case of the KaRaT e.V. racing car

This first early prototype of individual systems (e.g. components) and also the entire vehicle can lead to adjustments in the previously created requirement models in an iterative way. For example, different iterative loops optimizing the further requirement models, which can be tested again as a revised model of a prototype in a collaborative way with all involved cross-discipline experts and partners. This procedure links many individual partial models of the vehicle with each other in a holistic way and creates a highly innovative information transfer that is not exclusively forward-driven, but also includes equally backward-driven feedback processes. In the further phases in the engineering 4.0 lifecycle, the first physical components such as the chassis and many other components of the racing vehicle are also created in addition to the purely virtual prototypes. Together with prototypes of other product models, some of which are already virtual or simulated, these can grow into a more appropriate, fully integrated hybrid prototype. With the merging of all information technology data-driven systems, supported by AR, physical components can be combined with virtual aspects and systems and/or validated. As a basis for the new AR scenario, data from the earlier models can be integrated and processed according to the development status and needs at the specific maturity level of the system. This enables a very powerful network of all data and specific SPSS sub systems, models and information at an early stage in the engineering 4.0 lifecycle, which compresses detailed knowledge and leads to a deep SPSS understanding for discipline-dependent experts, beyond their actual competencies. The vehicle can be flexibly developed further in application-specific ways, for example in VR, AR, MR and/or other systems combined. Information from collaborative decision-making processes is also structured on a higher level through networking and can thus also be used for other systems and partial models. This creates a very powerful SPSS at an early stage in terms of its lifecycle.

In the vehicle's usage phase, prototyping is used for further validation (e.g. of new services and functionalities) and dynamic reconfiguration of the actual SPSS instance. The special feature here is the combination and variety of available data and possibilities. Among other things, technical analyses of usage, new software developments, but also the practical experience of the driver as an end user can be included and directly linked to the physical, fully operating SPSS in the field (like in this example the racing car). Hybrid scenarios can be built on its physical as well as information technology foundations and tested directly in real use cases. The new findings thus count as valuable fully validated further developments that can be used directly for new SPSS development.

For example, a further developed rear spoiler can be linked to the real vehicle as well as the existing models and the first steps for a new SPSS instance can be initiated. In small, functional prototypical implementations, possible changes can thus be tested quickly and iteratively directly on the vehicle.

The engineering 4.0 lifecycle is not completed at the end but enables a permanent connection back to the earlier phases in order to start the next development cycle or reconfigurate the existing SPSS instance in the field. Particularly at this late stage in the engineering 4.0 lifecycle, the continuous, lifecycle-accompanying consistency of the cross-disciplinary SPSS models, process-related and at the data level, supported by a strongly integrated IT infrastructure, is benefited from.

4 Outlook and Summary

The contribution shows how an adaptive innovation infrastructure is supporting a collaborative smart product and service lifecycle engineering. For this purpose, a conceptual framework for a collaborative engineering infrastructure was developed and presented on the basis of the discussed future challenges for the development of smart product service systems (as shown in Fig. 2), which includes the core components for a future comprehensive engineering infrastructure along the engineering 4.0 lifecycle (as shown in Fig. 1). Another focus is the integration of the various disciplines and partial models involved supported by an adaptive innovation infrastructure.

In order to be able to promote an adequate transfer of knowledge in future SPSS engineering, a further point of the framework is the transfer of knowledge, in particular to and from industry. Especially on knowledge transfer in and out of industry at different scales (e.g., industrial purpose, educational purpose) and levels of granularity (e.g., beginner, enthusiast, expert). Finally, the conceptual framework was translated into reality with the engineering 4.0 lab in Kaiserslautern, creating an adaptive innovation infrastructure. This includes the know-how of 9 professors and 20 scientists along the engineering 4.0 lifecycle (as shown in Fig. 3) as well as the integration of further experts (e.g. key software partners) and partner labs (e.g. design thinking tank laboratory). The possibility of integrating additional experts, for example, is a future-oriented approach in case further experts are needed along the engineering 4.0 lifecycle. This prevents knowledge gaps and enables seamless integration into the existing infrastructure of other fields of expertise and experts in the future.

Based on the topic of hybrid prototypes along the engineering 4.0 lifecycles, the scenario of the race car within the engineering 4.0 lab infrastructure was then used as a cross-disciplinary example scenario to demonstrate collaborative work within the adaptive innovation infrastructure in the operation of the engineering 4.0 lab. This includes various partial models from requirements development to the usage phases of the SPSS as well as its reconfiguration in the field (as shown in Fig. 4).

Further research is needed especially in the area of virtual collaboration in the context of the digital twin of the engineering 4.0 lab as one potential new normal, as well as in the further integration of additional disciplines such as economics and didactics on the one hand, and the integration of socio-political aspects in the area of sustainability on the other hand. As they are not covered completely by the participating experts and professors involved in the engineering 4.0 lab at the moment. In order to consolidate the lessons learned from the operation of the engineering 4.0 lab, there are already initiatives started such as the internationally ERASMUS+ project Connect4PLM to ensure the feedback in the area of transfer activities from research to future education and industry.

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Review of PPX Business Models: Adaptability and Feasibility of PPX Models in the Equipment Manufacturing Industry

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Abstract. The overall purpose of this study is to understand how manufacturing companies have so far made use of and can make use of pay-per-x (PPX) business models (BMs) largely in capital product markets, and which mechanisms have helped them in the implementation. Through systematic literature approach this study analysed 14 research publications which exclusively focused on PPX business models. The differences between PPX business model patterns were studied from three perspective, namely criticality of product, need of process knowledge and complexity of the process and its output. We find out that the pay-per-outcome business model, is more prevalent for products which are critical, needs extensive process knowledge and are rather complex. In contrarily, pay-per-output business model is more prevalent when these conditions are not met. However, none of these three factors prevents implementing other type of PPX business model but rather specific business model is more feasible when specific conditions are met. This paper contributes a much more in-depth qualitative view on the patterns and related qualitative arguments for the useful application of PPX models in equipment manufacturing industries and helps to understand the differences between PPX business model types.

Keywords: Business model · NOBM · Pay-per-x · Pay-per-output · Pay-per-outcome

1 Introduction

During the last decade, pay-per-x (PPX) services and related business models (BM) have established importance in many fields, e.g. in equipment and capital-intensive product

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manufacturing industries, where they were earlier found to be difficult to implement, due to inherent significant risks for their suppliers, as well as technological challenges [1]. Additionally, their scalability has been considered as a significant hindrance to their implementation, compared e.g. to the use of similar BMs and services in software business (i.e. SaaS models) or consumer product industry [2].

Due to the above type of challenges, many companies have struggled heavily with the design and implementation of novel pay-per-x services and related BMs for equipment. For instance, some of the pioneers, the large car tire manufacturer, Michelin, designed to sell pay-per-kilometer services for its tires, but struggled for many years to become commercially successful [3]. Furthermore, also one pioneering company in equipment manufacturing field, Kaiser, producing compressors, also struggled in the development and implementation of a feasible model [4].

The actual benefits and particularly the feasibility (and its preconditions) of pay-per-x and especially pay-per-output/outcome type BMs in equipment manufacturing companies have been very little studied and reported in academic literature. It is not yet properly understood in which types of products and more specific industries PPX BMs have been recently used, and thus, in which specific conditions they are feasible and profitable, and how they have been applied to provide feasibility in those cases [5]. In this respect, the equipment and capital product industries have been some of the most challenging ones to apply the above BMs [6], and only very recently, they have been applied and studied [7]. For example, [8] found that the PPX BMs are typical in the context of a capital-intensive, complex engineering product, with a long life cycle, where a product requires a considerable effort to maintain. In addition, Böhm et al. [9] have found that product innovativeness and technological turbulence has an impact on feasibility of different PPX BMs.

When applied usefully in proper setups, PPX services have been found to enable various strategic benefits, such as profitability and sales growth in equipment manufacturing companies [10, 11]. Furthermore, a recent study by Korkeamäki et al. [12] found that in a larger empirical survey, PPX offerings were found to be a profitable servitization strategy for manufacturers of equipment and machinery of not only large size but of many company sizes, as well as that many companies (often larger ones) struggled with e.g. scaling issues of the related BMs. The most commonly known and reported equipment manufacturing PPX cases are clearly large or huge companies like Kaiser or Rolls Royce. However, it is not yet properly understood in academic research which types of more detailed mechanisms related to the BM implementation help to create such feasible strategic benefits (here, especially sales growth and related profitability).

The overall aim of this study is to create a picture of more generic patterns on and thus to understand how manufacturing companies have so far made use of and can make use of PPX BMs largely in capital product markets, and which mechanisms have helped them in the implementation. Thus, we aim to study, making use of existing equipment industry studies and reported relevant case studies:

RQ*: What kind of products and more detailed industries' have made use of PPX business models, and how they have been able to do this feasibly (responding to e.g. the above-mentioned important challenges of the EM industry).*

We followed a systematic literature review approach to identify the relevant articles and cases from the current research. We make use of existing identified 44 case studies to distinguish some overall patterns related to the above aims and the RQ both quantitatively and qualitatively. We then use these to formulate propositions.

Earlier studies that we have been able to find that focused on equipment manufacturing (EMI) context did not make use of a large group of identified relevant case studies from various EMI fields, or a recent systematic review of existing cases. Thus, we will add to existing research by providing a recent review of the existing EMI cases from various EMI industries, and thus being able to create a good picture of existing patterns from the cases. Through the same approach, we contribute a much more in-depth qualitative view on the patterns and related qualitative arguments for the useful application of PPX models in the wide EMI industries.

2 Theoretical Background

The value proposition in the manufacturing industries has changed dramatically in recent years [13]. Designing and selling a combination of service and product is now seen as a prominent value proposition [14]. Companies are integrating services into their core business which have resulted in the evolution of Product-Service systems (PSS). In recent years, the business model literature has produced extensive knowledge on these PSS model [2, 10, 15–19]. The non-ownership BMs (NOBM) are one type of PSS BM where the ownership of the product is not transferred to the customer, but customer has only right to use the product. These NOBMs can be divided based on earning logic to three types of pay-per-x (PPX) business models: Pay-per-use, Pay-per-output and Pay-per-outcome BMs [20].

In pay-per-use BM the customer is paying based on usage (used time) of product instead of buying the product (e.g. pay-per-wash) [3, 16]. For commercial success, pay-per-use services depend on modularizing products and services and effective enforcement resources [3]. Although there are a lot of opportunities in this BM, there are also some risks, like the reduction of revenues due to a low level of product usage which does not cover the fixed equipment maintenance costs [21]. To reduce the risk, companies could enhance operational capabilities by deploying product usage data processing knowledge and optimize service delivery cost [22]. Sousa-Zomer et al. [23] has shown that companies which implemented a pay-per-use BM, has developed new capabilities related to financial activities (such as the financial impact of pay-per-use services and, monitoring the costs along the lifecycle) and legal activities. Other capabilities such as inter-organizational cooperation with different companies to acquire or develop required skills are also needed [24].

Though the literature explicitly does not provide a comprehensive definition of the pay-per-output BM, Wolfgang [17] defined it as "customers pay a fee that depends on usage and is measured according to clearly specified consumption, output, or other indicators". According to Menon et al. [20], the pay-per-output is monetized based on a quantified output of the machine rather than the usage of the machine. Only a few studies have explored the pay-per-output BMs. For example, Uuskoski et al. [25] studied benefits and difficulties during the implementation process of the pay-per-output BM in SME.

The third PPX BM type, pay-per-outcome BM (selling outcome-based services), has gained a lot of attention from equipment manufacturing companies in recent years [11, 26]. Like the pay-per-output BM, the pay-per-outcome BM is also focusing on the output but not alone in a quantified sense but also from a quality perspective [20]. In the pay-per-outcome BM, the provider is responsible for the equipment's or service's output's performance and accepts penalties for shortcomings relate to that as well [8, 11, 18, 19].

Although the pay-per-outcome BM seems more promising from the service provider perspective, it requires additional capabilities from the organization such as IT [8], performance measurement capability [27], efficient repair and logistics capabilities [28] and necessary information to manage cost and risk [11]. Böhm et al. [9] argued that when technological turbulence is high, buyers perceive significantly more benefits. Böhm et al. [9] also found that pay-per-outcome models demand not only extensive product knowledge and product's performance in the customer's processes.

3 Research Methodology

We followed a systematic review approach [29] to identify the relevant articles, and the cases pertaining to the current research. Since we were looking for cases published in high impact articles, we considered only the journal articles in English, and which were published in the database of Scopus and Web of Science. As, our research objective was in the context of PPX BMs for equipment manufacturing companies and we wanted to have published cases studies, therefore we used the following keywords and the search string: ("servitization" OR "pay per use" OR "pay per output" OR "pay per outcome" OR "outcome-based" OR "performance-based" OR "performance-based logistics" OR "performance-based contract" OR "product service systems" OR "product service systems business model") AND ("manufacturing" OR "manufacture" OR "manufacturer") AND ("case" OR "case study" OR "case studies").

Additionally, we complemented the above pool of articles by deploying articles from authors' own knowledge, and that from forward and backward search of references. Also, since we required an in-depth analysis of data to achieve our research objectives, therefore, we considered only the qualitative single or multiple-case studies. Besides, to adhere to our research objective we selected the advanced business models (i.e. pay-per-use, pay-per-output, and pay-per-outcome) cases studies in B2B context. The review was conducted during July 2020. Totally, we find 528 articles, and after following all the steps we accepted 14 articles with 44 cases.

The concepts were identified by using coding technique [30]. Coding was done in two phases. First the concepts were identified based on few case studies. Second the coding was done for all the cases based on these identified concepts. The three identified concepts were "*criticality of product*", "*process knowledge*" and "*complexity of customer's process and its output*". In addition, we classified each case company based on Global Industry Classification Standard (GICS®) [31] to get more information about industry patterns.

4 Findings and Analysis

We have found that, out of 44 cases, 13 companies (30%) have implemented pay-per-outcome BM, 20 companies (45%) have implemented pay-per-output BM and 11 companies (25%) the pay-per-use BM [10, 32–44].

With GICS classification, 11 (3 pay-per-use, 6 pay-per-output, 2 pay-per-outcome) cases were from *Moving Capital Goods*, nine (4, 5, 0) cases from *Standalone Capital Goods*, nine (2, 0, 7) cases from *Material*, eight (1, 5, 2) cases from *utility* and seven (1, 4, 2) cases from *Commercial & Professional Services* industries.

In the following sections, we discuss more in-depth these cases using the three identified concepts: *Criticality of product, Process knowledge, and Complexity of customer's process and its output.*

4.1 Equipment Criticality

The criticality of equipment was defined, in such that critical equipment is a central part of the customer's process and without that anything cannot be done. Semi-critical equipment is part of that process but does not have that big impact on the customer's end-product while not-critical equipment are add-ons which can be replaced rather easily, or the process can work even without them.

The case analysis has showed that all companies which have adopted pay-per-outcome model, are providing equipment which are either critical or semi-critical for the customer's process. Whereas pay-per-output BM is dominant in semi-critical equipment and all the not-critical equipment are provided through this BM. However, there is no clear correlation between the criticality and PPX BM type, albeit the distribution of PPX BM differs depending on the criticality (See Fig. 1).

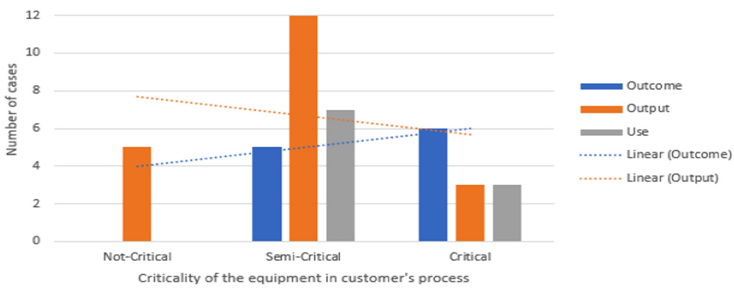

Fig. 1. Distribution of pay-per-x business model types by the equipment criticality.

From the case companies which provide critical equipment majority (8 out of 12) were from material industries. In addition, there were two cases from utility industry and one from moving capital good and one from standalone capital good industry. In contrarily, majority (3 out of 5) not-critical equipment were from office equipment industry. Other two case companies were from utility and standalone capital good industries.

For example, one case company [36] had struggles to utilize outcome-based BM in Cruise & Ferry ship segment. Their equipment, vessel propulsion system, was not critical in that segment and thus the failure of that system would not be major problem. Therefore, the customer was not interested in to invest additional money on that system. However, in Oil & Gas segment it is critical system, and the failure can cause huge losses in production. Thus, the implementation of the pay-per-outcome BM was possible for that segment [36]. This implies that the equipment's criticality has an impact on customer's willingness to invest on it.

Another case company [40] (Original equipment manufacturer) has implemented two PPX BMs in their offerings. The pay-per-use BM was implemented in division A and pay-per-outcome in division B. The product of division B was more complex and more critical part of the customer's process than division's A product. The division B stated that due to being central part of customer's system they need more closer relationship with the customer. The findings of this study show that the pay-per-outcome BM is implement in the companies, who provides more critical product in sense of customer's process.

In addition, one sheet metal processing and one power generator manufacturer [41] have been able to implement pay-per-outcome BM as they have moved from selling just individual equipment toward larger entities for the customers. These cases highlight that the implementation pay-per-outcome BMs became easier as the provider's responsible of customer's process increased. In other words, the criticality of the company's solution within customer's process increased as the proportion it covers of the customer's process increased.

Our analysis shows that pay-per-outcome BM is adopted in industries where equipment criticality is high. Based on these finding we present the following proposition:

Proposition 1: *High criticality of an equipment in customer's process in EMI context can enhance the overall ability to implement pay-per-outcome BMs (compared to other PPX models).*

4.2 Process Knowledge

The companies' knowledge, resources and their systematic management have become a critical success factor in the manufacturing industry [45]. We have analysed cases from the level of process knowledge perspective. Defining the need of process knowledge can be a hard and thus the case companies are divided only for three categories: low, medium, and high (see Fig. 2). High need of process knowledge means that the supplier must understand how the customer's end-product is made and how their equipment effect on it. For example, one equipment of paper machine cannot be sold if the supplier does not understand how it integrates to whole process line. The low need of process knowledge stands for products in which the supplier does not need to know what the customer is producing; such product would be solar panel which is just providing energy but does not have big impact on the end-product of customer's processes.

The Fig. 2 indicates that the pay-per-outcome BMs are more common in equipment where needed level of process knowledge is higher while the pay-per-output BM is contrarily more common in equipment which do not need such high level of process knowledge. For the prevalence of the pay-per-use BM the need for the process knowledge does not seem to have an effect. Majority of the cases (9 out of 11) which have high level of process knowledge have implemented pay-per-outcome BMs.

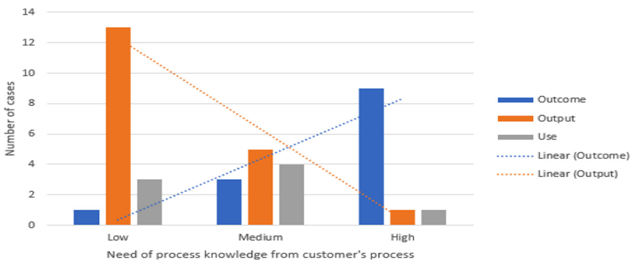

Fig. 2. Distribution of pay-per-x business model types by the need of process knowledge.

Out of the 11 case companies which had high level of process knowledge, six were from material industry. In addition, two from both commercial & professional services and moving capital good industries and one from standalone capital good industry. What comes to companies with low need of process knowledge, the distribution was rather even between moving capital goods (5), utility (5), Commercial & Professional Services (4) and standalone capital goods (3) industries.

The process knowledge such technical skills, experience and product knowledge plays a vital role in implementation of pay-per-outcome BM [36, 38, 42]. As Grubic and Peppard [36] summarize the equipment status cannot always be defined alone from the data, but the process knowledge is needed in order to interpret it, especially when the equipment is complex. With effective analyse of the equipment as part of the customer's process the company can increase its chances to improving the customer's processes and thus allow the company to create additional revenue [36]. Grubic and Peppard [36] has showed that the success of outcome-based BM depends on experts' skills, experience and knowledge rather than the technology. With technology alone, anybody can provide the value, but the process knowledge is the thing which distinguish the company from the competitors [36].

The risk is high in pay-per-outcome BM, where the company's revenue is dependable on the result of its equipment which is used by customer [42]. In some cases, introduced by Visnjic et al. [42] the companies implementing pay-per-outcome BM, have faced huge losses due to failure of meeting promised availability for the equipment. This highlights the vitality of understanding the environment and customer's processes for the companies to avoid promising too much. Paiola and Gebauer [38] showed that especially on the outcome-based BMs the importance of learning from the customers increased. The companies must have in-depth understanding about the customer's activities in order to provide pay-per-outcome BM [38].

In summary there is evidence that the understanding customer's processes plays important role in pay-per-outcome BMs. This leads us to following propositions:

Proposition 2a: *Equipment manufacturer's high level of customer's process knowledge can enhance the overall ability to implement pay-per-outcome BMs (compared to other PPX models).*

As noticed, based on qualitative analysis (Fig. 2), there is negative correlation between pay-per-output BM and need of process knowledge albeit there was no qualitative evidence to support this indication. The reason for lack of discussion about the lower need of process knowledge in pay-per-output BMs might be it has not been the focus of these studies. In addition, when the PPX BMs have been studied as a one, there have not been identified the differences between the PPX BMs. Based on this we can lead another proposition:

Proposition 2b: *Equipment manufacturer's low level of customer's process knowledge can enhance the overall ability to implement pay-per-output BMs (compared to other PPX models).*

4.3 Complexity of Customer's Process and Its Output

Equipment complexity is a key element to understand the interdependencies of production activities [46]. Even though defining the complexity of customer's process and its output is not unambiguous [47] we can make broad distinction between non-complex products and complex entities. Process complexity informally measures the "difficulty" of describing and executing a process.

The case analysis has showed that the adoption level of pay-per-outcome BM is higher among companies which make equipment for more complex processes. In contrarily, the adoption level of pay-per-output BM is higher among companies which make equipment for less complex processes (See Fig. 3).

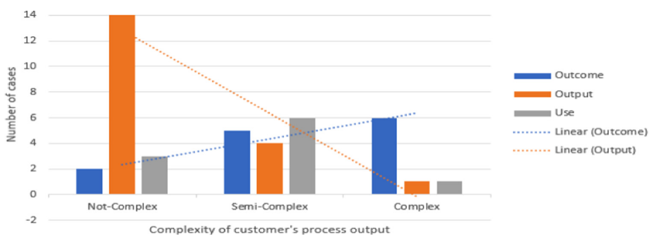

Fig. 3. Distribution of pay-per-x business model types by complexity of customer's process and its output.

The majority (7 out of 8) of companies providing equipment for complex processes were from material industry and only one were from utility industry. The distribution for equipment to not complex processes were following: moving capital goods (7), Commercial & Professional Services (5), utility (4) and standalone capital goods (3) industries.

Yang et al. [43] has showed that a company with right capabilities and resources was actually able to implement both pay-per-use and pay-per-outcome BM. In the pay-per-outcome BM the co-products of the product were monetized, and it was used especially in industrial parks where distribution of co-products was profitable. In similar manner, one case company [40] was able to implement both the pay-per-use and -outcome BM and actually the product itself and its role for the customer was the factor which was guiding the selection of the BM. The simpler and more standardized product was sold using pay-per-output BM while critical, more complex tailormade products were sold using pay-per-outcome BM. [40] Paiola and Gebauer [38] argues that the same requirements of the use-oriented BM stay as the company expands toward outcome-based BMs. A couple cases [41] support this idea by showing how the companies were able to provide pay-per-outcome BM as they expanded their offering from equipment to more complex bigger entities. Based on these results we can lead proposition:

Proposition 3a: *High process complexity in EMI context can enhance the overall ability to implement pay-per-outcome BMs (compared to other PPX models).*

From the quantitative analysis (Fig. 3) we can as well see that the prevalence of pay-per-output have negative correlation with the complexity of customer's process and its output. However, none of the case studies discussed about the low complexity of customer's process and its output in pay-per-outcome BMs and thus there is not qualitative support for this evidence. Yet, it is possible that the focus of these cases studies has been the complexity of PPX BMs in general and thus it has not been discussed that there are differences between the complexity within PPX BMs. Based on this we make another proposition:

Proposition 3b: *Low process complexity can enhance the overall ability to implement pay-per-output BMs (compared to other PPX models).*

5 Discussion

This study aims to address the research question: *What kind of products and more detailed industries' have made use of PPX business models, and how they have been able to do this feasibly?* As an outcome to this, we were expecting to learn more about PPX BM implementation pattern and what conditions favours PPX BMs. We identify three areas where our research contributes, namely "*Equipment criticality*", "*Process knowledge*" and, "P*rocess and its output complexity*" can have an impact on the ability to implement different PPX business models.

5.1 Equipment Criticality Impact the Ability to Implement Different PPX Business Models

The study finds out that equipment criticality has an impact on whether implementation of a pay-per-outcome BM is feasible. If failure of equipment can cause huge losses in production, the service provider can utilise this opportunity to implement a pay-per-outcome BM. In contrarily, if the failure of equipment does not have major influence on customer's processes, it might be difficult to implement a pay-per-outcome model. We can argue that the customer would not see the additional benefit of this model in guaranteeing the availability of the critical process. This was supported by the findings in cases [36, 40, 41].

The pay-per-outcome BM were most common in material industry (7/9) in which the process criticality as well is most common (8/12). In contrarily, in commercial & professional services industry where pay-per-output BM is more common the criticality of product for customer's process was lower as well.

5.2 Equipment Manufacturer's Knowledge of customer's Processes Impact on the Overall Ability to Implement Different PPX Business Models

The equipment manufacturer's process knowledge of the customer's processes found to be an important factor impacting the selection of PPX BMs. With in-depth knowledge of the customer's processes, the supplier is more probable to be able to improve the customer process, which again support the implementation of pay-per-outcome BM. However, great risk is involved in outcome-based BMs, because, if the supplier failed to meet the promised results, they may face huge losses [42]. Thus, it is vital that the supplier understand how the customer process is working before offering pay-per-outcome BM.

If the company want to implement pay-per-outcome BM, it needs to have in-depth understanding about the environment the equipment is running, be able to learn from customer and gaining the knowledge from the customer's activities [38]. The findings suggest that if these conditions are not met, it is more likely that pay-per-output BM is a better option for the company. Even though, sufficient qualitative data was not found to support this statement, it unfolds a future research avenue.

From an industry pattern perspective, we find out that majority of the case companies in the material industry had a high process knowledge of the customer's processes. As the pay-per-outcome BMs are most common in material industry, this support the above statement pay-per-outcome BMs are more feasible for companies which have high level of process knowledge. On the contrary, in the Utility sector, none of the case companies needed a high level of process knowledge. Similar manner, pay-per-output is dominant business model in utility sector.

5.3 Process and Its Output Complexity Impact Ability to Implement PPX Business Models

Process complexity informally measures the "difficulty" of describing and executing a process. Our study has shown that the adoption level of pay-per-outcome BM is higher among companies which make equipment for more complex processes. In contrarily, from the quantitative analysis (Fig. 3) we can see that the adoption level of pay-per-output BM has a negative correlation with the complexity of the customer's process and its output. However, there was no qualitative data support for this evidence which might be due to several reasons, but at least this unfolds an interesting avenue for future research.

We can argue that if the process is more complex (more difficult to operate), the optimization of the result is as well more difficult. Thus, the customer has a higher incentive to pay based on the result if they can't improve the process itself anymore. This indicates that the customer willingness to use the pay-per-outcome BM increase while the complexity of the process increases.

However, it is studied that lack of standardization hamper the implementation of PPX BM. The possible problems can be the limited amount of data, quality of data and lack of contextual information [36]. For example Grubic and Peppard [36] showed an example how based on sole vibration data there could not be seen any problems in the machine even though the problems were evident for the user of the machine who could hear and see the machine. Thus, we can say that even though pay-per-outcome BMs are more common in complex products, complexity alone is not making them feasible for pay-per-outcome BM.

From the industry perspective, the complex processes and outputs were most frequent in the material industry where pay-per-outcome BM were most common. The least complex processes and outputs were in moving capital goods industry, were pay-per-use and pay-per-output BMs were more common as compared to the pay-per-outcome BM.

6 Conclusions and Future Research

By analysing existing 44 EMI-related PPX BM cases, we were first able to identify three important concepts that showed interesting distinctive both qualitative and quantitative patterns in the EMI companies' exploitation of different types of PPX BMs: *1) criticality of product for customer's process, 2) suppliers' customer process knowledge and 3) complexity of the process and its output.* Based on these concepts and identified patterns, we devised propositions concerning different PPX BM types in EMI context.

Through these propositions and their analyses, we were able to create fully new academic understanding that contributes to the existing PPX literature by partially providing new understanding about PPX BM suitability in EMI context and related individual more detailed industries, but also by providing more depth to existing EMI-related PPX studies through detailed case examples regarding especially the three above concepts, and partially also by confirming earlier more preliminary findings about PPX use and overall PPX feasibility in the challenging EMI context.

We have not been able to find any other PPX studies in EMI context with similar findings. Regarding the existing PPX research, some earlier studies [8, 9] have reported e.g. some overall patterns regarding PPX use and overall feasibility in broader manufacturing context and some even more particularly in EMI context, but they do not report exactly same type of findings, and none of them have made use of systematic literature review of the broad pool of PPX cases studies. Thus, there is novelty also in respect to the exact context as well as the methodology and related analysis of existing EMI PPX cases.

Previous studies [8] have identified that the PPX BMs are typical in the context of a capital-intensive, complex engineering product, with a long life cycle, where a product requires a considerable effort to maintain but have not made distinction between different

PPX business model types. In addition, it is studied [9] that two environmental factors affects the feasibility of different PPX BM, namely product innovativeness and technological turbulence. However, the study suggested that other affecting characteristics should be studied as well.

These findings have both academic and managerial value. This study helps to extend our knowledge about some fundamental differences between different types of PPX BMs and why some EMI industries are more prone to make use of specific PPX BM types. The study also highlights the need for studying different PPX models independently, as separate type of BMs, albeit many current studies tend to study PPX models as a larger category of similar BMs. From managerial perspective this study helps to understand which PPX BM would be the best fit for specific type of products. The study showed that if the equipment and its output are rather simple, not critical or the company does possess in-depth understanding of customers processes and have expertise how to improve it, then more feasible PPX BM would be pay-per-use or pay-per-output. Our findings will be helpful to especially EMI companies of different types of industries, as well as their responsible business managers, which have been relatively little studied so far regarding PPX model design and implementation.

Some limitations of this paper are related to the collected data and the used literature review and its analysis method. Inherently, the identified existing case studies from the literature do not yet fully represent the EMI context and potential EMI PPX BMs necessarily, and they do not focus on the case companies' products in such a depth that would have been needed in order to understand the characteristic features of the case companies or their industries. Thus, as for the future research, the results should be validated with an empirical study with larger set of companies, or companies from specific EMI industries, which would focus solely on the found patterns of PPX BMs in EMI context. In this study, the underlying reasons why some companies are more prone to specific types of PPX BMs could be studied as well. Furthermore, in our study, so far only three concepts which impact the selection of PPX BM could be identified from these cases in sufficient depth. Therefore, future studies should focus on other factors like standardization level of EMI products and more detailed types of EMI products' output. Third, interesting topic of the future study could be whether it's always feasible to advance from a pay-per-use BM toward result-oriented BMs.

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Building Bridges: Development of a Redlining Interface Between VR and PDM

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Abstract. Virtual Reality (VR) has been used mainly as a complementary tool in the product development process for the depiction and evaluation of visual product features. Typical use cases are design review or assembly assessment. VR systems are usually used separately as stand-alone systems. Geometry data must be manually converted into viewable formats. If changes are necessary, the results are usually fed back to product developers in text-based reports or via screenshots with mark-ups. The objective of this approach is to achieve a continuous integration of these VR reviews into the product data management (PDM), which represents the core of the product development process. For this purpose, a VR redlining tool with a bidirectional connection to a PDM system was developed. This tool is able to automatically convert and show geometry data from the PDM database. In addition, properties such as part name, status or weight of the assembly components can be shown in VR based on connected PDM attributes. Redlinings created in VR, consisting of mark-up elements and voice-activated text fields, can then be transferred to the PDM system and processed in the internal viewer. Two methods have been developed for this purpose. One utilizes a 2D plane to position the redlining elements. The other allows them to be positioned freely including a camera to set the perspective. The research shows that an increased digitalization in the review process for product developers can be achieved between VR and PDM. However, further empirical studies comparing the different working methods are necessary.

Keywords: Product lifecycle management · Redlining · Virtual reality

1 Viewing and Redlining in the Product Development Process

One of the most important properties of project data is the visibility and availability of this data for everyone involved in the process [1]. This also applies accordingly to data generated during product development. Access to product data is greatly simplified by PDM software in the product development process. The use of PDM software provides targeted access to product data for people involved in the development process by applying role and rights management. However, there are additional challenges for geometry

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data or 3D models. They are often stored in a wide range of formats, viewing and editing them basically requires the associated authoring software. While product developers are able to work with and have access to the appropriate authoring tools on a daily basis as part of computer-aided design, problems arise for other areas involved in the product development process, such as testing centers, manufacturing, marketing or sales. These departments usually do not have access to CAD software [2] due to high licensing and training costs. Accordingly, an application exclusively used for displaying purposes is not economically viable and even a disadvantage for these departments [2]. However, all people involved in the product development process should have access to the required models at their own workstations [1].

The use of specialized viewers is an alternative solution. They are based on a neutral data format and primarily used to display 3D models; changes to the displayed documents are not possible [2]. Many viewers have tools for manipulating the 3D models, such as rotating, measuring, section view, comparing between multiple 3D models, or disassembling and assembling components [3]. However, the fact that viewed models cannot be changed might sometimes be an undesirable circumstance. Especially when checking geometry, it is useful to include results of these checks as comments on necessary changes and marking of areas called redlinings. Therefore, viewers often have tools, which allow annotations to be attached as texts or graphics [2]. These viewers are called markup viewing software or redlining software. Even though these operations seemingly modify the original model, its data is not changed. Instead, the created information is stored separately on a different layer that can be deleted at any time. Alternatively, separate files containing the redlining data only can be created in addition to the model data [2]. The actual use of redlining is still characterized by severe technical difficulties. Nowadays, in addition to independent viewing and redlining software, simple screenshots are used as well. Some users add information through drawing programs or presentation software and send them via e-mail afterwards.

Consequently, linking viewing and redlining software with PDM systems is beneficial for multiple reasons. Firstly, stand-alone software can be omitted if the PDM system has its own viewing and redlining components. Secondly, a PDM software with integrated redlining capabilities can start further actions as part of the workflow automation. Workflow processes outside PDM systems can therefore be avoided. For this reason, redlining functions are often listed as service functions of PDM systems [2] and are considered to be important components of them [3]. Accordingly, numerous PDM software solutions have their own viewers.

The situation is different when using immersive virtual reality (VR). In VR, the user has the opportunity to influence or change the virtual environment (interaction). Via stimulating the user's senses, they are immersed in the environment (immersion). How well the virtual environment works depends largely on the user's imaginative power (imagination) [4]. Head mounted displays (HMDs) and CAVE systems (projection-based VR environments) are classified as such immersive VR systems [5].

VR technology is already used in various fields of application in product development. The use of VR is mainly limited to the depiction and evaluation of visual product properties [6]. These are individual and isolated applications; a comprehensive or even cross-industry use of VR has not yet taken place. In some industries such as the automotive sector, VR has already been used for a long time. Typical applications for VR in product development are:

- Product presentation in the customer environment [7] and marketing [8],
- Design-Review processes [5, 9],
- Evaluation of design alternatives [10],
- Education and training of maintenance staff [8, 11],
- Visibility studies [9],
- Ergonomics studies [9, 10],
- Assembly and installation studies [10, 12],
- Visualizations of Finite Element Method and Computational Fluid Dynamics calculations [9, 10],
- Comparison of variants [10].

Very similar fields of application can be found in industrial manufacturing or in the digital factory [13]. It can be seen that the application fields of VR largely overlap with the application fields of classic viewers and redlining software. Design reviews are the most prominent application area for redlining. The design review is defined as a target/actual comparison at certain milestones of the product creation process. In a team and in the presence of higher management staff, the properties of the product are compared with its requirements. If those are met, the product is released for further process steps. The design review is also used between the milestones for internal releases [14]. The choice of VR as a form of presentation for design reviews and comparable areas of application can be justified by the high degree of immersion. Dimensions and shapes can be validated more accurately by the true-to-scale depiction in VR than with desktop viewers [15].

2 Research Approach and Requirements for Solutions

Despite the use of VR within some redlining applications, there has been no integration of VR into PDM systems to date, which is usually common for desktop viewers with redlining functions. Accordingly, there is a media disruption in the workflow. Annotations can only be summarized in text-based reports and, if necessary, enriched with screenshots. Such an externalization of work processes result in a higher probability for errors due to the existing interfaces. The exclusion from further processing in PDM systems and the loss for later reference could be the consequence.

The target of the presented approach is to investigate how VR redlining can be integrated profoundly into the PDM structure in order to avoid externalization of work processes and to achieve an increased information consistency in the product development process. The importance of such considerations is increasing due to the technological developments of the last 5 years, such as enhanced computing power and developments in the pixel density of displays. In theory, these developments make it possible to deploy low-cost VR HMD systems at any workstation. Extensive investments, such as in CAVE systems, are no longer required by companies in order to utilize the technology of immersive VR.

To achieve this objective, requirements for a PDM-VR coupling in the application area of redlining can be derived. VR systems usually work with data formats that do not correspond to the data formats commonly used in CAD. In order to ensure an unrestricted workflow, it is necessary to provide an automated conversion into VR-capable data formats within PDM systems. Furthermore, it must be ensured that redlinings generated in a VR environment can be transferred back into the PDM environment. This crucial step enables further processing in workflows within PDM. Although this requirement appears to be trivial, it is associated with diverse challenges. Saving VR redlining results exclusively in PDM systems is accordingly classified as insufficient. This would require everyone involved to have a VR system at their workstation in order to view the annotations that have been made. The problems of authoring systems described at the beginning would also apply here, further complicated by the hardware requirements. Such an approach is therefore not viable. Consequently, it must be ensured that redlinings created in VR are stored in a desktop-compatible manner. The creation of screenshots or the conversion into redlining for desktop viewers are possible approaches.

3 The VR Redlining Tool

Based on these requirements, a VR redlining tool was developed as a demonstrator with a bidirectional interface to the PDM software (see Fig. 1). Initially, the technical structure of the VR environment and the functionality will be described from the user's point of view. The implementation of two approaches for redlining will be dis-cussed separately.

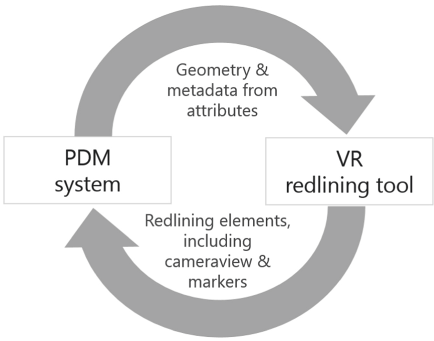

Fig. 1. Bidirectional interface between PDM and VR

3.1 Technical Design

The VR environment is based on the development environment Unity, which is widely used for commercial graphics and VR applications in the gaming industry. The commercially available HMD system "HTC Vive" has been utilized as VR hardware. This device offers a tracking system, which is able to detect the position of the HMD in a 3 by

4 m grid. Additionally, the system includes several controllers that provide the required interactive capabilities with the VR environment for redlining.

CIM Database 15.4 from Contact Software GmbH was used as the preferred PDM system. In addition to the usual functions of PDM systems, this solution also includes an internal viewer with redlining functions. Therefore, it is possible to integrate the VR redlining into the workflow application.

3.2 Functional Design and Mode of Operation

The structure of the VR redlining tool was designed to provide a complete user experience and to create an independent workflow. This user experience starts and ends accordingly in the PDM system CIM Database. All intermediate steps occur in the VR redlining environment. The entire user experience can be divided into the following work steps:

1. Preparatory measures
2. Analysis of the product or assembly
3. Creation of redlinings
4. Editing and saving progress locally
5. Uploading VR redlinings into the PDM system
6. Triggering further workflows in the PDM system

Preparatory Measures. If a user decides to work with the VR redlining environment, the PDM system is capable to provide all the required data for use in the VR environment locally. This mainly includes the CAD geometry, which is automatically converted into a VR-compatible format via the PDM system. This VR redlining environment uses the FBX format, in order to preserve the geometry as well as the assembly structure for the use in VR. Not only the geometry but also additional meta-data is transferred from the PDM system to the VR environment in this demonstrator. This includes the part numbers of the assembly or component to be viewed, as well as the part numbers of all existing subassemblies. This data is retrieved to enable distinctive identification of the geometry being viewed and the part numbers are also used to enable targeted data transfers in later process steps.

Analysis of the Product or Assembly. After the preparatory tasks have been carried out, the user can start to work in the VR application using an HMD. To analyze the product or assembly, the user is provided with common tools for viewers. These include the capabilities to move the object via translational and rotational movement, scale it or measure distances. In addition, a metadata display has been integrated that enables the user to retrieve attribute values for individual parts from the PDM system within the VR environment. When the user touches a component of the product or assembly with a controller, it will be highlighted and selected attributes such as designation, status, material, editor or weight will be displayed for this component. Figure 2 shows an example of the display presenting attribute values out of the PDM system. As soon as the VR application is started, the data is retrieved from the PDM system based on part numbers of the chosen assemblies. This enables an up-to-date status of the attribute values, even if the download of the geometry into the VR environment was performed a few days or weeks ago.

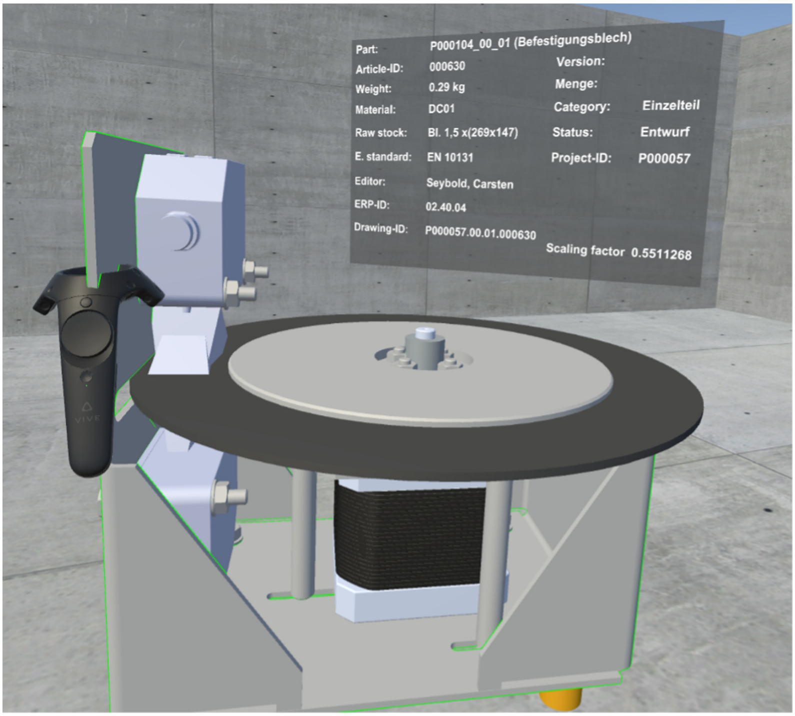

Fig. 2. Display of metadata in VR from the PDM system CIM Database for individual components by touching them with the controller (green edge highlight). (Color figure online)

Creation of Redlinings. In order to highlight identified issues or to provide a request for clarification about aspects of the model, it is possible to create redlining elements within the VR environment. The environment basically provides marking circles and rectangles to high-light areas of interest. In addition, the user has the option to create annotations on panels, which can be positioned according to the needs of the user. The creation of the annotations is based on a speech-to-text approach, without breaking the immersion by removing the HMD. An example for these functionalities can be seen in Fig. 3 as well as the prospective final result within the PDM environment. In order to implement a desktop-compatible storage format for VR redlinings as described at the beginning, two different approaches were implemented to create said redlinings. These will be explained in more detail after the general functionality of the VR environment is introduced.

Editing and Saving Progress Locally. Users are able to save and load their work progress locally on the client. Accordingly, work can be carried out at different times. All manipulations to the VR environment, such as the position and orientation of the object, measurements and redlining elements, are stored. If changes occur during editing, the positions of redlining elements can be changed or deleted.

Fig. 3. VR redlining during creation and depiction in the PDM system CIM Database

Upload VR Redlinings into the PDM System. After the completion of the VR redlining process, the user can click a button to transfer the created redlining to the PDM system. However, the redlining objects themselves are not transferred, only a configuration file is transferred to the PDM software. The VR redlining results in a group of objects in

3D space. Since the PDM redlining is basically a 2D picture of a 3D model with lines and shapes on top, it is necessary to convert the VR results into a PDM compatible format. For example, the rectangle is converted into 2 sets of 3D coordinates for its top left and bottom right corners. The configuration file is then used to automatically generate the redlining elements in the PDM system based on the internal class structure. The PDM system then creates a new rectangle based on the given data. Accordingly, geometry or graphics are not transferred. This reduces the amount of data, which has to be uploaded and the redlinings remain interchangeable in the PDM system.

Triggering Further Workflows in PDM. The remaining steps have to be done on a desktop workstation. At this point it is possible to access the VR redlinings via the internal PDM viewer and to edit them if necessary. The user will be able to trigger the regular workflows in the company via the PDM system and initiate further processing. Figure 3 shows a comparison of a redlining during creation in VR and the corresponding depiction in the PDM system CIM Database after the transfer.

The presented user experience shows that an integration of VR redlining into existing redlining structures is feasible. In order to achieve this, the strategic approach of how VR is used has to be adapted accordingly. The two approaches of redlining generation implemented here will now be briefly presented.

3.3 Differences Between Conventional and Immersive Redlining in VR

The creation of redlinings, possible in stand-alone viewers or in PDM-internal viewers, usually generates a two-dimensional picture of the object of interest. During the analysis phase, the geometry is freely movable in space for the user, but if the user decides to place annotations or other redlining elements, the perspective is fixed relative to the object of interest. The user's viewpoint is thus a fundamental part of the entire redlining process. Redlining elements are created perpendicular to the user's view on one or more planes between the 3D object and the user's viewpoint. Figure 4 shows the schematic structure of conventional redlinings. Besides the spatial coordinates of the redlining elements, the coordinates of the virtual viewpoint, its field of view and other factors have to be stored.

Creating a graphical screenshot of the view is the easiest way to avoid having to save coordinates of the point view. The redlining elements are then placed on the image. However, such a storage of redlinings does not allow any subsequent changes and is thus not considered any further.

When using an immersive VR environment, the creation process for redlinings can be fundamentally different. For instance, when using HMDs, the field of view within VR is controlled by the user's position and perspective. In order to avoid issues such as motion sickness the orientation of the viewpoint is not restricted. The perspective of the redlining can therefore not be determined by the users point of view alone. Theoretically, it would be possible for the user to position redlining objects and the point of view freely. However, it must be ensured that the redlining objects are perpendicular to the chosen perspective and are not obscured by other objects such as parts of the geometry. Accordingly, two different approaches were developed, which allow the free positioning of redlining objects and still enable interchangeability with desktop viewers.

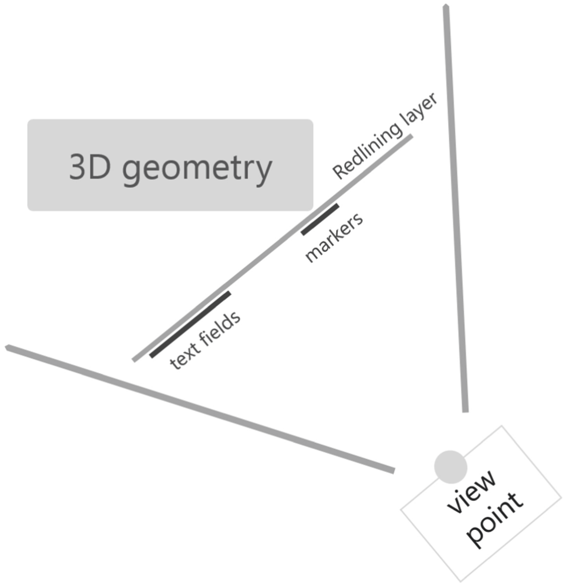

Fig. 4. Schematic structure of conventional redlining

Approach 1: The Camera - Projection Screen Principle. The camera - projection screen principle allows the user to position the redlining objects freely in space in the form of marking rectangles, marking circles and annotation fields. In addition, the user is provided with a schematized camera object in the virtual environment. This camera represents the point of view for the redlining. In order to check the perspective, the VR environment has a screen that represents a preview from the point of view of the virtual camera. The virtual camera can be freely positioned by the user, and the preview is displayed in real time. In addition, when the position and orientation of the camera changes, the redlining objects are also realigned in real time. Accordingly, these objects always remain perpendicular to the viewing direction of the camera and upright to the camera orientation. Figure 5 shows the first approach and names some elements of the environment.

Approach 2: The 2D Redlining Panel. In this approach, a two-dimensional auxiliary plane is used to create the redlining objects. The user can freely position this semi-transparent plane in the VR environment. Redlining objects such as markers and annotation objects can only be created on this plane. It is possible to subsequently change the position and orientation of the plane including the generated redlining objects. In order to determine the later point of view for the redlining, the auxiliary plane has a semi-transparent schematic image of a virtual camera. The final perspective of the redlining is determined by the virtual camera. The result can be previewed if the user aligns the perspective of the HDM with the virtual camera. Figure 6 shows the structure of the second approach.

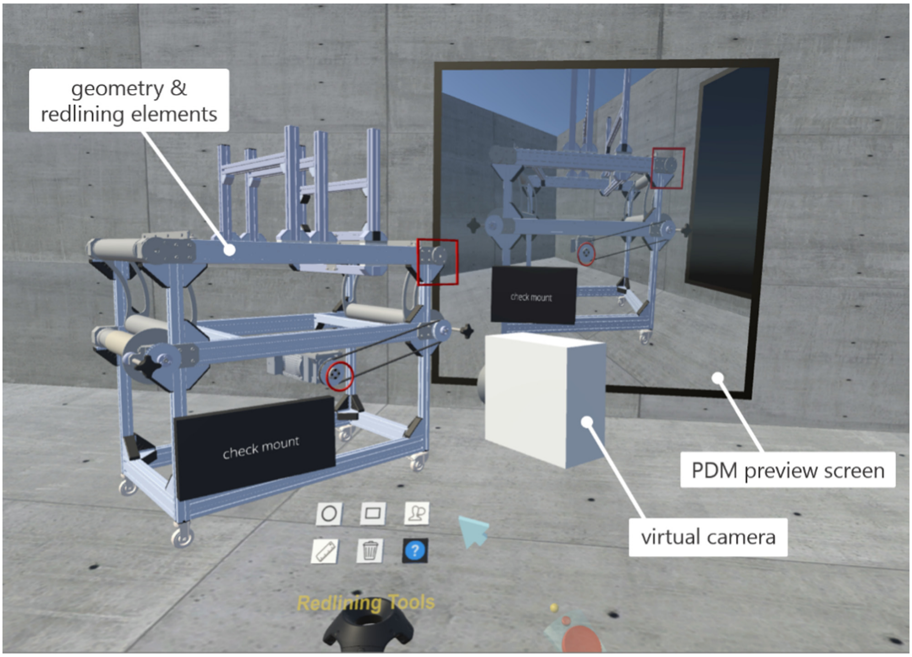

Fig. 5. Redlining approach 1: *camera-projection screen principle* – redlining elements arranged freely in space, user menu in front of the view

3.4 Critical Comparison of the Approaches

Many differences can be found by comparing the two approaches. By working with multiple participants and using several data sets different advantages and disadvantages of the respective approaches could be determined.

Approach 1 offers the user a greater degree of freedom in the positioning of redlining objects. However, there is still the possibility that redlining elements can be obscured by other objects. Approach 2 does not have this issue. However, to get a preview has proven to be difficult and error-prone. Manual positioning of the HMD by the user at the exact point of view is difficult. A deviation in the perspective of a few centimeters or degrees can lead to a very different expectation of how the redlining will look like.

In conclusion, both methods are suitable for creating redlinings even without special prior knowledge. To minimize the training effort in a practical application, a combination of both approaches would be the best solution. This would work like the second approach but it includes the virtual screen of the first one in order to simplify the preview process.

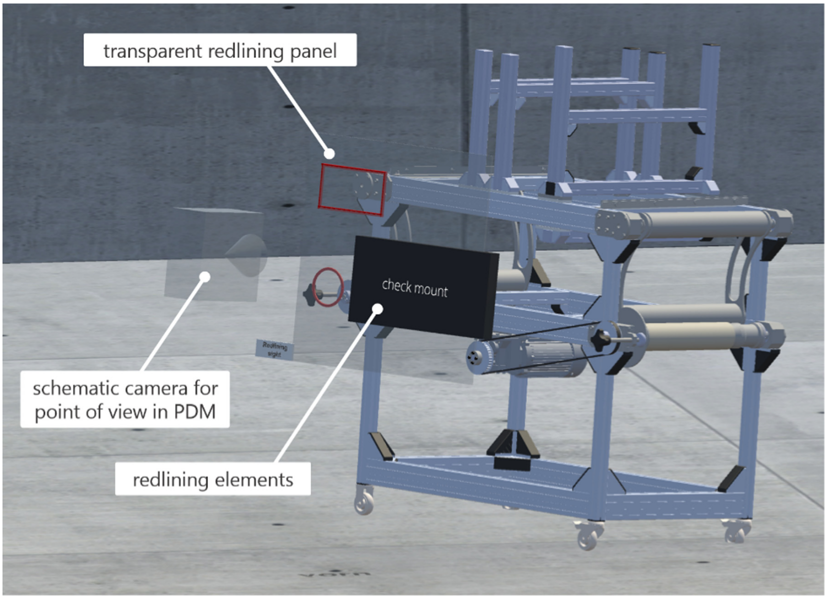

Fig. 6. Redlining approach 2: *2D Redlining panel* – Redlining elements can only be arranged on this panel

4 Conclusion and Approach for 3D Redlining

The discussed approach has shown that it is possible to generate redlinings in VR in a manner that enables their integration into an existing workflow and their assessments in conventional viewers. In principle, redlinings generated in conventional viewers are limited to one perspective. This is also the case for VR redlinings, which can be created according to the approaches described above. A fixed perspective can only convey information that is visible from its point of view. If the user wants to create a redlining for a spatial problem a single redlining might no longer be sufficient. Therefore, multiple redlinings have to be created. The perspectives should be chosen in such a way that ambiguities for markings in redlinings are avoided. Nevertheless, all relevant areas must be covered. This is even more difficult if the redlining is supposed to cover a three-dimensional space.

3D redlinings can provide a solution if they are not limited to one perspective. This would require that the user is able to place spheres of interest and annotations and still allow a free three-dimensional view of the geometry.

There are numerous possibilities to accomplish this. Markings of corresponding areas can be achieved for example by creating semi-transparent spheres or rectangles. The utilization of contour marking for components is also conceivable. Annotation fields can be provided with an anchor point, which establishes a relative position to the geometry while positioning all annotations in a circle around the object. The circle would have to always face the user. This way, the annotations are not influenced negatively if the perspective changes. Figure 7 shows an example of such a 3D redlining.

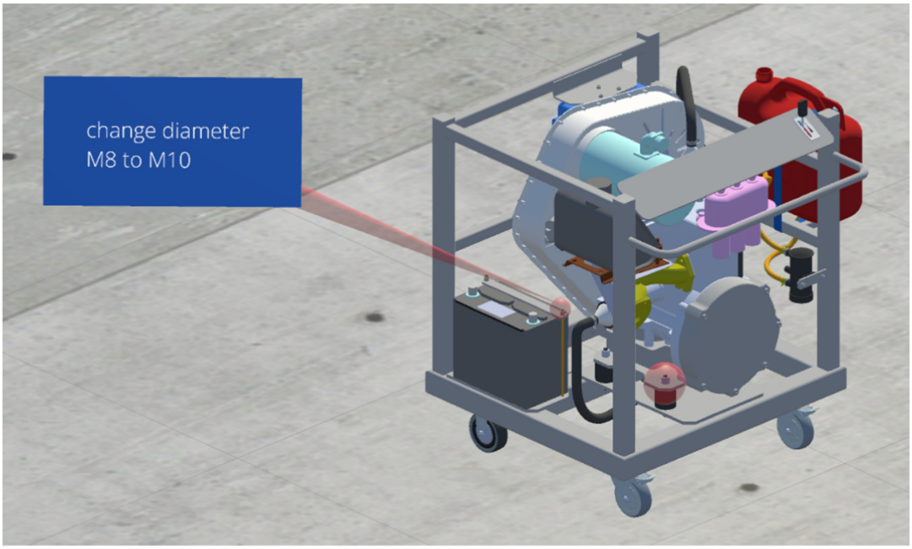

Fig. 7. Prototype for a 3D redlining in VR enabling a change of perspective using transparent spheres and view following comments

However, the creation of 3D redlining requires appropriate authoring software. The implementation in desktop applications is likely to be associated with an increased training effort for the user in terms of how to operate the application and how to create redlinings. These increased expenses have to be compared to the increased quality that a 3D redlining can provide.

Due to the high immersion and intuitive controls as well as an object which is true to scale, VR environments appear to be a suitable tool for the creation of 3D redlinings. This might lead to slightly higher costs due to the need to acquire VR hardware. However, these could be justified as part of a frontloading strategy [14, 16]: According to the rule of 10 every mistake found and fixed early is worth a lot of time and in the end money.

5 Summary and Outlook

This paper presented an interface between PDM and VR redlining. The objective of the approach presented here was to achieve increased consistency in the following workflow when using immersive VR and to prevent media disruptions in redlining processes. Characteristics of desktop-based redlining systems were presented, and key aspects of using VR technology in the area of product development were highlighted. A demonstrator was developed, which allows the creation of redlinings in two different ways, which can be further processed and translated for desktop-bound viewers. Core features of the developed VR redlining environment are:

- the automated conversion into a VR-capable format from the PDM system,
- the retrieval of attribute values of parts of the assembly from the PDM system and
- the transfer of VR redlinings to the PDM system.

The demonstrator shows that a continuous workflow can be achieved by using VR for redlining. In addition, a 3D redlining approach was presented that makes it possible to alleviate the limitations of conventional redlining structures. However, the benefits of a 3D redlining compared to a conventional redlining need to be evaluated in further research. Additionally, further research is necessary to discuss how a more general approach could be implemented in order increase the compatibility with other PDM and VR systems. This will require a standardized model, which has to define how VR, the product and its redlinings are to be connected, and which information has to be transferred.

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Maturity Models and Cost Justification for PLM: A Case Study in the Plant Engineering Industry

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Abstract. In recent years, there has been a noticeable trend towards a general contractor strategy for plant engineering companies. Multiple disciplines and departments must be administered in a joint project. In the process, different work results are often managed in various systems without any associative relationship. A possible way to address this complexity is to implement a specifically tailored PLM strategy to gain a competitive advantage. Maturity models as well as methods to evaluate possible benefits constitute increasingly applied tools during this journey. Both methods have been theoretically described in previous publications. However, this paper should provide insights in the practical application within machinery industry. Therefore, a medium-sized German plant engineering company serves as an example for determining the scope and value of a multi-national overarching Product Lifecycle Management architecture as the central piece of a future digitalization strategy. The company's current maturity levels for several digitalization capabilities are evaluated, prioritized and benchmarked against a set of similar companies. This allows to derive suitable target states in terms of maturity levels as well as the technical specification of digitalization use cases. In order to provide profound data for cost justification the resulting benefits are quantified.

Keywords: Product lifecycle management · Maturity model · Cost justification · Product configuration · Layout and visualization · BOM management

1 Introduction

Plant engineering companies face big challenges: difficult market environments in a global economy that is volatile, uncertain, complex, and ambiguous (VUCA), China is becoming a cost leader and pushing for more sophisticated plant engineering solutions through massive R&D investment, as well as new dramatically emerging trends towards

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a general contractor strategy. In order to systematically manage all accruing product related information and to support engineering processes throughout the lifecycle the concept of product lifecycle management (PLM) raised [1].

PLM could help plant engineering companies to address these challenges and stay competitive. In order to design future PLM architectures maturity models and methods to prepare a cost justification analysis represent proven means [2, 3]. First, we will discuss the trends and requirements in the plant engineering industry and report our approach of how we applied the maturity model to identify relevant use cases as well as their financial benefits to encounter those trends. We validate our approach with support of two companies in the plant engineering industry to provide insights on practical application. Within the scope of this we evaluate, prioritize and benchmark companies' current maturity levels for various digitalization capabilities and derive appropriate goals. The last section describes how to determine the scope and value of a multi-national overarching Product Lifecycle Management architecture as the central piece of a future digitalization strategy.

2 State of the Art and Trends for Plant Engineering Companies

Plant Engineering companies may benefit from following emerging trends regarding their customer requirements. As shown in Fig. 1, the German Engineering Federation (VDMA) and PwC report that from the plant operator's point of view, the five most important requirements regarding a plant are "*Transparency*", "*High production flexibility*", "*Shorter lead times*", "*Optimized investment costs*" and "*Trust-based relationships*" [4]. The study emphasizes that to be successful, business models need to meet customer needs and that digitalization helps to meet these requirements in a novel way.

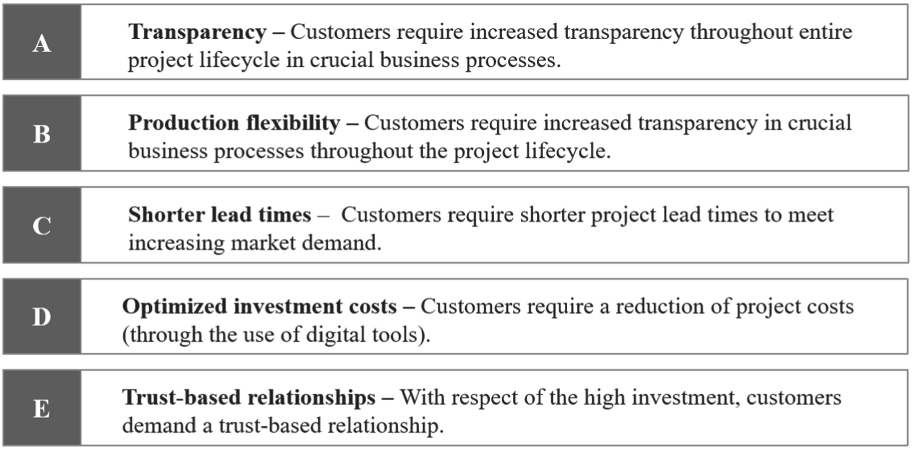

Fig. 1. The five most relevant plant operators requirements in 2025 [4]

Moreover, PwC/VDMA [4] highlight the trend towards providing individual customer advice, with individualized solutions for each customer. A quantitative analysis revealed that globally Engineering Procurement and Construction (EPC) firms are convinced that the turnkey solutions contract model will play a top priority in the future and many plant engineering companies aim to realize a general contractor business model. Turnkey solutions projects have shown a need for improvement in these ways:

- lack of transparency during project initiation and execution with limited information provided by the contractor.
- scoping processes at the project development and tender stage takes too long, especially in lump-sum turnkey projects.

The manufacturing industry is driven by technology advances and emerging trends such as artificial intelligence and machine learning, machines as connected fleets, and increasing involvement of the customer into the manufacturing process [5]. These trends will lead to changes in employment and working conditions [6]. As shown in Fig. 2, Dispan mentions that new technologies such as additive manufacturing and PLM systems play major roles in collaboration between various disciplines.

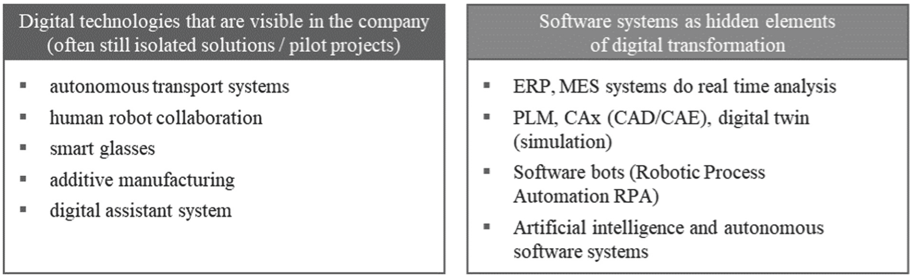

Fig. 2. Digitization of internal processes in mechanical engineering [6]

According to Wyman [7] "Digitization of plant-engineering processes will provide a third level of efficiency, with building information modeling (BIM) the key driver". Companies will need to build end-to-end integrated processes that match the requirements of BIM as well as PLM and adjust IT systems accordingly [8]. This will improve design-to-construction, design-to-procure and the reuse of equipment in a modularized plant and product configuration. Companies will see both reductions in product costs and lead time of more than 10% [7].

Addressing these trends, we conducted workshops with two plant engineering companies. We used a maturity model to see how they compared with other companies in the same industry.

3 Application of Maturity Models for PLM

3.1 The Maturity Model

In order to determine maturity levels of an organization, a reference model is needed that allows the classification of capabilities in selected competence fields. We used a maturity model [3] which has been applied more than 200 times in the last four years in Europe and the US.

At the center of the model are 50 capabilities, which in turn are divided into 5 knowledge domains. These describe operational skills and competences of the organization in the fields of product/plant planning (e.g. ideation management, requirements management, etc.), definition of assets (e.g. plant structure & configuration management, product costing, etc.), verification steps (e.g. visualization, simulation, virtual commissioning, etc.), manufacturing/production of equipment (e.g. derivation of manufacturing structures, definition of production processes, production execution, etc.), as well as the operation of plants (e.g. service tasks, plant monitoring, plant safety, etc.) (Fig. 3).

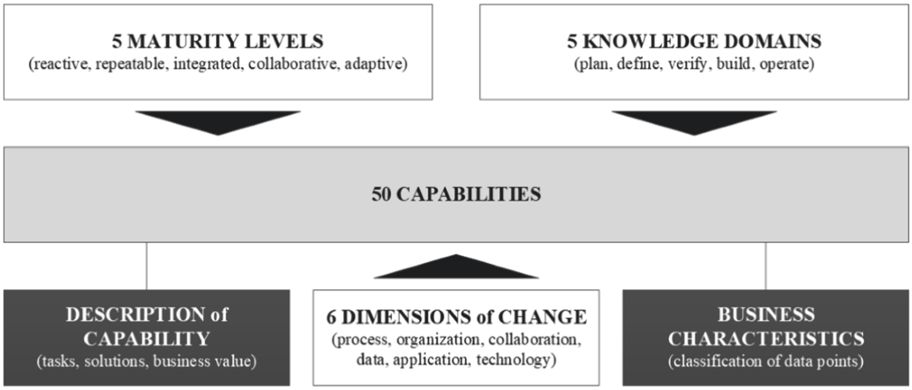

Fig. 3. Elements of the maturity model

The model works with 5 maturity levels. Level "reactive" corresponds to a minimal control of data and processes. With level "repeatable" the organization is gaining control of product content and processes. Level "integrated" describes elevation to enterprise Product Lifecycle Management skills. Level "collaborative" indicates demand driven value network product lifecycle management, with a robust horizontal and vertical integration of processes and data managed. Level "adaptive" is characterized by the agility for rapid response to market and technical changes. It also is empowered by leveraging disruptive technologies to enable new ways of collaboration and data exchange. Each capability is additionally viewed from 6 dimensions (process, organization, collaboration, data, applications, technology). This differentiation provides deep insights into the necessary improvements and is the basis for planning the transformation processes.

3.2 Application of the Model

The model is a building block of the consulting approach (Fig. 4) and needs accompanying activities to fully unfold its added value. We began by getting a solid overview of the company under consideration. We reviewed the company's history, examined the product and service portfolio, and determined the company's organizational structure and processes, as well as its financial status.

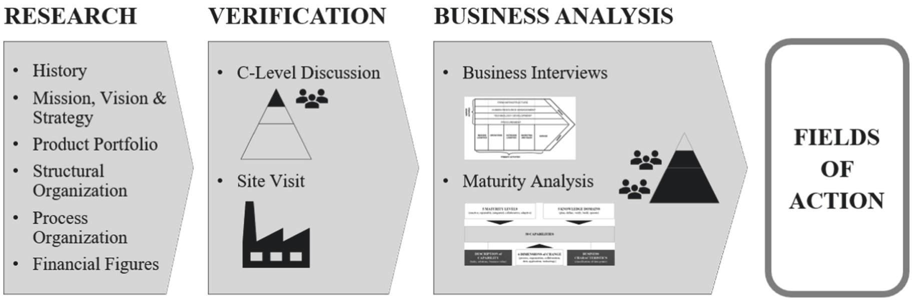

Fig. 4. Elements of the consulting approach

In a second step, the findings were verified in dialog with management. We learned about business strategy of the company as well as the current challenges on the market and ongoing initiatives from a C-level perspective. An inspection of the sites to be considered, in particular regarding production and logistics, completed the picture.

With the preliminary work done, we considered the business units by gathering 2–3 specialists from each area, some managers and some subject matter experts.

Individual workshop helped find out the organizational structure of the area under consideration and the roles of the employees. We identified processes with their inputs and outputs. If a process re-design was planned, appropriate methods were applied (e.g. brown paper analysis). Also, we asked about IT/OT tools, relevant base technologies, as well as internal and external collaboration.

Discussions also concerned current initiatives to optimize workflows, integrate new technologies, as well as known weaknesses. We ended up with a comprehensive understanding of the departments' functions and challenges, plus relationships among the departments. The aim was not only to present problems, but rather to get to the bottom of route causes and immediate effects (e.g. costs, quality, etc.).

The execution of the maturity analysis was the final step in the inventory and did built on the knowledge acquired in advance. In preparation for the maturity workshop, the capabilities to be considered have been preselected, as not all 50 capabilities are usually in focus. The scope could be derived very well from the knowledge gained in the interviews.

In contrast to the interview phase, the maturity analysis did not take place separately with the individual departments but was carried out in one run with all participants of the processes to be considered. Each capability was considered individually and discussed in the team. This procedure created a common understanding of the challenges and participants did find a consensus on an assessment of maturity of the individual subject areas.

In each case, the joint assessment of the current status and the level of maturity to be aimed for in the medium term were discussed. In addition, the business relevance (prioritization) of each capability was questioned. In order to arrive at usable statements, the workshop participants were called upon to decide for each capability whether it directly supports a core competency of the company, supports direct value creation, or was perceived as a support function [3].

With the conclusion of the maturity workshop, the data collection was complete. The insights gained made it possible to derive the relevant fields of action from the mix of business goals, identified weaknesses, and maturity levels to be achieved in individual capabilities. As a supplementary element, a benchmarking option came into play, which presented the company with its own position in comparison to other market participants.

3.3 Benchmarking

In order for the model with its collected market data to be used for benchmarks, each company under consideration was classified according to a uniform pattern [3]. To ensure this, the model offers a set of standard characteristics (e.g., business strategy, industry, company size, target markets, etc.) which make it possible to take a fingerprint of the respective company characteristics. This classification comes into play when we aim at drawing meaningful data points for comparison with market peers.

The benchmark is therefore based on a comparison of the companies' own perceptions. The top 20% of the peer group are shown as best-in-class. The middle 50% are shown as the industry average. The laggards are the bottom 30% of the comparison data base. This comparative view of the company's competencies is, in addition to the company's own assessment, an important indicator of its position in the market.

A complementary benchmarking option is the comparison of several locations of a company. In our specific case study, the customer used the maturity model to comparatively evaluate several European competence centers and production sites. Thus, the maturity workshop was conducted separately for each plant, resulting in a meaningful comparison. The findings were on the one hand the formal confirmation of a daring gut feeling, but also significantly helped to cast the necessary improvement measures into a meaningful deployment strategy.

3.4 Outcome

One of the companies considered in this case study has a global market share in the logistics industry (warehouse erection and automation). The comprehensive consulting for the European subsidiaries revealed necessary improvement potentials in the following capabilities.

Requirements Management: The planning process of larger warehouses offered by the company as a general contractor can take up to 2 years. At the end of the sales process, layouts of the plant and the service specifications derived from them are finalized. It became apparent that the various trades (steel construction, mechanical engineering, automation) do not have a transparent view of the contract sections relevant to them and the associated acceptance criteria, neither in the engineering phase, nor in the production phase, nor in the commissioning phase. The tracking of changes to the scope of delivery and their effects on the individual delivery items is also very time consuming and is handled by a large number of project managers. Here, integrated data models on a common PLM platform can create a high degree of transparency.

Asset structure management (later referred to as OBOM): Involvement of different competence centers without common data management for technical aspects and commercial processes prevents creating a common asset structure. Work of companies of different trades are finally brought together during commissioning, which requires tedious coordination and leads to costly errors. A common plant structure could provide transparency on the progress of work among different trades. This would make it easier for engineers from all disciplines to obtain current information about project progress.

Project Management: Another significant benefit for plant engineering lies in the consistent representation of the 4th dimension, time. As in shipbuilding, the successful construction of large-scale plants depends on the efficient and well-thought-out chronological sequence of development, production, delivery, and erection of the plant components. In a common PLM platform, schedules, phase gates and their deliverables could be transparently planned.

Product Configuration: Companies want the ability to provide customer-specific solutions based on standard products, modules, and components. Design automation in the Engineer to Order (ETO) process should make it possible to quickly derive new product variants by defining parametric models and storing sets of business rules. In addition to the engineering of parts and assemblies, the underlying manufacturing processes should also be available as templates. Machines that are fully described with their recurring modules (150% BOM) will be operated from PLM based on configure-to-order (CTO) processes.

Product Cost Management: The automation of customer-specific plant configurations goes hand in hand with accurate cost estimation. Product cost calculations should be stored in the models for both CTO and ETO elements. The goal is to derive a quotation calculation for the configured system (5th dimension).

4 Technical Specification for Interdisciplinary Collaboration Within PLM

The capabilities Requirements Management, BOM Management, Project Management, Product Configuration and Product Cost Management are of major relevance to the companies under investigation. This section presents the way to optimize these capabilities. The central component of the concept is a PLM solution that incorporates all locations and allows all technically relevant data, their life cycle and processes to be mapped in a contextualized manner.

As illustrated in Fig. 5, the PLM system runs not only the development process for standard machines but also the process for customer-specific plant engineering. This allows the already realized standard machines to be used in the overall system. Furthermore, the integration of several plant-specific ERP systems allows an efficient handling of logistic and commercial data and processes. This includes, among other things, the procurement and rough planning of production orders. For this purpose, material masters, parts lists, technical drawings, and routings can be provided to the relevant ERP systems. In addition, a bi-directional integration can also make logistical information accessible to the product designers, such as plant-specific warehouse stocks. Furthermore, downstream processes such as virtual commissioning or clash detections are also feasible, based on available engineering data.

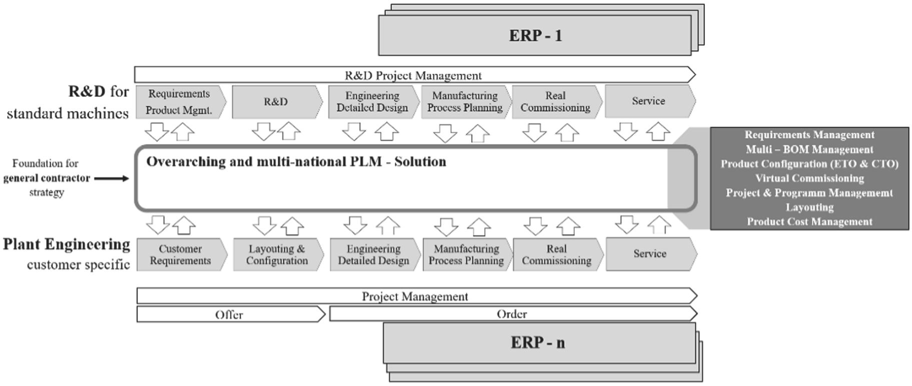

Fig. 5. Overarching and multi-national PLM solution to enable general contractor strategy

In the following sub-chapters, an excerpt of relevant use cases is introduced, helping plant engineering companies to realize interdisciplinary collaboration as part of an overarching PLM Solution. This use cases are: Requirements Management, BOM Management, Product Configuration, Layout & Visualization.

4.1 Requirements Management

The first use case in this case study deals with the introduction and improvement of requirements management. So far both companies realized it by managing contract data in documents stored within a central project folder. We propose to handle requirements within a PLM system in order to increase transparency in the development and engineering process. Therefore, a new structure – the *requirement specification* – is established. This structure incorporates all single requirements as separate objects and allows managing the lifecycle as well as the status of each requirement independently and on the other hand to build semantic relationships to other structures via trace links. To minimize the administrating effort the system can import customer requirements either via standardized exchange formats like ReqIF [9] or using structured documents. As Fig. 6 illustrates, a trace link between a requirement and a part of a bill of material indicates that a specific requirement is *realized by* an assembly or part of the overall product. Furthermore, a relationship between a requirement and a test case as part of a test specification could be used to express a *verified by* relationship.

This supports engineers in the change management process by making the possible impacts of changes visible. Moreover, the approach of handling requirements can be extended on demand to a Model-based Systems Engineering approach following a RFLP process as described in the V-model [10, 11].

4.2 BOM Management

An overarching and multi-national PLM system supports a general contractor strategy by gathering and managing all information in a customer-specific Order-BOM (OBOM)

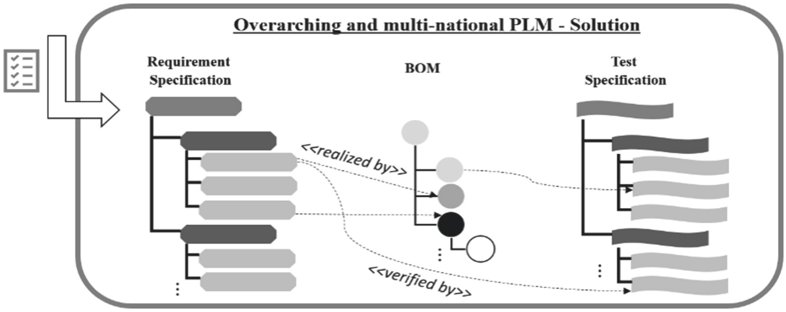

Fig. 6. Requirement structures with a relationship to BOM and test specification

(see Fig. 7). So far, all information has been stored in domain specific Bill of Materials distributed across several PDM and ERP environments, which in turn has not been integrated to one of the other systems. Administrating interdisciplinary collaboration between the domains involves use cases such as clash detection analysis, collaboration between electrical and mechanical engineers, material flow analysis, virtual commissioning, plant layouts, handling of Building Information Management (BIM) data as well as interdisciplinary processes such as change management.

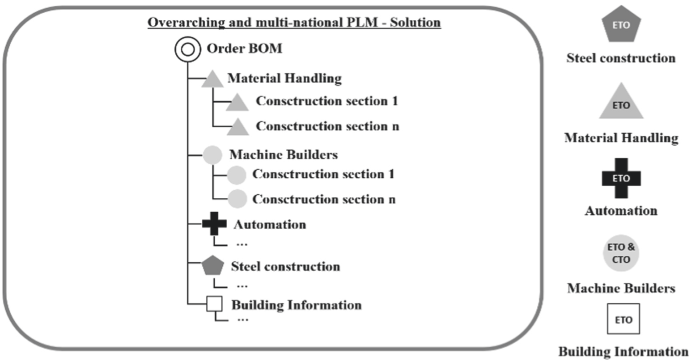

Fig. 7. Order BOM as cross-domain structure within plant engineering

As different as the work results, so are the processes to create product data of the different domains. In steel construction for instance, customer-specific product data is created depending on the boundary conditions provided by the architect's planning. Although standardized profiles are used, the overall planning is always customer-specific and therefore it follows an engineer-to-order (ETO) process. On the other side, many companies focus on standardization of machines following an configure-to-order (CTO) process. This allows to easily configure a machine for a customer project and to install the machine's variant BOM within in the Order BOM. Since such projects can become relatively large and complex, it has proven to be useful to divide the individual domain-specific bill of materials into construction sections. This allows the company to plan the chronological steps and to better plan downstream processes such as the disposition of individual parts and assemblies. Furthermore, one fundamental part for meeting the future requirements of plant engineering companies is the handling and the contextualization of BIM-Models as part of the Order BOM. This allows the company to utilize common use cases for architectural planning and equipment engineering.

Besides the Order BOM, other types of BOMs are essential as well, for instance the Engineering BOM (EBOM) and the Manufacturing BOM (MBOM). Because several publications cover these concepts [11], they are not considered in detail.

4.3 Product Configuration

Different portfolio elements and domains demand various engineering processes. In the case of plant engineering companies, we differentiate between configure-to-order and engineer-to-order processes. As depicted in Fig. 8 we propose two different configuration mechanisms, which are consolidated in an overarching PLM solution. Whereas a 150% BOM can be used for modularized configure-to-order products, we recommend for engineer-to-order products to utilize design-automation solutions, wherever possible.

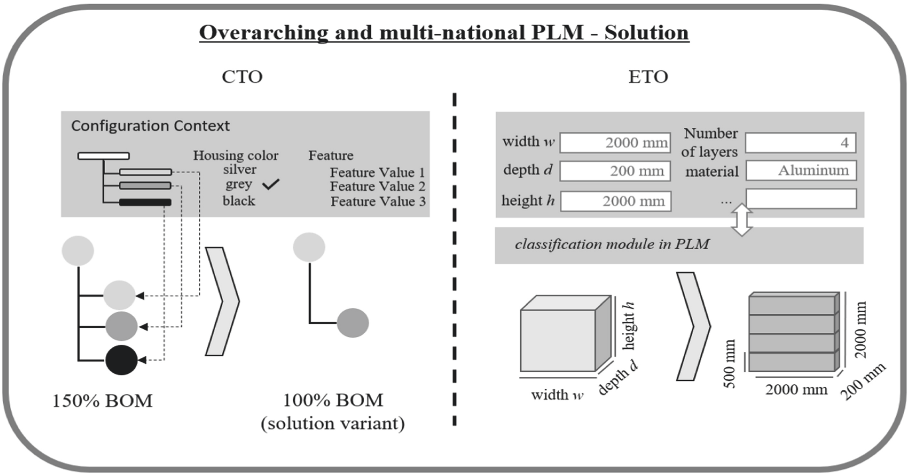

Fig. 8. Configuration mechanisms for CTO & ETO in PLM solution

On one side configure-to-order processes are used to enable the configuration of preconceived standard products as a result of the research and development process. A 150% bill of material is employed, which contains all parts and variants of a specific product type. Moreover, a configuration context is utilized including all configurable features and feature values of a product type. For instance, the color of a housing constitutes a feature, which can be defined during the configuration process. The colors *gray*, *silver* and *black* represent the feature values of the feature *housing color* and comply to one option to be picked during the configuration process. Modern PLM Systems are capable to combine both structures and to define dependency rules. This allows end-users to derive a specific BOM for the configured variant on basis of the introduced 150% BOM. This 100% BOM, also known as a solution variant, can be stored within the PLM system and installed within other structures like the Order BOM.

On the other side, design automation solutions enable engineer-to-order processes. A main characteristic of these processes is that not every variant of the product type must be designed in advance. These solutions enable companies to create customer-specific designs on basis of a predefined set of parameters. As shown in the example, a cube can be defined by its width, depth, height as well as the numbers of layers. By specifying these parameters, a new geometry and dimensional variant can be created. In order to avoid the creation of duplicates, it is essential to integrate a design automation solution with the classification module in the PLM system. If the desired variant already exists, no new design should be created but the existing design should be reused.

Furthermore, it should be mentioned that completely new products as well as products without any variation can also be part of a plant. However, for this type of products no configuration mechanism is needed as the product data is either available upfront or developed from scratch as part of the customer project.

4.4 Visualization and Layouts

During the different development phases in plant engineering, stakeholders expect various levels of detail. For instance, throughout the proposal phase the customer expects an initial visualization of his entire plant in order to evaluate the suggested solution. However, when looking at detailed engineering and the planning of manufacturing processes the company needs detailed models with tolerances and exact measures to prepare CAM Models and NC Programs based on a CAD models geometry. To meet these requirements, several representations of the part are mapped in the data model by so-called data sets. This mapping is also referred to as CAD-Part-Alignment. Here, all relevant product data is managed and linked via a n:m relationship between document and part.

In addition to the simplified and detailed CAD models, neutral format as JT (Jupiter Tessellation) [12] become increasingly relevant. Developing a whole plant needs further information such as proprietary CAD models, technical drawings or specifications which are also managed as data sets. Furthermore, a PLM System allows to handle revisions via the object type of item revision. As illustrated in Fig. 9, we have an Item revision *B* for the Item with the number *125756* defined. The data sets with their own lifecycle and revisioning are always assigned to an item revision.

This flexible data model also supports the creation of layouts. By utilizing the introduced configuration mechanisms, it is possible to position the generated variant in the layout and to install the variant within the Order BOM.

During this process the simplified geometry is applied and visualized. As a result of the positioning within the layout a transformation matrix is generated. By copying the generated transformation matrix of the simplified model to the detailed model, the structure of the layout can be reused in detailed engineering phase, as the simplified models can be substituted by the detailed ones.

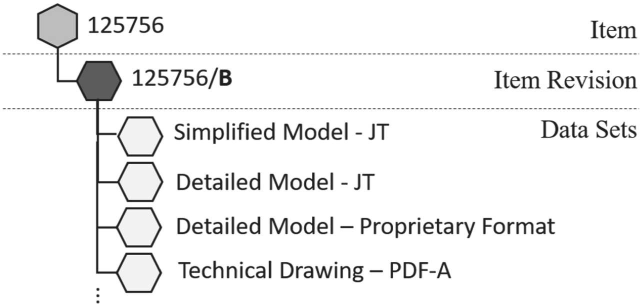

Fig. 9. Several data sets are available as part of item revision object

5 Cost Justification for PLM Solution

Adopting a central PLM solution may achieve various benefits. While profitability calculations often account for process improvements via the creation of activity profiles [13], other types of benefits such as customer satisfaction or improved hit rates become neglected.

Therefore, we recommend as proposed by Pfenning and Eigner [2], having an additional look at potential benefits other than process efficiency while creating a cost justification document. As depicted in Fig. 10, we recommend considering all benefits that may be realized for each use case, for example *Visualization and Layout.* As part of this use case a typical cost-based benefit is the reduction of subscription costs for redundant CAD licenses. This occurs as neutral data formats allow viewing and simple operations to CAD Models without the need of CAD licenses.

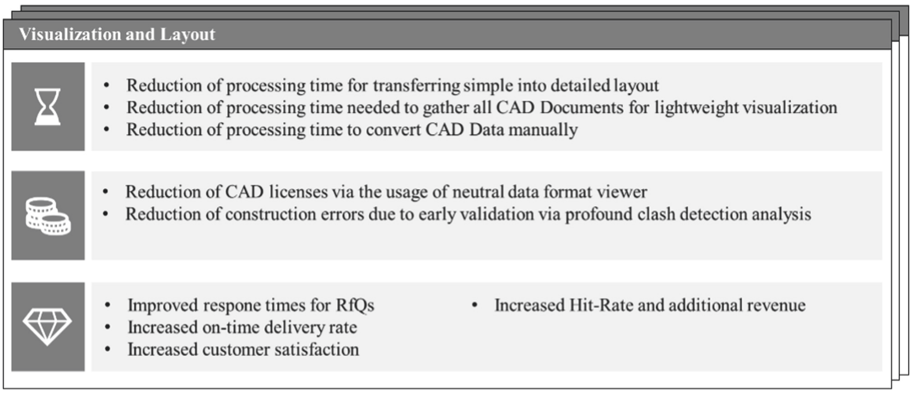

Fig. 10. Excerpt of potentials to be realized via the visualization and layout use case

In case of qualitative benefits, it is difficult to directly monetized the value added and therefore they are often not included in a profitability calculation. However, we recommend making the qualitative benefits visible during the implementation of the PLM Solution. For this purpose, predefined key performance indicators allow a retrospective evaluation of the positive impact of the PLM introduction. A suitable instrument for that are strategy maps [14], which are based on the balanced scorecard of Kaplan and Norton [15]. A strategy map allows to visualize the relationship between measures of the various perspectives following a linking principle. This allows for instance link *increased customer* satisfaction from the customer perspective to *increased revenue* on the financial perspective.

As part of our case study we analyzed the contribution of several use cases to the overall value of the proposed PLM solution. As depicted in Fig. 11, we visualized the identified benefits, which has been evaluated together with the customer after presenting the proposed solution concept.

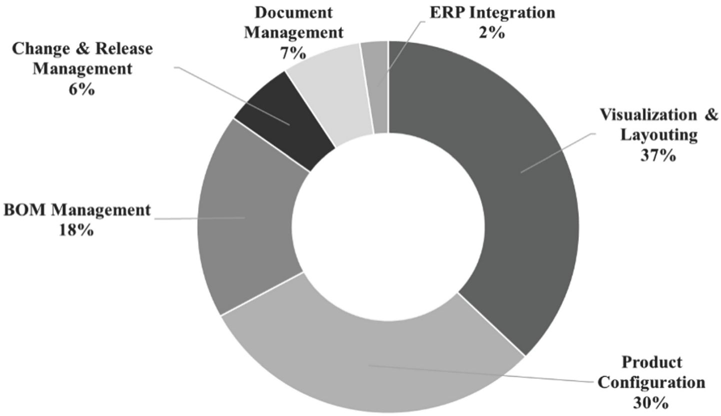

Fig. 11. Use case contribution to overall identified and monetized value of our case study

While quantifying the potential benefits of an overarching PLM Solution we identified especially three value drivers of the proposed solution. The use cases Visualization & Layout, Product Configuration and BOM Management constitute the most promising use cases and contribute in our case study with 85% to the overall value identified. Although the contribution of percentages is always company specific, it functions as a general guidance while identifying relevant use cases for a future PLM Solution. We therefore see great potential for plant engineering companies, particularly in these use cases.

6 Discussion

Both the application of the maturity model and the preparation of a cost justification analysis assist companies to encounter new trends and requirements with appropriate capabilities and technologies. In the area of plant engineering, especially three use cases have been identified as recommendable – Visualization & Layout, Product Configuration and BOM Management. These use cases will help a company to realize a general contractor strategy by streamlining the collaboration of various disciplines for a common project within the PLM System.

As part of the cost justification we recommend visualizing qualitative benefits via a strategy map. Therefore, we propose to further explore the possibilities in the application of this methodology in order to make the advantages of a PLM System visible.

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Evaluating the Maturity of MBE Application

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Abstract. Nowadays the organizations want to be flexible and responsive to the market changes and to keep up with technologies, optimizing the time and cost of products life cycle. The product development process has become increasingly dynamic and complex, also requiring the collaboration among business partners. For this reason, companies need to create a robust interoperability between disciplines and departments. Traditional engineering practices, processes, tools and mindset should evolve to use a single definitive data source to ensure accuracy and consistency of data throughout the product lifecycle and to enable rapid and cost-effective distribution of product information from upstream to downstream. In this context, the Model Based Enterprise (MBE) represents a fully integrated and collaborative environment that embraces feedback from the various stages of the product lifecycle improving the model representation. The key component of this approach is the concept of Model-Based Definition (MBD). There are several barriers to the implementation and adoption of model-based approaches within the companies, although this does not limit its adoption at different levels.

The concepts of Model Based Enterprise and Model Based Definition are analysed in order to clarify their relationship with the product lifecycle management and to identify existing maturity models. The objective of the paper is to evaluate the maturity of MBE applications. Following a theoretical approach, the Core-MBE framework is developed as an innovative tool for assessing the level of maturity of organizations in a model-based transformation process. Two manufacturing case studies (an aerospace company and a mechanical carpentry SME) were carried out to validate the proposed framework.

Keywords: Model based definition · Model based enterprise · Maturity model · Product lifecycle management · Manufacturing

1 Introduction

We live in the era of digitization [1] in which the product development is becoming increasingly complex and dynamic. Furthermore, respect to traditional business environments, it is required new forms of collaboration and synergies. Therefore, traditional engineering practices, processes, tools, and mindsets need to evolve not only to address this complexity but also to capitalize on it.

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Nowadays, the product design process is generally carried out by many engineers who work independently and in parallel in a waterfall of design and manufacturing efforts. So, most product development is no longer a serial, step-by-step process [2]. Product development collaboration is time consuming and costly; demanding that engineers employ clever methods to achieve a collaborative design process that gains time.

With these premises, it is fundamental to use a single definitive data source to ensure data accuracy and consistency as product moves through the lifecycle [2]. In this manner, manufacturers can transition to "high value" production and compete on a basis of productivity and excellence as opposed to low-cost labor sources [3]. This main concept gave rise to the paradigm of the Model Based Enterprise (MBE). MBE is seen as a fully integrated and collaborative environment based on 3D product definition details and shared across the enterprise with the intention of enabling rapid, seamless, and affordable deployment of products from concept to disposal. The key component of this approach is the product definition, called "Model-Based Definition" (MBD) [4].

Until recently, most engineering and manufacturing activities relied on hardcopy and/or digital documents, including 2D drawings, to convey engineering data and to lead the manufacturing processes [1]. Nowadays, advanced model-based technologies and methodologies are emerging to support digitalization by creating digital representations of real business processes and products [2]. Model-based enterprise concepts can only provide point solutions without wider coordination. The realization of the model-based enterprise could potentially cut costs by 50% and reduce time to market by 45% if compared with previously used conventional practices [3]. A critical issue resides in the difficulty in formally establishing the exact procedures, the associated implementation costs and the practical steps that can lead companies to these savings. Many barriers exist in the adoption of model based approaches, from technological, resources and capabilities needs, to organizational structure and standardization [5]. Also, organizations still have difficulty in understanding what MBD is and confusing it with the MBE. In addition, to use these innovative technologies, companies need to have from a medium to high level of management, as well as of standardization policy and training sessions for the internal staff. On the other hand, employee training and software licenses imply some costs and the inherent complexity of 3D-based processes are often listed as reasons that small and medium-sized manufacturers (i.e., automotive and aerospace suppliers) do not adopt or implement MBD technologies and processes [4, 6]. Nevertheless, the adoption of MBE practices is becoming a reality in industry, as evidenced by the increasing number of companies that are moving to model-based environments [6].

Starting from this scenario and considering the most important drivers and issues, the concept of Model Based Enterprise, and consequently that of Model Based Definition, will be analysed in order to first support industrial organizations in distinguishing them. After building a knowledge base of reference, it will be possible to clarify the relationship that these topics have with the concept of product lifecycle management. In addition, it will be investigated the presence of existing maturity models to assess the readiness of organizations in the adoption of model-based approaches. Consistently, the paper focuses on evaluating the maturity of MBE application. Finally, an original maturity model will be proposed with the aim to assess in a comprehensive framework the maturity level of MBE within organizations.

The following sections provide an overview about the state of the art on the topic of MBE and related existing maturity models. Then, the Core-MBE maturity model will be presented and applied in some industrial contexts. Finally, practical considerations, including limitations and further potential research actions will be discussed.

2 Theoretical Background

2.1 MBE Definition

Technical drawings have played a fundamental role in man's progress from the time of the ancient pyramids and the classical Parthenon to the geodesic domes and Skylabs of today [7]. Engineering drawing is considered a graphic universal language that can be traced back to prehistoric times. Although it is believed that formal and systematic engineering graphics began with an academic book by French mathematician Gaspard Monge in 1795 [8]. Historically, drawings were used in industry to clearly communicate information about the product definition because of the tools used in the design and manufacturing environments. Therefore, they represented the most effective way of explaining to someone what to do and how to do it, on the basis of the design tools available at the time [4, 7]. The fundamental purpose of an engineering drawing was to design, control and maintain a product's definition in a precise and clear way with no risk of misinterpretation or assumption. And also, to communicate complexity in a comprehensible and effective manner. Later, drawings gave way to 2D Computer Aided Design (CAD) systems, even if the preliminary outputs were still paper-based artifacts. Even though CAD tools facilitated the design process and enabled engineering drawings to be generated faster and more accurately, 2D CAD was still nothing more than an electronic drafting board. But over time, drawings became more sophisticated in their information content and their representation of the object in analysis, requiring to readers a contextual understanding to make sense of that information. This level of needed contextual understanding is typically dependent upon the reader of drawing tasks in his workflow. So, the 2D drawings started to become more difficult to read than a 3D model [9].

A turning point was represented by the introduction, at the beginning of the 1970s, of the first commercial 3D CAD packages. By the early 80's these were widely available in the market but still expensive, restricting their use to large industries such as aerospace and automotive [9]. Indeed, since the 1980s, occurred the advent of solid modelling and specialized drafting software packages, which have contributed significantly to streamlining the production of engineering drawings.

As solid modelling has evolved, several analysis systems have been created to analyze more precisely how a designer would design and manufacture products. This because more complex shape definitions for increasingly complex products is able to be captured. The 3D definition of geometry has become reality and engineers can easily construct the solids through mathematical models with computer software and display them on the screen. However, the 3D model lacks some needed requirements such as the annotations. While being able to capture complex shape, 3D models typically did not effectively capture information for manufacturing as well, that is did not incorporate the behavioral and contextual information. The variety of information historically found on a drawing is often missing from 3D CAD models due to the software's inability to completely capture behavioral and contextual information.

Due to the absence of relative 3D definition standards, the 3D model played an assistant role to the 2D drawing until the emergence of MBD (Model Based Definition) technology. MBD changed not only the product definition but also the whole design process. This is because MBD technology can contain much more information than a drawing and many companies choose to make annotated 3D models a key component for communication within their company [4, 7, 8]. The model-based definition should be rich in information, providing input to the various consumers who need it [4], including new functionalities to manage, incorporate and show the necessary information of products directly in the 3D model [10] and avoiding the risks of data errors and ambiguities during the transition from drawings to 3D models [11].

In addition, now there is much discussion about which information elements have to be included in these models in order to support the extended enterprise not only in the engineering field. In this context, the concept of Model-Based Enterprise (MBE) was born. Another main motivation for achieving MBE is the increasing competition in the global market [12]. In fact, in a highly competitive globalized market, the transition towards a MBE model represents a significant opportunity for increasing efficiency in product development.

A model-based enterprise can be conceptualized in an environment where the model serves as a dynamic artifact used by the various authors and consumers of information for their respective tasks. The MBE embraces feedback from the various lifecycle stages to improve the model representation for the creation of subsequent products and product iterations [4]. Just as people in the past used drawings in their job functions throughout the product lifecycle, today people are beginning to use a model-based definition in their job functions inside engineering, manufacturing, supplier management and other areas of the organization.

However, there is much debate about what information elements to include to support the extended enterprise outside of the engineering function. Considering that not all the stakeholders need the same information to perform their work, the model often needs to be translated into a different form that show different amounts of information. This issue did not typically exist when drawings were used because that could seamlessly pass from one person to another. Therefore, the evolution of MBD towards the replacement of two-dimensional drawings has created a need to understand the minimum amount of information required in specific workflows so as not to inadvertently expose intellectual property or to unintentionally increase model complexity. Since the necessity to ensure that the information required for specific workflows could promotes effective communication, the use of models poses some challenges with model-based software compatibility and information complexity.

2.2 MBE Maturity Model

Organizations are constantly called to obtain and retain competitive advantage, invent, and reinvent new products and services, reduce costs, and time to market, and enhance quality at the same time [13]. Maturity models have been developed to help decision-makers to balance these sometimes-divergent objectives in a more or less comprehensive way, and thereby assist organizations in this endeavor [14]. Indeed, maturity models are also designed to assess the maturity (i.e., competence, capability, sophistication level) of a selected area based on a specific topic and on a more or less complete set of criteria. They are used as an evaluative and/or comparative tool to increase the maturity level of a specific area within an organization and to determine whether effectively this key area has been implemented [14, 15].

The term maturity can be defined as the state of being complete, perfect, or ready, fullness of development [16]. If the term is applied to a person it might refer to the state of being physically, emotionally, and mentally mature. Indeed, personal maturity can be defined in terms of a person's experience, wisdom, independence, willingness, and ability to take responsibility, to work towards achieving the goals, to be serious and emotionally stable. In the same way, organizational maturity can be seen underlying the state of perfection of an organization. When an organization is maturing it means that its performance is improving, and consequently it is becoming more productive and effective, more competitive, and profitable [16]. So, maturity implies an evolutionary progress in the demonstration of a specific ability or in the achieving a target from an initial to a desired or normally occurring end stage [13].

Hence, a maturity model is a structured set of elements that describes and determines an evolutionary path of improvement from immature processes to mature, effective and qualitatively better processes. Thus, maturity models are adopted to assess the status of a company, or its specific area, according to one of the specified conditions to obtain useful information regarding the starting point for process improvement in existing organizations [17].

In addition, concerning maturity assessment models in the literature, the term "maturity" is in most cases perceived in a one-dimensional way, focusing on [13]:

1. process maturity: how much a specific process is explicitly defined, managed, measured, controlled, and effective.
2. object maturity: how much a particular object like a software product, a machine or similar reaches a predefined level of sophistication.
3. people capability: to which extent the workforce can enable knowledge creation and enhance proficiency.

The contexts where all these three elements under examination register an improvement of their maturity level can therefore be seen as ideal cases [13]. In other cases, specific actions can be implemented to assess and then improve the maturity of some specific dimensions.

According to [18], maturity models have the following properties: i) the development of a single entity is simplified and described with a limited number of maturity levels; ii) levels are characterized by certain requirements, which the entity has to achieve on that level; iii) levels are ordered sequentially, from an initial level up to an ending level; iv) during development, the entity progresses forward from one level to the next.

A maturity model is used to define a set of levels or stages, which describe the development of the examined item in a simplified mode using the properties just described.

Furthermore, regarding the practical application and the methodological purpose, maturity models can be categorized according to the objective for which they are designed [19]:

- Descriptive: the maturity model is applied for the as-is assessment.
- Prescriptive: the model indicates how to identify desirable maturity levels and provides a guide on how to implement improvement measures.
- Comparative: the model allows companies to compare themselves with other companies and also to learn from their experiences.

Once having defined what a maturity model is and what it is used for, the next step is to search whether maturity models exist in the literature relating the field of MBE.

The origins of maturity models lie in the software industry for improving its process maturity and, over time, they spread to many other areas [17]. One of the most important framework used in the assessment of process maturity is the so-called Capability Maturity Model Integration (CMMI) developed by the Software Engineering Institute (SEI) [20]. It inspired the conceptualization of other important framework: the EAMM (Enterprise Architecture Maturity Model) provided by the National Association of State Chief Information Officers (NASCIO) for assessing enterprise architectures and information technology infrastructure [21]; the RACE (Readiness Assessment for Concurrent Engineering) method proposed by the Concurrent Engineering Research Center (CERC) to assess the performance of product development process form the concurrent engineering viewpoint [22]; the BPM (Business Process Maturity) model [23] for enabling the identification and assessment of the maturity of business process policies and practices within organizations; the PMMM (Project Management Maturity Model) created for improving the management of business projects [24].

Concerning the assessment of the maturity level of the model-based enterprise, a relevant contribution is provided by the National Institute of Standards and Technology (NIST) [25] that, in collaboration with the US Department of Defense, developed the "MBE Capability Index Assessment Tool" [26]. It is a tool designed to help in assessing the capability level of an organization implementing MBE practices and methods in the following areas [27]: design activities, change management and data management activities, manufacturing planning activities, quality requirements and planning activities, miscellaneous enterprise activities.

The purpose of the model was defined as the development of a tool to calculate the MBE maturity level of organizations in the industrial sector that want to understand what they can improve. In these terms, the model provides a descriptive picture of the organization allowing for the as-is scenario assessment. The model is structured in seven maturity levels ranging from L0 to L6, in particular: L0 drawing centric – no connection to any models; L1 model centric – drawing derived from model but disconnected; L2 model centric – model managed with drawing; L3 model based definition – model contains some PMI (Product and Manufacturing Information) and drawing is supplemental; L4 model based definition – model contains complete product definition in PMI; L5 model based enterprise – model is used in some non-traditional activities; L6 model based enterprise – model drive all associated activities.

The study of the NIST's model allowed the understanding of the level of detail to structure an original maturity model, including the business areas to assess, the maturity levels and the categorization of these levels. Moreover, concepts related to clarity, comprehensiveness and easy-of-use are considered to facilitate its deployment. The following section presents the proposed maturity model: the Core-MBE maturity model.

3 The Core-MBE Maturity Model

Both models are designed for descriptive purposes by allowing the maturity of the company's as-is scenario to be assessed, but they can also be adopted for prescriptive purposes to assess the target to-be score.

The development of the Core-MBE maturity model has been driven considering the methodologies for a maturity model development suggested by [14] and [19]. In this way both the structure and the content of the model improve in terms of methodological reliability and robustness. Moreover, the Core-MBE maturity model is inspired by the model provided by NIST in order to create an easier-to-read guide for companies to use it effectively. For instance, both models have been designed for descriptive purposes and to take a picture of the as-is status of a company. But the Core-MBE maturity model has been provided to also be adopted for prescriptive purposes in order to asses some targets to reach in a desired to-be scenario. Moreover, it was born from an integration of knowledge referenced on existing maturity models, comprehensive methodologies and design principles. All of these elements contribute to shape the innovativeness of the Core-MBE maturity model.

The Core-MBE framework consists in the maturity model itself and a complementary structured questionnaire useful to collect data from the applicative scenario. The maturity model is composed by four levels of maturity that can exclusively represent the status of an organization. These levels are sequential and a gradual improvement from a level to the next one is usually expected. Incremental improvement actions, rather than disruptive changes or breakthrough impacts, can ensure more easily a maturity improvement in a specific area selected by an organization.

The four maturity levels are:

- Level 0: Drawing Centric

The design and manufacturing processes of the organization rely on traditional 2D drawing and depend on skills and experiences of people. There is no use of 3D models. The Bill of Materials (BoMs) – both engineering BoM (EBoM) and manufacturing BoM (MBoM) – are not linked with any CAD tools. Engineering analysis and calculations are based on manual and ad-hoc methods, as well as the transmission of product information among activities or departments. Model or drawing data are manually created, modified and sent to external partners or suppliers. The organization is not aware of the potential value it could achieve by using 3D models and consequently does not intend to invest in such technologies.

- Level 1: Model Centric

The organization begins to use 3D models. The drawing is still the master practice, but both drawings and models are managed together. The EBoM and MBoM are integrated and connected with CAD models. Some forward enterprises reuse and exchange CAD data in collaboration in their ecosystem. Companies begin to realize the potential value of using 3D models and are interested in investing in these technologies.

- Level 2: Model Based Definition

The organization reaches an important level of maturity where the model can contain the comprehensive PMI and drawings are no longer used. 3D CAD models with annotations is the main source of the product definition. In some cases, supplementary drawing still exists to capture information that is not available in the model. Technologies are well integrated within departments but may not be globally. In addition, the company has an optimal degree of governance of the 3D models.

- Level 3: Model Based Enterprise

The 3D CAD model with annotations is the master of the product definition, and represent the only source of truth for the all internal tasks, including decision making activities. The organization is configured as an extended enterprise that is seamlessly connected both within as outside its boundaries, involving all the partners and stakeholders of its supply chain. Drawings no longer exist and up-to-date view of the product definition is shared commonly in accordance with access rights (Fig. 1).

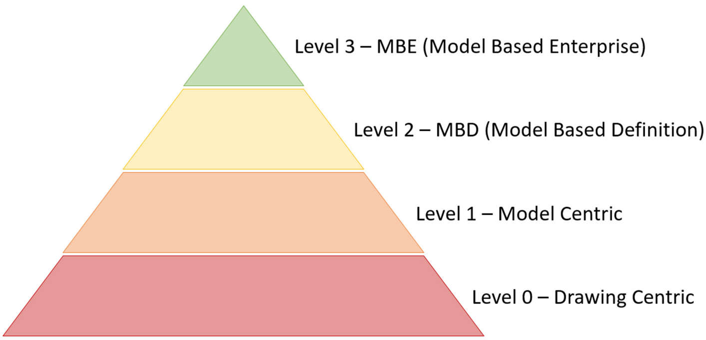

Fig. 1. Maturity levels of Core-MBE maturity model.

The maturity model has been defined in relation to the specific target objectives for industrial realities referring to the already existing maturity models. In this way, it is possible to detail and refine the contents under examination and to make the model easy to use respect to already existing models.

The second component of the Core-MBE framework is the questionnaire. It has been developed to collect useful data for the model application and the maturity evaluation. The questionnaire can be submitted online or offline, since it is detailed in all parts, including sections, questions and answers modalities. As for the NIST's maturity model, the Core-MBE maturity model focuses on some specific topic to investigate within organizations. The questionnaire is intended to help organizations to measure their current level of MBE maturity, based on how the company implements: design processes, change and configuration management practices, data management process, production planning, quality and inspection activities, collaboration and data exchange.

Firstly, the questionnaire is structured with a brief description of the topic (i.e. MBD ad MBE approaches), including the scope and the composition and the description of the maturity levels. Then, a preliminary section (interviewee data) is designed to gather information about the company and the interviewees. This data will not influence the maturity of the organization. Basically, the questionnaire should be completed by professional figures who know how the design and production processes, including the relative data, are managed within the company.

Following, six sections are designed to investigate specific topics:

- Design data – This section mainly explores how the company documents product information and how it manages design data, annotations, and BoMs.
- Technical data packages – They are a set of electronic files (e.g. 3D models, annotations and PMI, BoMs) created to describe a product or item in a way that is appropriate for transferring information into purchasing, production, engineering, and logistics support activities.
- Change and configuration management data – The focus is to investigate how the company manage and control the change and configuration management processes, including relative data and documents.
- Manufacturing data and planning activities – It aims to explore manufacturing operations and planning activities and how data are transferred from engineering to manufacturing areas.
- Quality and inspection activities – This section explores how manufacturing verification, part inspection and product acceptance activities are managed.
- Collaboration and data exchange – It is investigated how and whether the company collaborates and exchange data with partners and stakeholders.

The all sections aim to gather information about the specific business activities that can be encompassed for the evaluation of MBD and MBE approaches are. 33 structured closed-ended questions have been defined in order to have exclusive answers. Each question can have a different number of answers. To each answer a corresponding ascending maturity level is assigned on the basis of the maturity status. To facilitate the evaluation of the maturity of the organization, an appropriate matrix scheme has been designed. In addition, there are some questions that also have the answer "other". These are included to give interviewees the possibility to add additional information to better detail his company status. Furthermore, a final section "notes" allows for suggesting some improvement actions of the questionnaire such as missing elements to consider.

Based on the collected answer, the maturity level is calculated. A score is assigned for each answer: Level 0: 1 pt.; Level 1: 2 pt.; Level 2: 3 pt.; Level 3: 4 pt. Once the score has been assigned to all 33 questions, it can be calculated the average of each section in order to be independent in terms of number of questions in each section. The final score can be obtained by averaging the partial results of the all sections and converting it in percentage in order to establish the maturity level at which the company belongs. In particular, the ranges of each maturity level can be expressed as follow: Level 0 (Drawing Centric) – from 0% to 25%; Level 1 (Model Centric) – from 25% to 50%; Level 2 (Model Based Definition) – from 50% to 75%; Level 3 (Model Based Enterprise) – from 75% to 100%. Since the descriptive purpose of the Core-MBE framework, only the final result about the maturity level of MBD and MBE approaches can be communicated to the organization. In fact, no additional information can be provided such as improvement actions or suggestions, because it goes beyond the scope of the model. On the other hand, imaging a to-be scenario, companies could adopt the Core-MBE framework with prescriptive purposes to just identify the desired maturity level of the organization itself or of specific internal topics.

4 The Core-MBE Maturity Model Application

In order to test the usefulness and the validity of the Core-MBE maturity model and the complementary assessment tool in evaluating the maturity of MBD and MBE approaches, an empirical evidence has been planned focusing the attention on two case studies. The first one represents a SME industrial company operating in the manufacturing sector of medium-light carpentry and that deals with the main realization of forklifts. The second one refers to a large aerospace company that operates in the design, production and maintenance of civil and military aeronautical components and systems.

By submitting the questionnaire to them, preliminary information has been collected about the companies (i.e. size and industrial sector) and the interviewees (i.e. role and years of experience in the company), as shown in the Table 1 below.

Table 1. Information about case studies.

	Carpentry company	Aerospace company	
Industry	Mechanical carpentry	Aerospace	
Size	150	5500	
Interviewee role	Cost planning manager	Engineering team leader	Technical project manager
Experience	9 years	13 years	2 years

Mechanical Carpentry Company

For the carpentry company, it has been possible to gather only one questionnaire that has been fulfilled by a figure with the role of cost planning manager. The company entrusted to him the assessment activity since his knowledge on the topic of MBD and MBE and his awareness about the design and manufacturing processes as well as the practices of product data management. He stated the usefulness of the framework due to the fact that it pushes people to reflect about the level of maturity of MBD and MBE approaches, routine activities and practices that could also be improved such as in terms of standardization and collaboration.

After the analysis of his answers, it has been possible to declare that the maturity of the company corresponds to the "model centric" level, in view of the result of 45,5%. Therefore, considering the Core-MBE maturity model and its structure, the organization status consists in an initial understanding of the potential value coming from the usage of 3D models. However, drawings are still considered as the authoritative sources of product information.

The company receives customer orders through primary 3D CAD models and supplemental drawings. PDF and STEP (Standard for the Exchange of Product model data) files are used for data exchange. The technical teams of the company adopt 3D models for the product geometric definition but the complementary PMI and annotations are described on 2D supports. Design data and annotations are defined as text on 2D drawings and are managed in a separate database that is not connected with the PLM (Product Lifecycle Management) enterprise system. Moreover, calculations and engineering analysis are carried out manually on spreadsheets, and the engineering bill of material is manually defined into the ERP (Enterprise Resource Planning) system. Also, both the delivery and the collection of technical data packages are processed in ad-hoc manner, as well as the configuration management and the document management processes are managed manually. Releases and potential changes are managed with a kind of structured model-based reference.

Regarding the manufacturing operation and the planning activities, the MBoM considers the CAD product tree but some components are often added manually. Manufacturing models are mainly used with supplemental drawings. There are no digital associations between design models and manufacturing data. In fact, also the manufacturing data are managed in a separate database. The manufacturing process relies on 2D drawings but models, images and text are used for work instructions. The drawings and models are used to drive the quality inspection of products, while raw materials are monitored with 2D supports. Also in this case, data are managed in a separate database that is not integrated with the PLM or the ERP systems. Design data are provided with digital drawings and defined in the EBoM, which are accessible through the PLM system. But this information is not automatically connected with manufacturing suppliers who could, for example, streamline the supply chain.

Aerospace Company

Within the aerospace company, the questionnaire has been fulfilled by two professional figures: a technical project manager and an engineering team leader. The former allowed the evaluation of the maturity of MBD and MBE approaches considering the main business contract program, while the latter was focused on other small programs. It is important to consider this aspect because of the remarkable different maturity that has been assessed in these two contexts and, for this reason, it was chosen to discuss the result separately. In both cases, the interviewees have recognized the usefulness of such assessment activities and of the Core-MBE framework as well, considering their effects in terms of increasing awareness of some specific topics and stimulation for continue business improvement.

The analysis of the first questionnaire returned a total score of 81%, which corresponds to the "model based enterprise" maturity level. The company is seamlessly connected both within and outside its business, including the whole ecosystem such as vendors, suppliers, and customers, and 3D models represents the main source of product data.

The 2D drawing is almost all deleted and represents just an output of 3D models which contains the full product definition, including geometric information, annotations and PMI. Moreover, design data and models, as well as the EBoM and TDP, are fully managed within the PLM system that is also integrated with the CAD tools used by designer. The configuration management and the document management are handled in structured way within the PLM, as well as release and change processes. Regarding the manufacturing operations and planning activity, the MBoM is strongly associated with the CAD product tree and MBoM components. 3D models are used to generate process plans and work instructions which also rely on pictures and texts. Digital associations exist between design models and manufacturing data, since the adoption of CAD and PLM systems as the authoritative sources of information. Both drawings and models are used to define the process of quality inspection for both incoming materials and products. The quality requirements are fully managed in the ERP and MES (Manufacturing Execution System) systems. Structured policies are adopted in order to ensure in accordance with the role of the users the access to product data, which is mainly segregated with respect to data attributes. Some PMI and other data can be accessible by downstream groups through the PLM system. Product information and 3D models are often exported and manually sent to external suppliers, which are also used for procurement requirements. CAD, PDF and STEP files are used for information exchange. Both 3D images and 2D depictions are used and elaborated to create technical manuals.

The analysis of the second questionnaire returned a total score of 29%, which corresponds to the "model centric" maturity level. In this case, the organization seems to just gain the awareness about the potential of 3D models, even if drawings are massively adopted. In fact, drawing contents are manually validated, PMI and annotations are defined as texts, and even if engineering analysis are carried out on CAD models, the EBoM is defined manually within the ERP system and then imported in the PLM system. The product configuration and the management of documents are manually handled using applications not integrated with the PLM system, while releases and changes are exclusively drawing-based. The MBoM is manually created through the fulfilment of item lists with the support of drawings; then manufacturing data are stored and managed in the PLM system where also some design models and data exist. The drawings are used for quality inspection and verification for both parts and raw materials, but quality requirement data are not integrated in the PLM system.

Finally, considering that the two assessment cases belong to the same aerospace company, it could be useful to summarize the general level of maturity of MBD and MBE approaches. By averaging the two partial results, it is possible to define that the overall maturity of the company corresponds to the "model based definition" level.

5 Conclusion

Enabling technologies and useful aligned methodologies are essential to support the digitization phenomena and the increasingly complex and dynamic market as well as the progressively interconnected and collaborative business environment. For these reasons, model-based approaches, including the Model-Based Enterprise (MBE), are considered to improve the quality of engineering activities in accordance with the concepts of fully integration of product data and adoption of 3D models. Compared to traditional approaches, they can significantly contribute to cut internal costs and reduce time to market. The main problem faced in this research is connected to the lack of accurate procedures to be applied; companies struggle to understand what Model Based Definition is, and on which Model Based Enterprise is based; their knowledge and awareness depends on the level of maturity that exist within their business structure. Starting from these issues this research allowed the clarification of these concepts and the definition of their relationships along the product lifecycle management. In addition, the aim of the research was to define an original framework for assessing the maturity of model-based approaches and, in particular, of MBD and MBE. The Core-MBE maturity model and the questionnaire have been developed and applied for validation purpose. The research has demonstrated that the framework can be applied in different industrial sectors and to assess a company in its overall perspective or by considering specific applications.

Heterogeneous maturity levels emerged from the case studies. A very high level of maturity has been assessed for the aerospace company considering the main contract programs (81%), while for the other small programs a lower level (29%) has been identified. This scenario can be justified by strategic choices oriented to a more structured maturity for the core business that, considering the structure of a global extended enterprise, need to rely on effective interactions and strong collaborations in the whole ecosystem. By averaging these results, it is anyway possible to declare a comprehensive medium-high level of maturity with a massive adoption of 3D models and a decreasing usage of drawings. Considering the aerospace case study, the fulfillment of more questionnaires allowed the better understanding and evaluation of the company. Moreover, it has highlighted some useful considerations related to the application of the Core-MBE framework.

On the other side, referring to the mechanical carpentry case study, it has been possible to identify a medium level of MBE maturity (45,5%). Only one response has been collected from the empirical evidence. This level of maturity can be interpreted in line with the general business structure. Considering the size of the company and its narrower business, other technological initiatives could be invested respect to model-based approaches that anyway appears to be quite mature.

The empirical evidence allowed to test and validate the usefulness of the Core-MBE framework which collected positive feedback from interviewees. However, the research suffers some limitations due to a limitative case study applications and their qualitative approach, which also impact on results generalizability. In addition, since the descriptive purpose for which the framework has been designed, other explorative applications could be carried out to shape the future maturity desired by the companies. In fact, only descriptive statements can be extracted from the application of the framework. Future improvements can be oriented in the evolution path from descriptive to prescriptive to comparative purposes. Moreover, further improvement actions could be based on suggestions received by interviewees.

Concluding, it is also possible to state that the research provides academic implications considering the knowledge enhancement about the topic of MBD and MBE, as well as practical implications due to its usefulness in stimulating the maturity awareness of industrial companies.

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User Experience of PLM-Systems Analysis of the Current State of Research

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Abstract. This paper sets out to analyse the current state regarding the user experience (UX) provided by PLM environments. Our literature review sets focus on commonly used methods in UX research, and the identification of research gaps regarding UX in the field of PLM. The resulting list of research methods and gaps was allocated to previously defined research questions. This leads to an extensive list for further research, highlighting the gaps, describing the questions, and proposing methods on how to bridge these gaps.

Keywords: User experience · UX · Human computer interaction · Human PLM interaction · Human centricity

1 Introduction

What does it take make employees love their PLM systems? This initial question raised from an interesting observation in industry. While most software engineers love their code repositories and DevOps tools almost in an emotional way, mechanical engineers and other PLM users often do not feel very comfortable with their data management solutions. So, what is going wrong in PLM? To answer this question, we first need to understand what defines the user experience in PLM.

UX is a widely researched topic. The insights of this field have changed the way we interact with products and especially with computers. For several reasons we believe that further research is needed to enhance the UX provided by ICT tools in the field of PLM. First, initial studies have shown that the overall user is not very happy with his tools [1]. Second, the implementation of PLM environments has originally been driven by the complexity of data and processes. This led to tools that excel in the backend aspects but have not been developed with a clear user focus. Third, the acceptance for low levels of usability and a poor overall UX is dwindling. The high levels of usability provided by consumer software leads to higher expectations in the work environment [2]. The fourth and last point, is that PLM environments often consist of a unique mix of different tools. Which creates an additional challenge for the user. An engineer may need to use multiple tools to complete a given process step. Even if all these tools by themselves offered a high level of usability, the sum of the tools and their (possibly) different usability-philosophies may lead to a very poor over all UX. This is a point which is hard to overcome for a single tool provider. It requires the development of standards and general approaches for PLM environments.

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2 Current State of Research

2.1 Components of UX

The term UX is used in various contexts and is ambiguous [3]. Law et al. conducted a survey among 275 researchers and practitioners. The goal of this survey was to evaluate the usage of certain definitions of UX. The most picked definition is in line with the one made by the ISO [4]. Therefore, the definition of the ISO can be considered suitable to clearly define UX and its scope. UX is described as "A person's perceptions and responses resulting from the use and/or anticipated use of a product, system or service". The standard describes several factors influencing the resulting responses. Hereby two main categories of influential factors are used. These are the product-related factors and the user-related factors. An overview of the categories is shown in the Fig. 1 below [5].

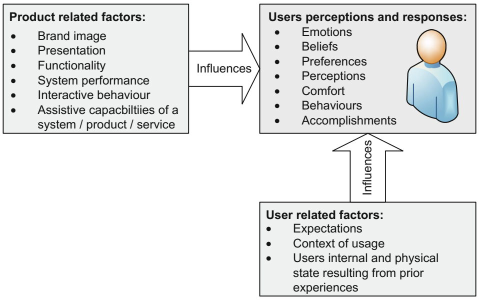

Fig. 1. ISO 9241-11 definition of UX

Factors making up the UX have been subject to research. Various models have been developed to describe the interaction of these factors and their relevance to certain aspects of the UX. Thüring and Mahlke propose a model that includes factors such as aesthetic qualities, emotional experience as well as instrumental aspects (usefulness and usability). The model is based on three experiments highlighting the importance of non-instrumental qualities in UX research. An overview of the model is given in Fig. 2 [6].

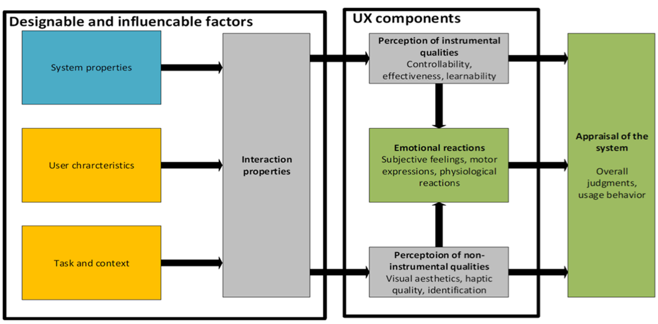

Fig. 2. Component of user experience model

A different model has been developed by Bongard-Blanchy and Bourcard. This model is based on findings from the field of neuroscience. The model aims to help designers and product developers to gain a more holistic view of UX. It describes the UX as an ongoing direct interaction between a system and a user. Hereby both, the system and the user, try to interpret the signal given by the counterpart. After the processing of the input they react as adequately as possible under the given circumstances (context of usage). The model is shown in Fig. 3 [7].

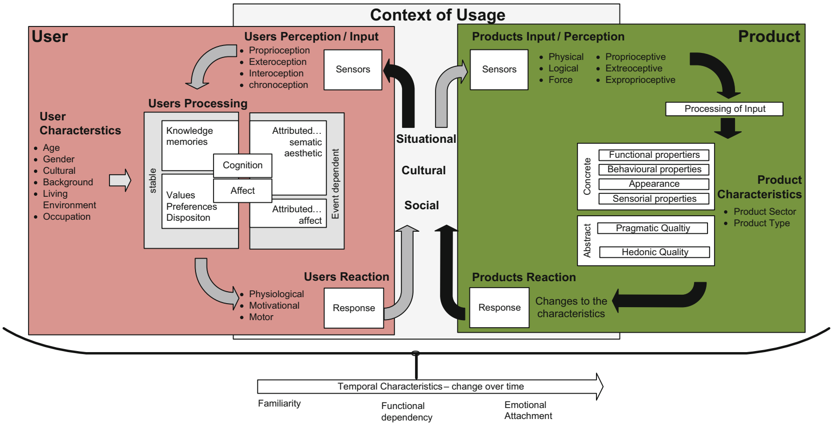

Fig. 3. Components of UX

The model of Bongard-Blanchy and Bourcad and the model of Thüring and Mahlke can both be abstracted to the same three main areas. These areas can also be found within the definition made by the ISO. This leads to the conclusion that UX has the following main components:

1. The Users Characteristics
2. The Context of Usage
3. The Products Characteristics

Kujala et al. argued, that the experience of a user changes over time. According to their analysis, UX often consists of hundreds of interactions between the user and the product. Thus, they conclude, that UX is influenced through current but also by past experiences. This means that the components of UX dependent on the user's history. Thus, time may change the UX provided by a product drastically [8].

2.2 Evaluation of UX for Software Products

After establishing a clear-cut definition of UX and its components the question arises. How can the overall UX and its components be evaluated? Several different approaches have been proposed. Rivero and Conte performed a systematic mapping study, aiming to categorize the available methods for UX evaluation.

In total they identified 227 evaluation technologies. The attributes of Table 1 were used to categorize the technologies [9].

Table 1. Categorization of UX evaluation methods

Type of technology	Assed period of experience
• Written reporting	• Before usage
• Oral reporting	• During usage – single episode
• Observation/monitoring	• During usage – long term
	• After usage
Information source	Collected data
• Users	• Qualitative
• Development team	• Quantitative
• UX experts	• Both
Location	Supports correction of identified problems:
• Controlled environment	• Yes
• Field	• No
Type of assessed application	Availability
• Generic	• Available for free
• Web application	• Available under a license
• Mobile application	• Not publicly available
• Other	

The work of Rivero and Conte is based on the analysis of Vermeeren et al. published in 2010. Vermeeren et al. analyzed and categorized a total of 96 methods. They concluded that there is a need for additional methods. These methods should focus on the early phases of product development. Additionally, they empathized the importance of the practicability of the methods. Another point raised is the need for multi-method approaches. Vermeeren et al. argued that several methods focused on certain aspect of UX. The combination of methods may lead to more holistic analysis [10]. In their update of the first analysis by Vermeeren, Rivero and Conte did reach a partially different conclusion. They identified three main gaps. The first is the need for more methods focusing on qualitative data, as these could help to improve software. Further, they identified a need for methods to analyze usage of a product overtime and on different platforms (mobile, laptop). Finally, they concluded that new, simple methods that do not depend on expensive equipment are needed [9].

Another perspective of UX research methods comes from Christoph Roher. He distinguishes the methods in three main dimensions. Attitudinal vs. behavioural, qualitative vs. quantitative and the context of use of a research method. The main difference to the categorization of Rivero and Conte is the focus on the scope of the method. Rohrer utilizes the classification of the results (attitudinal vs. behavioural) to simplify the selection process of a given method. Hereby methods classified as attitudinal refer to the attitude of user towards a product. Whereas behavioural methods try to describe a user's behaviour. Rohrer used this framework to classify 20 methods, which have been commonly used as part of research projects of the Nielsen Norman Group [11].

2.3 Current State of Research Regarding the UX of PLM Systems

This paper utilizes the definition of PLM coined by Terzi et al. They describe three main elements of PLM. These three elements are the ICT (tools, standards, and architectures), the processes (human actors, skills, and organisation) and methodologies (practices, procedures). These three main elements guide a product through the three main phases of its lifecycle. Hereby Terzi et al. distinguished between beginning, mid and end of life. Throughout the lifecycle all three main elements may change. This means that different ICT, processes and methodologies are used depending on the stage of the lifecycle [12]. This paper focuses on the UX of the employees, managing a product throughout its lifecycle. Certain aspects of the UX of PLM environments have been analyzed in the past.

One key factor in understanding the current state of UX in PLM environments is user satisfaction. Brown conducted a survey among 500 users in 2015. Surveying them about their satisfaction with the PLM tools. The results do not show a clear-cut picture. Overall, the level of satisfaction varies strongly. One finding of the study is, that satisfaction depends on the role within the organisation. Hereby differences between management and design engineers as well as differences between recipients of information (e.g. manufacturing) and design engineers have been reported. The design engineers were the least satisfied with their tools. Another finding from the study is that people who use the products more frequently tend to be more satisfied with overall usage. When asked what should be changed, the most common response was "ease of use". This indicates that users feel that their tools should be simplified. The participants were recruited via direct e-mail, social media, and online postings. The participants have a varying level of experience, the size and industrial sectors of the companies they work for varies, as well as their cultural background. These factors have not been analyzed in-depth as part of the study [1]. Another analysis of an ICT-tool used for PLM was carried out by Saenz et al. The authors set out to investigate the current state of UX in a Fortune 500 industrial company. The result was obtained using three main steps. In the first, an initial survey was carried out (participants: 24). In the next step, contextual inquiries to a selected group of engineers were made. The final step consisted of in-depth interviews. In the first phase 24 participants have been recorded in the second and third 9. On the base of their analysis the authors proposed 9 guidelines for improvement [13]. To improve the usability of PLM products, De Pinel et al. proposed an approach which would integrate UX in an agile model and add usability metrics to the product development process of ICT tools used for PLM. This improved process is based on findings from user-centred design as well as methods used for agile software development [14].

Certain aspects of UX have been utilized in maturity models. Kärkkäinen and Silventoinen analyzed and categorized different maturity models. In their work, they describe PLM as consisting of people, processes, and IT. According to their analysis, certain maturity models focus stronger on the "softer capabilities" of PLM. These models can be seen as relevant for analyzing the UX of the PLM environment. Because these models evaluate the human interaction with PLM systems (Fig. 4) [15].

3 Methodology of this Paper

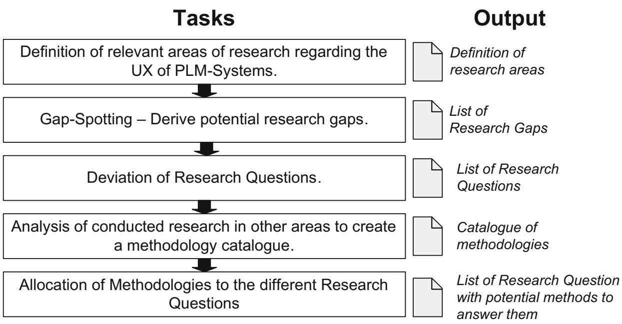

Fig. 4. Chosen research approach

3.1 Methodology to Find Relevant Research Objects

The described UX models of Thüring and Mahlke, and Bongard-Blanchy and Bourcad have been used to define relevant research areas. These areas have been selected on the basis of the key question of whether or not a particular aspect of UX is specific to PLM systems.

This can be broken down to the key question: Is the component of UX influenced by the fact that that it is a PLM systems?

Example 1: The way a person perceives, and processes information may be relevant for the UX when it comes to PLM systems. However, the fact that a person is using a PLM system does not change the way of perception and processing. Thus, the results from experiments in a more general domain are applicable for PLM products.

Example 2: The user characteristics influence the UX. PLM environments are highly specialized setups and restricted to certain domains. Therefore, it is assumed that the user group and user characteristics are different from other domains and experiments.

3.2 Methodology to Define Research Gaps

A literature search was carried out for all research areas. The following journals, databases and search engines have been used to conduct the literature search:

- IFIP International Conference on Product Lifecycle Management
- International Journal of Product Lifecycle Management
- **Search Engines:** Web of Science, Google Scholar, and Swisscovery

The Journals have been selected because of their relevance to the topic and their scope. They represent an extension to the search conducted with the search engines.

The following criteria have been used to define results as relevant for the task at hand:

- Date of publication: Not older than 25 years
- Type of publication: Peer-Reviewed Journal/Conference Papers

3.3 Methodology to Find and Allocate Suitable Research Approaches

Conducting a literature search on the status of current research on the methodologies used in UX was evaluated. The following databases, search engines, conferences and journals have been used:

- Human Factors in Computing Systems
- International Conference on Human-Computer Interaction
- ACM Transactions on Computer-Human Interaction
- **Search Engines:** Web of Science, Google Scholar, and Swisscovery

The Journals have been selected because of their relevance to the topic and their scope. They represent an extension to the search conducted with the search engines.

The following criteria have been used to define results as relevant for the task at hand:

- Date of publication: Not older than 25 years
- Type of Publication: Peer-Reviewed Journal/Conference Papers/Scientific Literature
- A method was defined as suitable if the same or a similar scientific question has been answered for a different product/domain.

4 Results

4.1 Relevant Research Objects Regarding the UX of PLM-Systems

Table 2 lists the identified research objects and gives a brief introduction to their scope. Every research object has a unique ID.

Table 2. The seven selected research objects

ID	Research object	Description
01	User characteristics	Characterization of the user regarding his demographical, educational, and other traits.
02	User reaction	Users reaction to the usage of a system.
03	Context of usage	The environments and settings in which a product is used.
04	Processing of input	The way a system processes user input.
05	Product characteristics	The unique traits of a product.
06	Products reaction	The system's responses to a certain input.
07	temporal aspects	The changes of all components of the UX over time.

Table 3. Found research gaps

ID	Research object	Description of the gap
01	User characteristics	Characterization of the user of an ICT-tool in a PLM environment
02	User reaction	Analysis of the reaction of User to the usage of PLM systems
03	Context of usage	The environments and settings in which ICT-tools of a PLM environment are used
04	Processing of input	The way a PLM systems processes users input including the UX considerations during the processing
05	Product characteristics	The unique traits of the ICT-tools of PLM environments influencing the UX
06	Products reaction	The responses of a system to a certain input including the adaptation to the users' needs
07	Temporal aspects	The changes of all components of the UX over time, in respect to the tools used in a PLM environment

4.2 Found Research Gaps

Table 3 gives an overview of the research gaps that are found. Every gap is linked to a research object and describes a PLM specific issue.

4.3 Deviated Research Questions

Figure 5 shows the 23 research questions found and their dependencies. The colors visualize the research objects and correspond to the gaps.

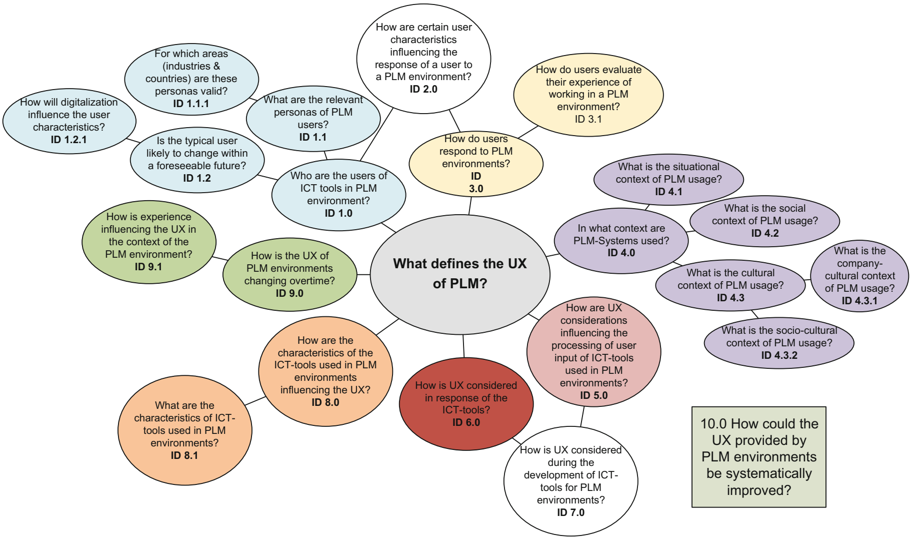

Fig. 5. Deviated research questions

4.4 Methodologies used in UX Research

In Table 4 the selected high level research methods are shown. These are categorized according to the framework of the Rivero and Conte [9]. The selection of methods is based on the proposed general methods of Rohrer [11]. Some methods may be applied in a lab or a in the (Location). However, in some cases the methods have been developed for a certain location. In these cases, the secondary location is displayed in brackets. Meaning, one could utilize the methods in that location as well, but the commonly used approach would the other one.

Table 4. Methods to analyze the context of usage and the user's characteristics and responses.

M-ID	Focus area	Approach	Tech.	Information source	Location
01	Generic	Interviews	Written Oral	Users, Developers UX-experts PLM-experts	Lab Field
02	Generic	Surveys	Written	Users, Developers UX-experts PLM-experts	Lab Field

(*continued*)

Table 4. (*continued*)

M-ID	Focus area	Approach	Tech.	Information source	Location
03	Generic	Focus group	Oral	Users, Developers UX-experts PLM-experts	Lab (Field)
04	Attitudinal	Intercept surveys	Oral	Users Developers	(Lab) Field
05	Attitudinal	Participatory design	Oral	Users, Developers UX-Experts PLM-Experts	Lab Field
06	Attitudinal	User-diary	Written	Users	Field
07	Attitudinal	Card-sorting	Oral	Users, Developers	Lab
08	Attitudinal	Desirability studies	Written Oral	Users, Developers	Lab Field
09	Attitudinal Behavioral	Ethnographic Field studies	Observation	Users	Field
10	Attitudinal Behavioral	True Intent Studies	Oral	Users	Field Lab
11	Behavioral	Unmoderated panel Studies	Observation	Users	Field Lab
12	Behavioral	Unmoderated UX studies	Observation	Users	Field Lab
13	Behavioral	Moderated usabiltiy studies	Observation & oral	Users	Field Lab
14	Behavioral	Usabiltiy Lab Studies	Observation	Users	Lab
15	Behavioral	Usabiltiy benchmarking	Written	Users Developers UX-Experts PLM-Experts	Lab
16	Behavioral	Eyetracking	Observation	Users	Field Lab
17	Behavioral	Clickstream analysis	Observation	Users	Field Lab
18	Behavioral	A/B testing	Obseravation	Users	Field Lab

4.5 Allocation of Methods to Research Questions

The result of the allocation process is shown in Table 5.

Table 5. Scientific question and proposed methods

ID	Research question	Proposed methods
1.0	Who are the users of ICT tools in PLM environments	Surveys, interviews, focus groups, ethnographic field studies
1.1	What are the relevant personas of PLM users?	Surveys, interviews, focus groups, ethnographic field studies
1.2	Is the typical user likely to change in the future?	Surveys, interviews, focus groups, ethnographic field studies
2.0	How do certain user characteristic influence the response of a user to PLM environment?	Interviews, focus group, User Diary, True Intent Studies, Ethnographic Studies, Usability Lab Studies
3.0	How do users respond to PLM environments?	Interviews, Surveys, Focus Group, User-Diary, Desirability Studies, Unmoderated panel Studies, Unmoderated UX studies, Moderated Usability Studies, Usability Lab Studies, Eye tracking
3.1	How do users evaluate their experience of working in a PLM environment?	Interviews, Surveys, Focus Group, User-Diary, Desirability Studies, Unmoderated panel Studies, Unmoderated UX studies, Moderated Usability Studies, Usability Lab Studies,
4.0	What is the context in which PLM tools are used?	Interviews, Surveys, Focus Group, User-Diary, Ethnographic Field Studies
4.1	What is the situational context of PLM usage?	Interviews, Surveys, Focus Group, User-Diary, Ethnographic Field Studies
4.2	What is the social context of PLM usage?	Interviews, Surveys, Focus Group, User-Diary, Ethnographic Field Studies
4.3	What is the overall cultural context of PLM usage?	Interviews, Surveys, Focus Group, User-Diary, Ethnographic Field Studies
4.3.1	What is the corporate culture of PLM usage?	Interviews, Surveys, Focus Group, User-Diary, Ethnographic Field Studies
4.3.2	What is the socio-cultural context of PLM usage?	Interviews, Surveys, Focus Group, User-Diary, Ethnographic Field Studies
5.0	How are UX considerations influencing the processing of input of ICT-tools used in PLM environments?	Interviews, Surveys, Focus Group, Participatory Design, Clickstream Analysis
6.0	How is UX considered in the response of the ICT-tools?	Interviews, Surveys, Focus Group, Participatory Design,

(*continued*)

Table 5. (*continued*)

ID	Research question	Proposed methods
7.0	How is UX considered during the development of ICT-tools for PLM environments?	Interviews, Surveys, Focus Group, Participatory Design,
8.0	How are the characteristics of the ICT-tools used in PLM environments influencing the UX?	Surveys, Interviews, focus groups, ethnographic field studies
8.1	What are the characteristics of ICT-tools used in PLM environments?	Surveys, Interviews, focus groups, ethnographic field studies
9.0	How is the UX of PLM environments changing overtime?	Surveys, Interviews, focus groups, ethnographic field studies,
9.1	How is experience influencing the UX in the context of the PLM environment?	User-Diary, Desirability Studies, Unmoderated panel Studies, Unmoderated, UX studies, Moderated Usability Studies, Usability Lab Studies, Usability Benchmarking, Eye tracking
10.0	How could the UX provided by the PLM environments be systematically improved?	Surveys, Interviews, focus groups, Participatory, Design, Card-Sorting, Unmoderated panel Studies, Unmoderated UX studies, Moderated Usability Studies, Usability Lab Studies, Usability Benchmarking, Clickstream Analysis, A/B Testing

5 Discussion

With this paper we set out to find and analyze the potential research gaps of UX in PLM environments. The methodology chosen led to a number of research gaps and questions. As well as methods which would be suitable to help answering the defined questions.

Our research is based on the definition of UX and different models defining UX. These models have been used in psychology and usability research. Any changes to the model or the underlying definition may lead to different results. This makes the scoping of UX crucial. UX is often applied in online marketing and for consumer products. Thus, most of the models and methods are aimed at this type of products.

One huge difference between the usage of PLM products and the usage of consumer products is the choice. The use of ICT-tools in a PLM environment is often involuntarily. Meaning that an employee in a company hardly ever gets to choose their preferred ICT-tools. Using a particular tool is simply part of the job. This certainly influences the overall UX. The used UX models take this factor into account in the context of usage.

Another aspect of PLM environment is, that it is often made up of several different systems. Developed by different companies, following a different approach in user guidance. An engineer may work with a CAD, a designated tool for extended stress simulation of a components, a PLM-system, and an ERP. All these systems are only a part of the everyday UX of the engineer.

This makes research very difficult because not only can an isolated tool/GUI be optimized, but the entire system landscape needs to be considered as well. While the technical gap between them may be bridged utilizing state of the art interfaces, UX gaps may be more difficult to bridge.

There are a number of approaches available to evaluate the UX of a given tool. The selection made for the found research questions is simply an initial set of methods. It refers to methods that would be suitable but does not represent a finite set. Meaning, the proposed methods are suitable for answering the questions. However, there are a plethora of other methods that can be used to answer the proposed methods. Furthermore, the method is limited to the methods currently used in UX research. The PLM community and other research areas may propose additional methods that could help to answer the questions. A pleasant UX in a PLM environment may mean that a suitable tool supports a user as effectively and efficiently as possible. This particularly refers to the ability of a product to learn and the transparency within a product.

6 Conclusion

Certain aspects of UX have already been analyzed and improvements have been proposed. The full picture in in terms of UX has not yet been analyzed. The isolated analysis of ICT-products used in a PLM environment, does not reflect the everyday reality of a user. We suggest to further investigate and develop methods to better understand UX in the full context of a PLM user.

The research gaps and research questions and methods described are suitable starting points to analyze one key factor of all PLM environments: the user.

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Industry 4.0 and Emerging Technologies

Improving Design of Enabling Collaborative Situation Based on Augmented Reality Devices

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Abstract. Industry 4.0 needs the help of technology 4.0 to improve production apparatus flexibility and productivity and decrease non-quality costs. However, these technologies aren't well integrated in already existing processes because we try to correlate the technology to the norms and standards we have previously set, in a time when augmented reality systems were not part of the industry's toolbox, by neglecting, the human factor. Some researchers in ergonomics develop concepts to create a symbiosis between Human and machine in these production tasks. This is notably the case for the paradigm of Enabling Collaborative Situation (ECS) where researchers investigate the collaboration between Human and machine over time. We relied on this paradigm to build a study where we have questioned multiple interactions between a user and an Augmented Reality (AR) device in order to find what kind of features might be considered as relevant to improve the HMIs and the AR devices in the future. This study has been conducted on a training workstation for automotive industry with a Hololens 1. We present in this paper the results of this study and envisage the technical solutions to move towards an ECS through the redesign of Human-Machine Interface. At the end of the paper, we draw the outlines of a future experience where we want to compare, the former HMI versus the new one redesigned thanks to the previous study in a first time, and the Hololens 1 against the Hololens 2 in a second time in order to understand how the new features move to an ECS.

Keywords: Industry 4.0 · Enabling collaborative situation · Augmented reality · Human–machine interaction

1 Introduction

Industry 4.0 is an industrial concept which allows the cooperation and the communication between humans and technologies, and between technologies themselves, in real time. Thanks to dedicated tools like Internet of Things and data management, industrial staffs will soon be able to predict the future production turnovers. All along the production line, smart sensors record all information regarding the process and the products made. The staff is now sufficiently informed to adjust supply chain, measure performances and take decisions in real time. We call this kind of factory, smart factories. In a smart factory, all products have sensors, e.g. RFID chips, dedicated to send and receive data

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from the products on production lines through IoT in order to optimize delivery time to the customer, reduce consumed resources and learn from former production runs to predict certain events of its future operational processes.

Companies needs to be both, more flexible and improve their productivity while they facing to great challenges as "*increasing market volatility, shorter product lifecycles, higher product complexity, and global supply chains*" [1].

Another important point to emphasize is the mass customization needed by the consumers and considered as relevant by the companies. In article [2], a survey done on 30 Flemish companies at the beginning of 2017, highlights the mass products customization as one of the most important business challenge for industrials behind a more products diversity and lead times reduced. To make these demands real, it is important to digitize production apparatus and facilitate crowdsourcing [1] in order to help to a faster products design process.

If technological innovation is the first and obvious way to improve and make production more flexible, a second pillar, maybe the most important, is to keep Human at the centre of the production. Called *social innovation* [1], or *social perspective* [3], main idea is allow to the workforces to improve their digital skills and culture [2], by new organizations, laws, regulation and/or business models [1], in order to give up responses to societal needs, and assist ageing, disabled, or apprentice workers [3]. Both words, *social* and *sustainable*, are correlated to technologies and, more specifically to cyber-physical systems, by a collaboration between humans and machines.

Enhanced human's knowledge, sensorial or cognitive abilities inside working environments is mandatory if they want remain competitive and meet the societal needs. Future industry worker would be able to oversee the production by controlling it through cyber-physical systems as augmented reality, being trained to new digital processes and/or workbenches on the production line via virtual reality, work more efficiently with collaborative robots on assembly lines especially if we are talking about impaired workers. Some authors [3] called *operator 4.0*, a human trained about digital culture and skills, "*aided by machines as and if needed – by means of human cyber-physical systems, advanced human-machine interaction technologies and adaptive automation*" [3] in order to be more flexible and accountable in case of change of production series, and unforeseen events on the production lines.

We previously mentioned three technologies 4.0: augmented reality, virtual reality and collaborative robots. Despite of the wide range of possibilities to integrate technologies 4.0 inside the production apparatus, it remain a large types of challenges to solve before considering a human-machine interaction.

If we focus on augmented reality we can observe that many study cases in Literature point out the increasing performances and the reducing of error rate after implementing AR on an existing processes [4, 5], and [6]. However, it never pointed out how we could improve the user experience during job in order to increase the user acceptance during the technology 4.0 implementation process. Other lack, technologies are implemented in an existing process without consideration regarding the production workshop and organizational processes [7]. It is necessary to respond to the organization in order to reorganize it with regard to the integration of new technologies in the company's processes [8]. Finally, certain ergonomic features of the technologies can have an impact on the operator's work (e.g. visual fatigue regarding the type of technology [9], the effects of discomfort resulting from the weight of the device [10], or the effect on the perceived image facing to panel type embedded inside your AR device [11]).

Concerning collaborative robotics, Literature brings out a lack of energy autonomy and a low social acceptance on the one hand, a weak in, bilateral communication between human and robot, voice recognition, comprehension and utilization of natural language, and perception and interpretation of human behaviors from the other hand [12]. This paper focuses on many other issues such as safety and security of work in a space shared with humans, *reprogrammability* of robots and user-friendly interfaces to simplify use on production lines by unskilled or cognitive impaired workers.

To avoid a failure of integration in production, it is necessary to consider industrial organization and processes. They must provide space for work debate and times for collective regulation, an enabling management in order to fight against work stress and for improve performances and innovation [13]. Compan et al. [13] recommend also to design the future workbenches with operators since the beginning of the process design in order to increase the acceptance of the technology implementation. Regarding technologies, they must be understandable by operator 4.0 and this last must be able to change process characteristics and/or information displayed through HMI. The setting up of criteria previously exposed is called Enabling Collaborative Situation (ECS) by Compan et al. We will rely on this work to build an efficient human-machine collaboration in industrial workshop.

All criteria needed to build an ECS in order to reach a successful production implementation will be described in details in the next section, Sect. 2. To explain the concept of an ECS, we describe the genesis of this paradigm through former ergonomics works.

Then, in Sect. 3.1, we present the workbench where pre-tests are carried out and where we want to improve user experience by redesign HMI in the case of using AR technology and redesign workbench in the case of collaboration between human and robot. After presentation, always in Sect. 3.1, we explain and describe in details the results of our pre-tests where a set of ten people realized assembly tasks of components on a dedicated sub-assembly.

The improvements planned to move towards an Enabling Collaboration Situation of work between human and machine is presented in Sect. 3.2 just before conclusion of this paper.

2 Enabling Collaborative Situation

Enabling Collaborative Situation (ECS) is a concept born following the work of Amartya Sen [14] who exposes the idea that an operator's ability to act depends on the capabilities offered by the process with which he interacts. Thus, a person may possess abilities allowing to reach desired performances without being able to used them. This concept named *capability approach* (CA) defines a range of conversion factors, which determine the power for a person, to act on a process (Fig. 1). These factors are sorted in three categories: individual (gender, age, experience, level of education, etc.); social (work team, etc.); and environmental (technical means, work organization, etc.).

Fernagu-Oudet et al. [15] conclude on the capability approach: "*Capability defines, according to this logic, a field of possibilities both for the individual who is the bearer* *of the capability and for the organization that can benefit from it. It is based on a set of mobilizable resources (internal and external to the individual) that will undergo conversions in order to be actualized in selected achievements or behaviors. Sen [Amartya] speaks of accomplishments or operations*". Thus, capability approach enables individual intrinsic capabilities to be taken into account and weights the opportunities that the individual has to develop his or her personal skills and knowledge. It is from this approach that the idea of the enabling environment emerges.

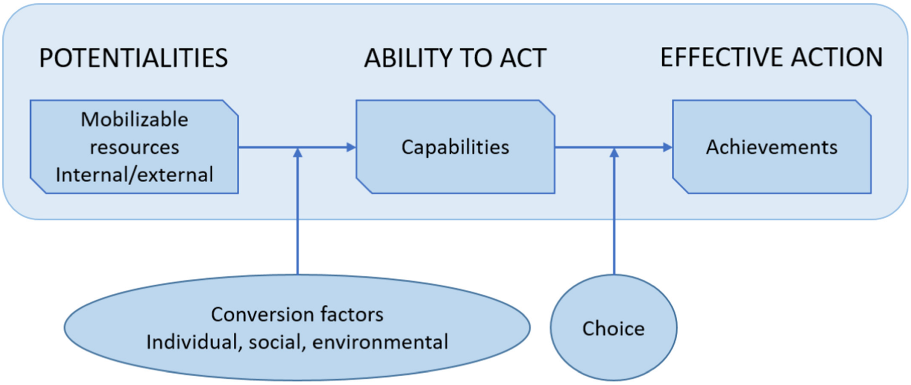

Fig. 1. The capability approach theory (adapted from [15]).

Pierre Falzon [16] defines an enabling environment as: "*an environment that allows people to develop new skills and knowledge, to broaden their possibilities of action, their degree of control over their task and the way in which they carry it out, i.e. their autonomy*". Fernagu-Oudet et al. [15] add: "*[…] energizing work environments to make them empowering, consists in helping individuals to mobilize and use the resources at their disposal, not just make them available*".

The enabling environment is therefore a set of physical data and information flows arranged in such a way as to optimize the work and learning of the individual in the context of his or her function. However, because of its intrinsic nature, enabling environment is very exogenous to the individual, and the individual seems to be relegated to the background. The focus should not be on the work environment of the operator but rather on the operator himself in relation to the 4.0 technology he uses, to perform the tasks assigned to him/her.

Based on the concept of an enabling environment describe by Falzon, Compan et al. [13] bring out three following criteria:

1. *Learn a new and more efficient way of doing things.*
   Authors explain the fact it is necessary to build an ecological assessment of the performance close to real situations of technology use in order to define relevant performance criteria.

   Human needs to know that his work is done correctly and even improved by using technology. It increases the sense of utility of the technology used by him.

2. *Increase the available possibilities and ways of doing things.*
   In the face of increasing product complexity and frequent changes in production runs, operator 4.0 has to deal with a large range of situations. That improve his experience of work, and it is important to leave him the possibility to add new ways of doing things in order to improve quality and/or productivity. If necessary, process steps can to be modified if operator is seeing a better way to do things. Technology 4.0 should not prevent him from changing the procedure and should even help him to do so.

3. *Adjust the Human-Machine couple attributes according to the evolution of situations over time.*

Last criterion is based on the time during which human works with machine on production. It investigates the united couple through interactions between entities and eventually, the situation evolution during work. To do that, it is important for operator to be able to understand technology and modify it according the lived situation. The understandable characteristic is named by [13] *operational transparency*. The operational transparency is the minimum understanding required to anticipate the device behaviour and modify its internal characteristics in consequence. The ability for the operator to modify the characteristics of the technology is called *continuous design in use* [13]. This last help to modify process step if operator knows a way to do better (criterion 2) or modify graphical interface in order to display only relevant information for him (e.g. an expert/novice mode as pointed out in [4]). At the end, it helps to do a joint evolution/construction of the human-technology couple over time.

Finally, this criterion questions the industrial organization and operational processes in order to define whether they are consistent with increased operator responsibility, enhanced individual skills and knowledge, and improvement performance at the workstations. To achieve this, industrial managers have to develop spaces for debate on work, times for collective regulation and set up an enabling management.

As seen before, all these criteria have emerged from ergonomics disciplinary field. If technologies have been called up, any experiment has been made in order to confirm or refute if these criteria are relevant in an organization, and more specifically, inside an HMI. If it is impossible to verify organizational and operational processes, we could check, inside a laboratory experiment, the relevance of criteria 1 and 2, as well as operational transparency and *continuous design in use* of criterion 3.

To do this, we will use an industrial case study in our laboratory as it was designed and built for a past laboratory experiment [17]. This is a replica of existing French industrial training workstation (see Fig. 2(a)). Moreover, we have decided to prospect both types of following technologies: augmented reality and collaborative robots. Next section will present the workbench in details, the limitations observed during the pre-test carried out in a first step and the experimental method.

3 Workstation Presentation and Experimental Method

3.1 Workstation Presentation

How Does It Works? The workplace is a training workbench dedicated to pick and place parts (two plastic clamps, a rubber, and a wire) on an existing sub-assembly. It uses Hololens 1 augmented reality technology to help user to pick right component and place it at the right location on sub-assembly, but also gives to the operator, the safety rules and assembly steps. The workbench allows assembly of four parts on a rear windowscreen, that we will call now, *main part*, used in automotive industry.

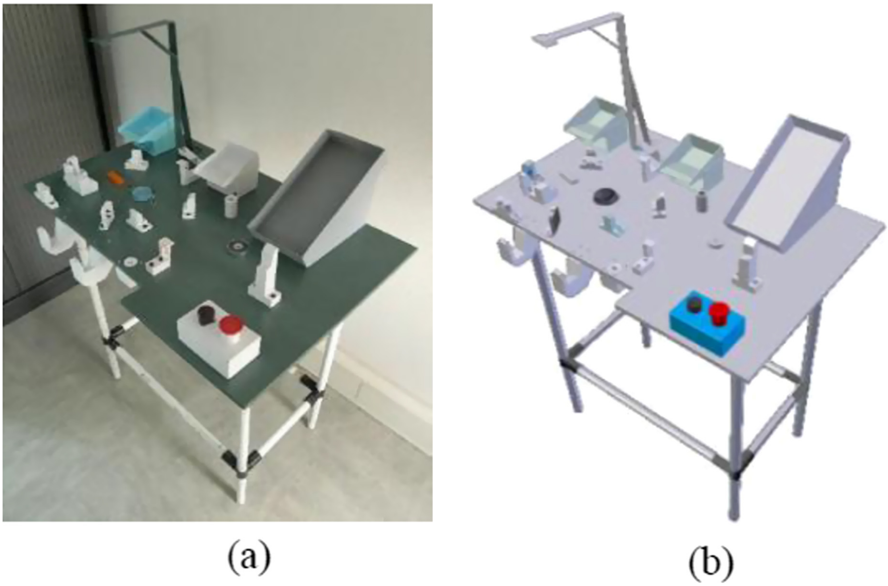

Fig. 2. Industrial workstation replica (a) and its CAD model (b).

There are eight steps, from step 0, reminding the security rules, to step 7 useful for packaging the sub-assembly in the packaging bin after components assembly (Fig. 3). The assembly procedure can be broken up as follows (for confidentiality reasons, some steps are not explained but replaced by "*confidential*"):

1. Confidential;
2. Assembly rubber;
3. Confidential;
4. Confidential;
5. Setting up wire on main part;
6. Confidential;
7. Packaging sub-assay in the packaging bin.

In augmented reality, via see-through glasses, for displaying virtual information at the right place, it is mandatory to calibrate AR device with the real environment. To do that, a CAD model has been created it is necessary to positioning this virtual avatar on the real one (see Fig. 2(b)). Calibration operation is made by placing CAD model on real mock-up. For that, it was proposed to position a white cube under the rear left foot of real workstation, then, it is possible to adjust CAD model position by translational and/or rotational movements, through keyboard buttons. It is important to notify that the well positioning of every next displayed information in the User Interface regarding the real prototype is depending on the good initial calibration realized by the user.

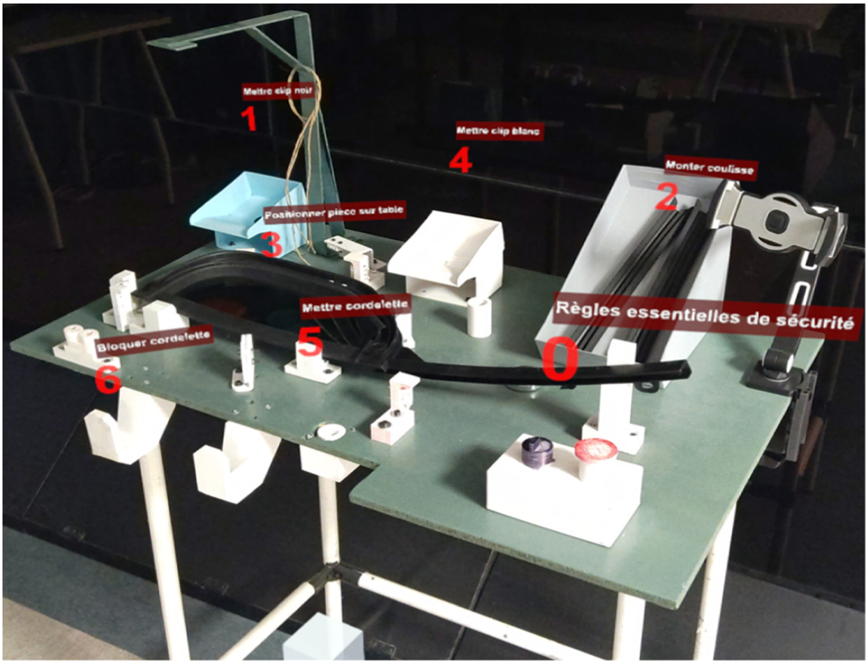

Fig. 3. General process view.

User Interface (UI) provides two types of modes: first, the training mode where all steps are explained and operator follows steps one-by-one assisted by UI with a lot of explanations during process through watching videos, reading information and/or observing pictures at each step (Fig. 4), by providing audio instructions and by observation of 3D kinematics. Videos can be paused, moved in the operator's field of view, and operator could skip a step to go backwards or forwards. Additional information can be displayed by clicking on a yellow *plus* virtual button, the latter being transformed into a *less* yellow one. Audio instructions can be replayed if wanted by operator. 3D kinematics are displayed showing how the component must be placed on the main part. 3D model of main part is stacking on real one and 3D model of component moving from the box where it is stored to main part where it is placed with the right orientation.

Second, the validation mode. Here, operator can watch videos and kinematics and read information if he wants but the mode is built for assembling components on sub-assembly and validate his productivity and quality made. Any time counter or quality mismatch detector has been implemented in the UI for this training workbench. Normally, in validation mode, numerated steps (Fig. 3) are enough for operator to carry out his tasks.

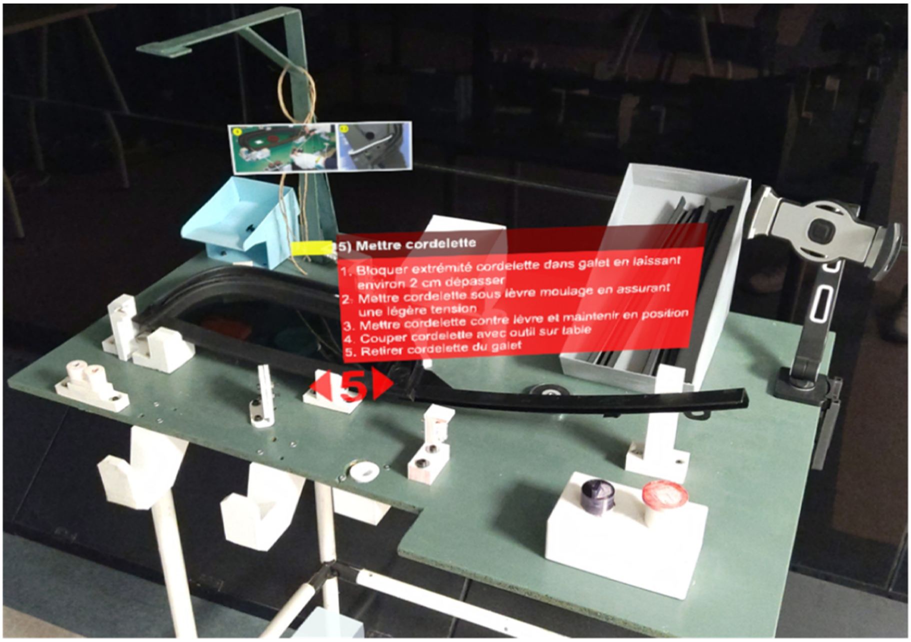

Fig. 4. A process step detailed with more information and pictures.

UI is able to recognize both following human-machine interactions: gesture recognition through *Air tap*, Hololens 1 dedicated gesture, and through the clicker, tool delivered with Hololens bundle, and speech recognition. However, Hololens 1 API expects user to speak in English to use this type of recognition.

UI provides also guidance cues in order to guide user's gaze if the projected information isn't in the device's field of view. These cues are displayed via the form of red arrows.

Limitations. To detect limitations on the workstation, we carried out pre-test with ten students in July 2020. These people following engineering courses in MSc or was Ph.D. students. They were not necessarily experienced in the use of an AR device especially with an HMD device. However, they all know what AR technology is. People was all young (<30 years old).

All people made both mode: training and validation in this order and learned Hololens 1 *Air tap* gesture during training mode. In this mode, they all watched the videos and the kinematics, read all information, listened all audio instructions and followed all needed gestures in order to assembly the components on the main part. They could ask help to do task, or the selection dedicated gesture (*Air tap*). In validation mode, no help was provided but if they want, they could watch the videos and the kinematics and read information if necessary.

At the end of the experiment, an interview was realized in order to know what kind of problems has been experienced and/or detected by users and what improvements could be made in UI and on the device in order to increase the user experience and the performances on the training workbench.

Limitations observed and reported by users are listed in the table below. They are sorted in three categories: User Interface issue, device issue, and other. We have added also the number of times (*n*) when the problem has been reported by operators (*n*/10 operators).

As we can see in the table, there are three types of issues observed during our experiment. First, device problems. They are resulting from the device characteristics and design. We can mention the *Air tap* gesture (6 people on 10 tested said that this gesture is very difficult to learn), the weight of the device, its Field of View (5/10 people complained about it), the accuracy of the selection gesture (2/10 people), and for one people, the difficulty to wear the device with big glasses. A good point detected is the clicker because it replaces the *Air tap* gesture (2/10 people exposed this good point) (Table 1).

Table 1. Details of issues reported by operators during experiment.

Description of issue explained by user	Type of issue	Number of complaints reported (n)
– Hard to click with Air tap	Device issue	6
– Calibrate the system is difficult	User interface issue	6
– FoV not enough important	Device issue	5
– Videos aren't useful. Kinematics and audio are enough	User interface issue	5
– Confirmation of validation and/or selection not shown in HMI	User interface issue	4
– Any representation of final assembly	User interface issue	4
– Cognitive overload because of information displayed in HMI	User interface issue	3
– Hard to see component's orientation. Edges not defined and images colors too dark or bright – Don't want to be fooled by the system. Want to see the difference between virtual and real elements	User interface issue	3

(*continued*)

Table 1. (*continued*)

Description of issue explained by user	Type of issue	Number of complaints reported (n)
– Clicker useful	Device issue	2
– Need to have another viewing angle in videos	User interface issue	2
– Ask for adding a deported screen in order to give at the trainer the mean to see what the trainee see	User interface issue	2
– Click accuracy isn't sufficient	Device issue	2
– Questioning about utility of AR	Other	2
– Guidance cues (red arrows) not enough visible	User interface issue	1
– Wearing the HMD with big glasses is difficult	Device issue	1
– The HMD is too heavy	Device issue	1
– Undefined technical terms used	User interface issue	1
– Colors problems inside HMI	User interface issue	1

Besides, concerning UI, a lot of people exposed problems linked to the concept of operational transparency. We can mention the selection/validation not explicitly shown, with 4 individuals complaining about that. Also, displaying issues as difficulties to see component's orientation or problems displaying virtual elements overlaying the real environment resulting from colors, luminosity and/or virtual elements' edges.

One person told us he experienced a problem with virtual elements rendering. Indeed, she don't want to be fooled by the system and wanted to keep the knowledge of whether she was dealing with a virtual element or a real one. We think we could resolve this problem by using a rendering technic called cel-shading. It allows to emphasize the virtual elements' edges and operators could see the difference between the virtual elements and the real ones. We could resolve the problem of misunderstanding between real and virtual elements and the difficulties to see the edges at the same time.

The calibration of the virtual mock-up on real prototype is considered also as difficult for 3 people. They preferred add a trihedron in order to place the virtual workbench more easily on the real one. Some people told us that accuracy of the location between the virtual elements and the real was not good. This is the result of the calibration process. These people were not aware of and did not express this cause but because we know the root cause of this problem we added these three people to the three first, and the calibration process was thus a problem for 6 people.

Three people think HMI provides too much information. They want would expect to hide or remove information from the graphical interface. We can associate this limitation to the fact that 5 people think videos aren't useful when they have already audio instructions, assembly kinematics and information displayed on the field of view. Four people think it will be a good improvement if the final assembly was projected at the beginning of the process in order to know what the expected final result is. Adding a button in this mean seems needed in order to give to the operator the possibility to add or not this final result. Hide/removal or add this video or any other information in the graphical interface is the way to reach the concept of *continuous design in use* as explained by Compan et al. [13].

Last relevant issue exposed by users, the questioning about utility of AR device. It's a good question because in [13], the first criterion (of an ECS; *Learn a new and more efficient way of doing things*) questions the affect, the utility and the *sense-making*, of the technology 4.0 implementation on already existing workbenches, in addition to the performance criteria.

3.2 Experimental Method

Outcomes Expected. Based on these pre-tests carried out, we can imagine a future experiment where we will check the increasing of utility, performances, and users satisfaction during use of AR technology on our training workbench. To do that, we want to explore two ways: first, the same device, Hololens 1 with the former UI (the one used during pre-tests) versus the new one (improved thanks to users feedbacks). We want to see if operators can see the difference during the completion of their tasks with the help of improvements points previously exposed (e.g. are the virtual elements and their edges more visible thanks to cel-shading rendering?; Does HMI create cognitive overload with possibilities to hide/add information inside?; Operational transparency and continuous design in use are achieved during use by operators?; Finally, are the operators in an enabling collaboration situation with the technology?).

In a second time, we will test the new User interface projected inside Hololens 1 versus Hololens 2. We want to audit if the improvements of AR characteristics are increasing the sensation, for the operator, to be in an Enabling Collaborative Situation with his technology and how (e.g. is just a characteristic which allow to reach that or a set of characteristics which help to create and to live an ECS? In a same way, is just one characteristic which allow to solve an issue or is it a bundle of new characteristics which allow to reach the resolution of this issue?).

To answer these questions, we will experiment these both AR devices, Hololens 1 and Hololens 2, with our new User Interface improved thanks to relevant issues exposed by operators in pre-tests.

Moreover, in addition of improvements integrated in new UI, we need to know if performances are reached in order to confirm the usefulness of AR technology to the industrial companies. We decided to explore two types of performances indicators: time to assemble components on main part, and the error rate (the number of errors made on the number of assemblies built). These both indicators are usually the most indicators measured during experiments.

Concerning users tested, we will try to make our experiment with people with a large range of age, gender and education level. It is important for us to explore with a large panel of people in order to be as close as possible to the employee profiles present in the companies.

Regarding collaborative robotics, we need to redesign the workbench in order to create a working situation between human and robot in a shared-space. For example, we could imagine a situation where a disabled worker could be assisted by a collaborative robot in order to reach or even exceed the required industrial performances. In order to help the operator to understand robot when it runs, a static screen could be placed beside it and human could interact with robot, the latter ask to human what are its need and human could answer in consequence. Operational transparency being fulfilled by this setting up.

Concerning the continuous design in use, operator could change the robot speed in order to increase the work pace. Other example to illustrate the concept of continuous design in use, we could add a task to be made by the robot at the place of the human or the contrary, remove an action made by robot and replace it by an action did by human. We need to elaborate an UI to allow collaboration and interaction between human and robot through the static screen.

For both technologies, AR and collaborative robotics, we need to give to the operators the means to reorganize the assembly tasks. Indeed, the second principle of an ECS (*Increase the available possibilities and ways of doing things*) sets to search the ways to give at the user the possibilities to change the tasks order if he found a better way to doing task, or a way which improving performances. Thus, the operator must have the possibility to reorganize steps between them, in process, merely, through HMI and without computer skills.

4 Conclusion

In this paper, we have defined the industry 4.0 framework and the concept of operator 4.0, then we pointed out the problems for setting up the technologies 4.0 in the production apparatus and the intrinsic defaults of AR devices and collaborative robots that make it difficult to integrate them into the production environment because of dissatisfaction of operators and/or performances decreasing at workstations.

We decided to rely on the works of Compan et al. and the paradigm of Enabling Collaborative Situation. This latter is based on former ergonomics works such as capability approach and enabling environment. After, defined an ECS, we have exposed the experiment, based on a former industrial training workbench for automotive industry, where we have detected a lot of issues thanks to the help of users, inside the HMI and with the device used (Hololens 1). This pre-study seems to confirm the relevance of ECS' criteria but to validate them, we must realize a new study to design and redesign workstation according to issues pointed out during pre-tests in order to move towards an ECS. Thanks to the pre-study we have been able to consider technical solutions for the problems encountered.

In the case of the assembly with the augmented reality device, we will rework the UI, by redesign interaction between Human and AR device, by rework visual rendering, and by adding new buttons/options/menus/etc. inside the UI. We will analyze also the contribution of device in the operator's work improvement by testing Hololens 1 and Hololens 2, this latter having a more important field of view, a reduced weight, another fixations design on head, another gesture to interact with UI (which replace the Air tap) and a lot of other improvements.

Concerning the collaborative robot, we will redesign the workbench in order to create a shared-space between human and machine, create an HMI via a static screen beside the robot to allow to human to understand and interact with the robot during the production.

For both technologies, and according to the second principle of an ECS elaborates by Compan et al., we will give to operator the means to reorganize the order of assembly tasks through the created UI.

Finally, we will measure for both technologies in interaction with human, if the performances indicators are reached or exceed. These indicators will be the assembly pace (time to assemble all components on the main part) and the error rate (the number of errors made on the number of assemblies built).

All these experiments aim to make a problem/solution cartography which cannot be independent of the technologies used. The enabling criteria are key elements for this mapping. Besides, the analysis of test cases from the literature will allow to consolidate this knowledge base. In the long term, we wish to build a heuristic for the development of ECS between operators and machine in industry 4.0.

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Systematic for Process Improvement Using Cyber-Physical Systems and Toyota Kata

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Abstract. There are several benefits reported in the literature regarding the Lean approach and Industry 4.0 integration. In general, the most significant justification for integrating these two concepts is that incorporating new technologies in a production system should only occur once the system is operating without waste and in an optimized way. Thus, implementing the Lean approach represents an excellent opportunity for organizations that want to use the technologies of Industry 4.0 (I4.0). Although Industry 4.0 brings new opportunities for digitalizing production systems, machines and equipment cannot suggest improvements independently. In this way, employees will continue to be an integral part of production systems. However, when analyzing the specialized literature, it was possible to observe that the discussion about workers' participation to effectively implement the new technologies of I4.0 in the productive systems is incipient. Thus, this work presents a new framework developed called Systematic for Process Improvement Using Cyber-Physical Systems and Toyota Kata that use the Improvement Kata and Coaching Kata routines and the cadence of activities from the training of employees to the development of the Cyber-Physical System of the organization to implement the new technologies of Industry 4.0. The systematic was tested in a theoretical case study, and the results showed that it was possible to develop a Cyber-Physical System using SIMIO® software. Improvements could be developed and simulated in the digital environment with data from the actual process.

Keywords: Lean · Toyota Kata · Cyber-Physical Systems · Industry 4.0

1 Introduction

The benefits reported in the literature regarding the integration of the Lean approach and Industry 4.0 (I4.0) are real-time communication of the worker at the workstation

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and the Cyber-Physical System (CPS), real-time recognition of errors, and the consequent elimination of process waste and mutual transfer of knowledge between senior managers and shop floor workers, among others [1–4]. However, there is an absence of frameworks that describe the role of shop floor workers to actively implement the new technologies of I4.0 on the process level and develop the organization CPS. Besides that, the sustainability of changes arising from the Lean approach is often inefficient, and the improvements get lost over time because they are not part of the routine of workers [5].

When investigating how Toyota maintains its improvement standards over time, [6] described the Toyota Kata (TK) approach. This method consists of two complementary routines that, when repeated constantly, can make the continuous improvement part of the culture of organizations. TK approach can establish routines that can conduct workers towards the same direction, stimulate organizational learning, and make the continuous improvements process daily for the organization. Based on this scenario, this paper aims to demonstrate how the TK approach can be used with the technologies of I4.0 to develop the CPS of an organization and present the initial results of its application on a theoretical case study.

2 Methodology

Initially, an extended Structured Bibliographic Research (SBR) following the Systematic Search Flow (SSF) [7] method was conducted to gather information about the integration of Lean and TK approach with I4.0. We search leading journals and conference proceedings using the keywords that the online databases Scopus, Web of Knowledge, EBSCO, Engineering Village, ProQuest, and Google Scholar offer. The query string used was ((“Lean” OR “Value Stream Management” OR “Toyota Kata”) AND (“Industr* 4.0” OR “Smart Factory” OR “Cyber-Physical Systems”)). The research was also complemented with exploratory research.

Based on the SBR, the literature gaps were identified. The constructs and best characteristics were selected to develop a framework for applying the Toyota Kata approach to integrate I4.0 technologies and develop the CPS on the production systems of organizations.

In order to demonstrate the result of the framework developed, a theoretical case study was performed. As recommended by [8] and [9], we opted to use a case study as a research strategy. We intended through the case investigate the research object crucial characteristics, being our analyses unity. The manufacturing field is an area in which process simulation tools are essential to validate methods and architectures before applying them to the shop floor [10]. For [11], simulations bring benefits such as low cost, ease of use, and the wealth of details concerning a natural system.

The article is organized as follows: initially, state-of-the-art on integrating the Lean approach, TK, and Industry 4.0 is presented. Then, the Toyota Kata approach is briefly described. Then, the new framework is presented, and its phases are described. Finally, the theoretical case study, discussion, and conclusions are presented.

3 Integration of Industry 4.0 and Lean

By analyzing the studies referring to I4.0 and the Lean approach in the literature, it was possible to verify how these concepts worked in theory and practice. I4.0 is a contributor to the activities of an organization, as it focuses on optimizing and improving the efficiency of processes. The use of the technologies of I4.0 aims to acquire and present new data and information about the production environment to assist the decision-making of employees. To convert resources into intelligent objects, I4.0 uses a set of technologies based on the concepts and interactions between the Cyber-Physical Systems (CPS) [12] and the Internet of Things (IoT) [13].

The motivations for integrating I4.0 and Lean concepts are diverse, but they can be summed up with the statement by [14], which says that "the automation of inefficient processes will continue to make the process inefficient." Thus, [15–17] suggest a progressive order, in which first the Lean approach is implemented, which is responsible for optimizing and organizing the manufacturing environment, and then the technologies of I 4.0 can be used to connect and digitize processes.

According to [4], the use of sensors on the shop floor generates performance data and metrics transmitted in real-time to the organization's Cyber-Physical System. Thus, through the Value Stream Mapping (VSM) tool, these data can optimize production systems. [18]. Furthermore, [19] presented the use of the VSM tool in conjunction with the I4.0 technologies in detail. According to the authors, its use allows a comprehensive visualization of socio-technical systems, including technologies, organizations, and people.

According to [2, 4, 14, 20], excessive automation may not be beneficial since, currently, machines and equipment are unable to suggest improvements on their own. Therefore, the human factor should be better described in the existing models for integrating the two approaches since employees will continue to participate actively in adding value.

Some authors like [21–25], present the Toyota Kata approach as a contributor to Industry 4.0. According to the works, the TK approach can characterize the current condition and design the future states of production systems. Besides that, the TK approach is presented to implement the continuous improvement process with PDCA cycles.

Although the works mentioned above cited the TK approach as a contributor to industry 4.0, some opportunities for improvement were observed. None of the authors discuss using the Value Stream Mapping tool in conjunction with the Toyota Kata approach and the Cyber-Physical Systems of the organization to characterize how the production system behaves and the possibility of simulating optimized future states. Furthermore, no work has shown the step-by-step that an organization must take to effectively implement Industry 4.0 on its production process and develop the Cyber-Physical System of the organization.

4 Toyota Kata Approach

When investigating how Toyota maintains its continuous improvement standards, [6] presented an investigated approach within the company called Toyota Kata.

Kata means routine or "way of doing" and is described as a repeated pattern and develops skills and a new mindset for improvement. This pattern directly interferes with the reasoning and behavior of employees, as it is a routine of continuous improvement that provides the training of people through the application of the scientific method for sustainably solving problems [6]. The practice of Kata is based on two concepts, as shown in Fig. 1: Improvement Kata and Coaching Kata [6] and [26].

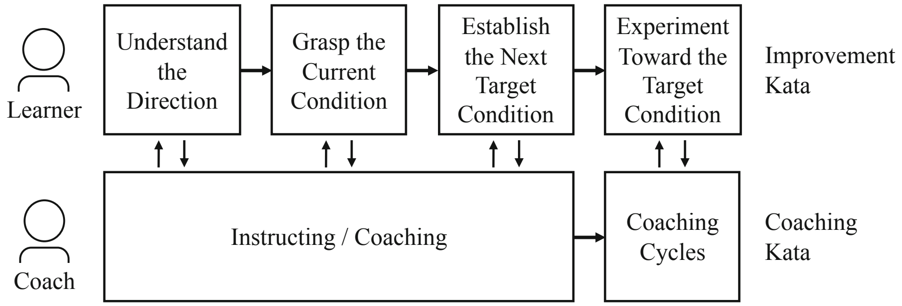

Fig. 1. Improvement Kata and Coaching Kata [6, 26].

4.1 Improvement Kata

The Improvement Kata routine is performed by an apprentice and can be used at all organizational levels, but the process level is where much of the continuous improvement occurs [6]. The Improvement Kata routine is divided into four steps, as shown in Fig. 2 and described below.

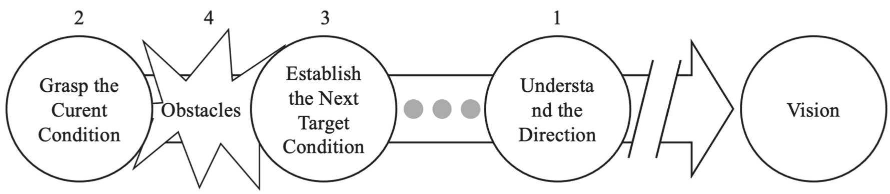

Fig. 2. Four steps of Improvement Kata [6].

1. Understand the Direction: This is what the organization seeks in the long run. The challenge pursued by the teams is usually selected by the leadership and is in line with the company's vision.

2. Grasp the Current Condition: The purpose of this step is not to discover potential problems or improvements but to analyze and understand the Current Condition of the process and obtain the facts and data necessary to establish an appropriate Target Condition for the following process.
3. Establish the Next Target Condition: After understanding the Current-Condition, a Target Condition is established, that is, a better future state that can be reached in a short time.
4. Interact towards the Target Condition: It is at this stage that the Apprentice and his team carry out small experiments, using the scientific method for solving problems through the PDCA (Plan, Do, Check and Act, in English), to exit from the Current-Condition and go towards the Target-Condition. The obstacles that prevent the team from reaching the Target Condition are lifted, and one obstacle at a time is chosen to be addressed. After each stage, a reflection is made, and the next stage is planned.

4.2 Coaching Kata

Coaching Kata is how the Improvement Kata routine is taught. The coach is responsible for guiding the learner through the learning cycle. The Coach performs cycles with the Apprentice next to a Storyboard board, where notes and information from the PDCA cycles are taken, guided by five questions. Often these cycles are performed aided by a card, with the script for the Coaching Kata cycle, as shown in Fig. 3.

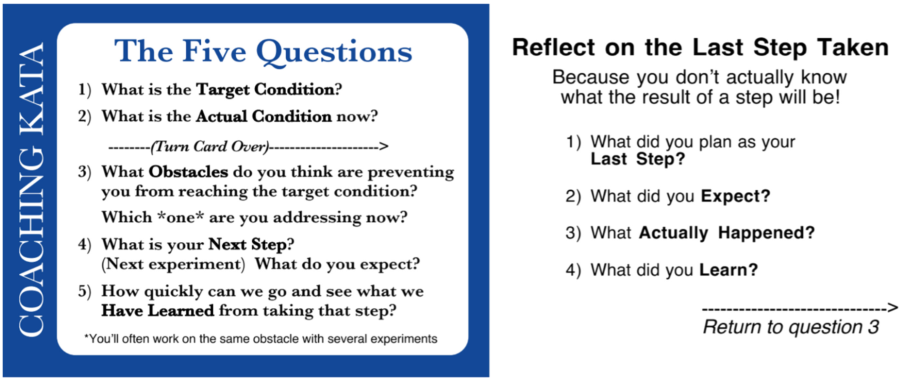

Fig. 3. Card with the five questions for the Coaching Kata Cycle [6].

As mentioned before, [21–25] presented the TK approach as a contributor to I4.0. Nevertheless, there are several applications of the TK approach in different environments. [27] used the TK approach to implement the Value Stream Mapping in an organization. [28] combined the TK approach with the TRIZ approach to developing a method for sustained innovation. Moreover, [29] and [30] used the TK approach to implement Lean Construction. [31–33] used the TK approach to improve different processes in hospitals. In sequence, the new framework developed in this work is presented.

5 Systematic for Process Improvement Using Cyber-Physical Systems and Toyota Kata

For this work, systematics is understood as improving methods based on the interpretation and critical reflection of the lessons learned, characterized by the organization of data, practices, and concepts that lead to a reflection and re-elaboration of thought [34]. Therefore, this topic aims to present the system developed for process improvement using Cyber-Physical Systems and Toyota Kaya. The systematic aims to guide the subjects involved in the process by maintaining the sustainability of improvements and the innovation of solutions. The improvement is based on the Improvement Kata and Coaching Kata routine, resulting in sequencing target conditions.

The systematic is composed of five phases (team training, unfolding the company's vision, value stream mapping, implementing the technologies of industry 4.0, and elaborating the Cyber-Physical System.) presented in Fig. 4.

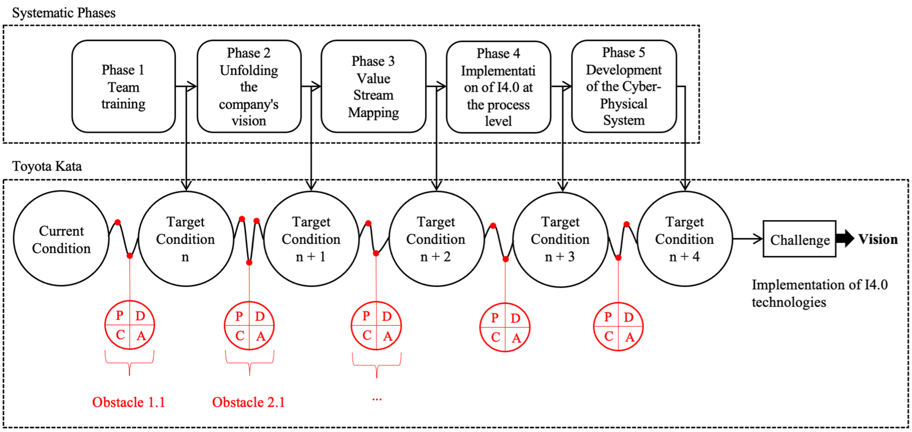

Fig. 4. General overview of the systematic.

- Phase 1 – Team training: The improvement process is necessary to evaluate the organization's current condition concerning TK, I4.0, and CPS knowledge. Thus, according to the company's maturity level, participants in the improvement process should be trained with the fundamentals of the necessary concepts if there is a knowledge gap.
- Phase 2 – Unfolding the company's vision: To use the Toyota Kata routine, the True North or the company's direction must be clear, and its unfolding to the lower levels must be carried out. Thus, based on a larger objective of the organization, the challenge for each team is defined. This way, the challenges of the different levels will be linked to the organization's objectives, and the new Target Condition of one level will be the challenge of the lower level.
- Phase 3 – Value Stream Mapping: It is from the Value Stream Map that the opportunities to implement the technologies of Industry 4.0 are identified. The tool also ensures that the improvement does not arise from an isolated initiative. Instead is guided in

what the company is prioritizing. It is recommended that the elaboration of the VSM is carried out with the participation of everyone directly involved with the processes that belong to specific flows, such as supervisors and employees at the operational level, to identify the real problems of the value flow and make the correct definition of the direction of improvements.

- Phase 4 – Implementation of I4.0 at the process level: From the Value Stream Map and the breakdown of activities at the different hierarchical levels of the organization, the team can select a specific process and start the implementation of Industry 4.0 technologies at the process level. The new technologies to be implemented in the value stream must assist employees and not replace them; currently, they will continue to participate in the improvement process.
- Phase 5 – Development of the Cyber-Physical System: The organization's Cyber-Physical System is the center of Industry 4.0, as it integrates the physical and digital components of the process. Sensors are responsible for capturing the production process parameters in real-time, and these data are sent to the company's Cyber-Physical System. In this way, a Digital Twin can be created, and the modifications can be simulated in the digital environment before being implemented in the actual process. Not only that, but the Cyber-Physical System can communicate with operators and inform the parameters of the production process in real-time.

During all phases, the Coaching Kata routine is used to understand the challenge, characterize de Current Condition, set the Target Condition, and list the obstacles blocking the team from going from the Current Condition to the Target Condition using the five-question card. This way, the team can iterate in short PDCA cycles towards the Next Target Condition. When the team achieves that Target Condition, another Target Condition towards the Challenge is set. By repeating this process, the organization can reach the final challenge that is the implementation of I4.0 technologies.

With the Toyota Kata approach carried out in the form of short cycle experiments, improvement is encouraged as a routine among the participants in the process, as it requires the presence and involvement of all employees to think about solutions and test them, thus aiming the sustainability of improvements in the organization. Using the system proposed in this work, organizations can start Industry 4.0 and make their processes more efficient and connected. Industry 4.0 technologies enable faster and more efficient decision-making and creating a Digital Twin factory that allows improvements to be tested in the digital environment before being implemented.

6 Theoretical Case Study

The Systematic for Process Improvement Using Cyber-Physical Systems and Toyota Kata developed in this work was implemented in a hypothetical and simulated case study conducted by post-graduate students at the GEPPS (Engineering Group of Products, Processes, and Services) of the Federal University of Santa Catarina.

According to [35], simulation models can provide most of the information needed to design, analyze, and operate complex systems. The manufacturing field is an area in which process simulation tools are essential to validate methods and architectures before applying them to the shop floor [36]. For [37], simulations bring benefits such as low cost, ease of use, and richness of details concerning a natural system. In sequence, the elements used in this theoretical case study are presented. Furthermore, Table 2 presented at the end of this topic summarizes the Systematic for Process Improvement Using Cyber-Physical Systems and Toyota Kata developed in this work with the case study outputs.

The simulation environment used for this study is based on a model developed by [26] that represents a bicycle manufacturing process of a fictitious company called Pedal+. The model reproduces a company's manufacturing system in terms of logical and quantitative aspects, which can be manipulated and altered to observe how the system behaves. Different types of workstations (such as material receiving, assembling components, welding, painting, and final assembly) can be changed to check their influence on system behavior. Thus, several scenarios can be tested and their implications directly observed.

The model's objective is to assist teaching, research, and training of Lean practices, carrying out experiments in an environment similar to the industrial one.

In the initial stage of the simulation, Pedal+ has three production lines with four working cells and a painting process that works in batches. Raw material deliveries take place daily, and shipment takes place weekly. Inter-process inventories have no control.

Following the phases of the Systematic for Process Improvement Using Cyber-Physical Systems and Toyota Kata, the information on the Current State of the production system was given to participants. As the students were already familiar with the TK approach, I4.0 and CPS, no training or capacitation was needed (phase 1). Next, the unfolding of the company's vision (phase 2) was developed as being "become a reference in quality and service, consolidating the brand in the regional market, maintaining above all the well-being and satisfaction in the organizational environment."

With the information of the productive system in hand, the team started using the TK approach to draw the Current State VSM (phase 3) with the help of the software SIMIO® (Fig. 5). After the characterization of the current state, the team begins to think about which I4.0 technologies should be implemented in the production system to understand better how it is working (phase 4) and what improvements could be implemented.

As the main objective of the implementation of I4.0 is to acquire information about how the system is behaving, the team opted to implement RFID sensors to develop the Cyber-Physical System of the Pedal+ (phase 5). The team decided to implement supermarkets between the cells and pulled systems, controlled by electronic Kanban (e-Kanban) to control the inventory. The team could calculate and simulate the ideal parameters for all the e-Kanban systems from the RFID sensors and the CPS data. The comparative results before and after the e-Kanban systems are presented in Table 1.

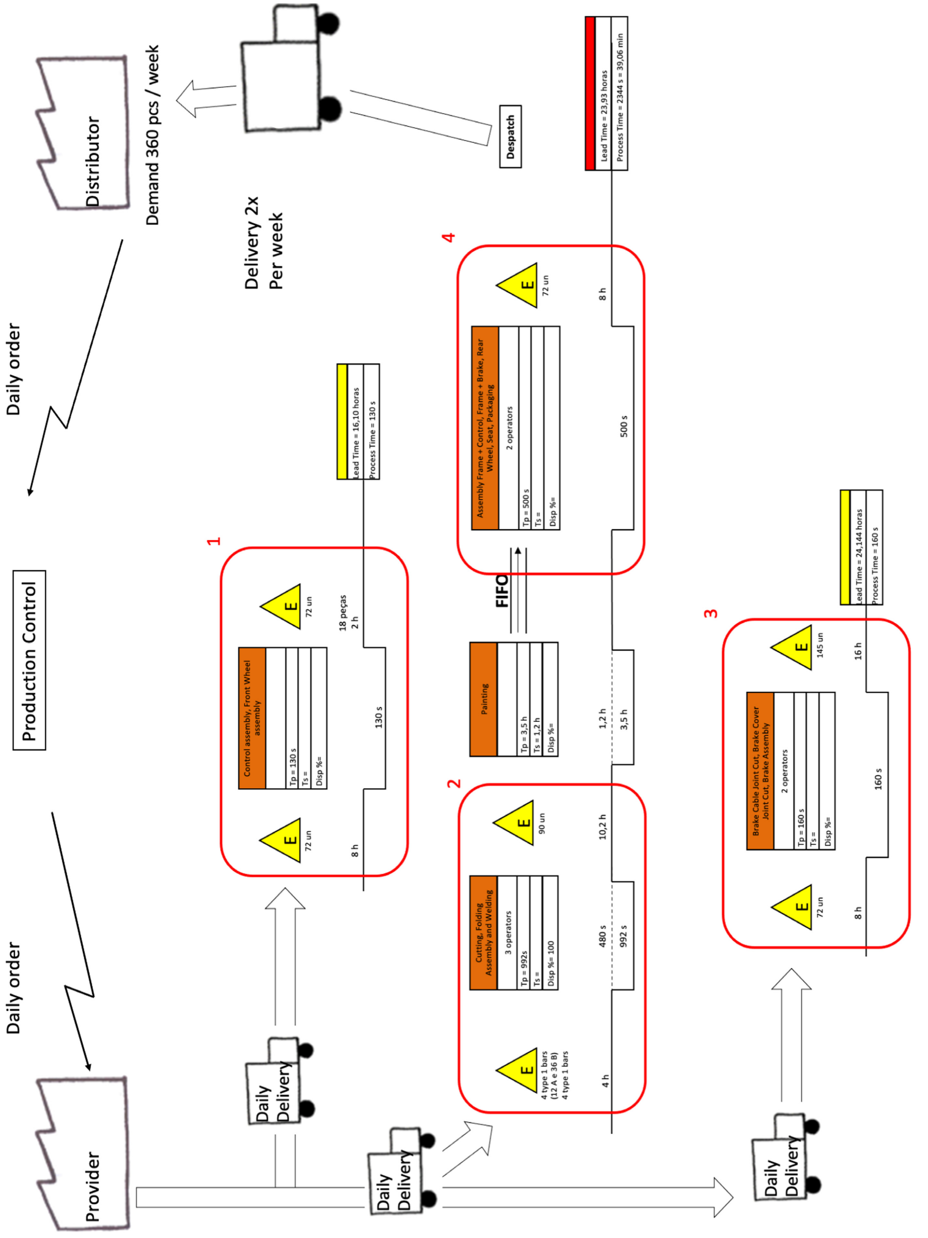

Fig. 5. Current state VSM.

Table 1. Inventory before and after e-Kanban

Process	Before e-Kanban [uni]	Time [hours]	After e-Kanban [uni]	Time [hours]
1 and 2	72	8	18	2
Two and painting	90	10,2	30	3,4
3 and 4	145	16	18	2
Total	**307**	**34,2**	**66**	**7,4**

With this modification, the number of units stocked between Pedal+ production processes decreased from 307 units to 66 units, representing a reduction of 26,8 h of the total Lead Time. With the modification implemented, it was possible to observe that the sensors of Industry 4.0 had the role of providing information from the production system for the team's decision-making. The Lean approach was responsible for the optimization of stocks with the implementation of supermarkets.

Another problem identified by the team was the defects produced by cell 4, which had a 23% rework. In this simulation scenario, errors occur during the bike's assembly stage since the parts arriving from the auxiliary lines are placed in boxes, and the assembly happens at random; that is, the operator decides the assembly sequence of the parts. To correct the errors identified by the assembly process. The team implemented a process so that the bicycle assembly occurs in a standardized manner and the sequence determined, as shown in Fig. 6.

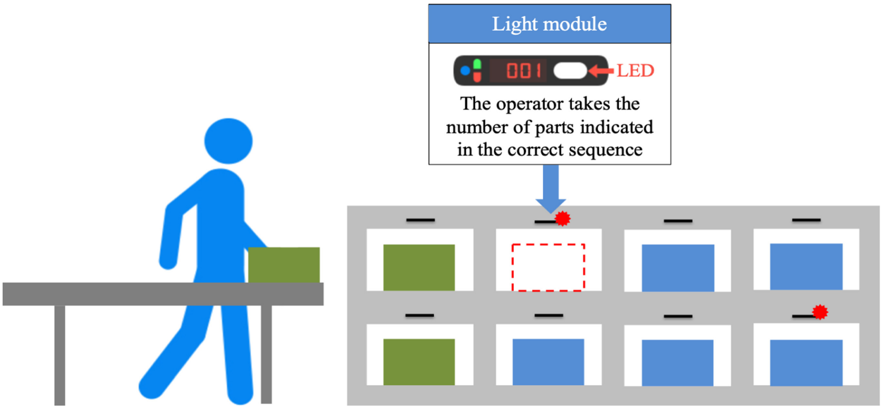

Fig. 6. Pick to light and put to the light system.

With the implementation of the system, the team verified that errors in the assembly process were eliminated.

The improvements proposed in the VSM of the future state were implemented in the SIMIO® software to simulate the new Current Condition of the organization (Fig. 7).

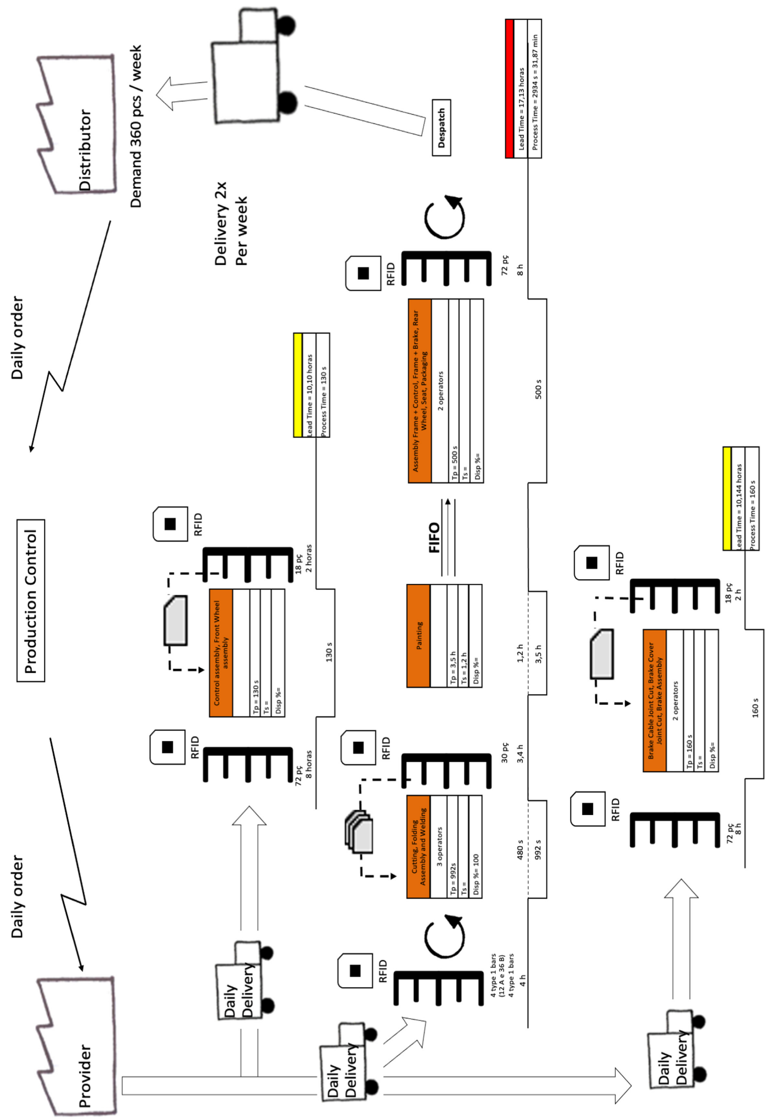

Fig. 7. Future state VSM.

Table 2 summarizes the use of the Systematic for Process Improvement Using Cyber-Physical Systems and Toyota Kata, its phases, and its outcomes for this case study.

Table 2. Phases of the Systematic for Process Improvement Using Cyber-Physical Systems and Toyota Kata and its outcomes.

Phase	Description	Outcome
1	Team training	As the participants were already familiar with the TK approach, I4.0 and CPS, no training or capacitation was needed
2	Unfolding the company's vision	The company's vision was developed as being "become a reference in quality and service, consolidating the brand in the regional market, maintaining above all the well-being and satisfaction in the organizational environment"
3	Value stream mapping	The team used the TK approach and the software SIMIO® to draw the Current State VSM, as shown in Fig. 5
4	Implementation of I4.0 at the process level	Implementation of RFID sensors, implementation of supermarkets between the cells and pulled systems, controlled by electronic Kanban (e-Kanban). Implementation of a pick to light and put to the light system to correct and avoid errors
5	Development of the Cyber-Physical System	The Cyber-Physical System was developed on SIMIO® with the information acquired by the I4.0 sensors

7 Conclusion

From the case study carried out in this work, it became evident that Industry 4.0 does not alter an organization's production processes' physical capacity but facilitates and controls the exchange of information more efficiently.

Concerning the understanding of the systematics proposed in this paper, simulation fulfilled its role of exemplifying the Systematic for Process Improvement Using Cyber-Physical Systems and Toyota Kata in a simulated company. In this specific case, there may be a double interpretation when using the SIMIO® software. If the information about the value flow were acquired from a natural process and fed into the software, creating a Cyber-Physical System can help organizations visualize their process flow and simulate a future state with improvements. Thus, the effect of the changes can be evaluated before they are implemented on the shop floor.

Finally, we conclude that the Toyota Kata approach provides a managing structure that can be used to develop the Cyber-Physical System of an organization and improve its processes with simulation and a connected production system. For future works, we recommend applying the systematic developed in a natural environment to understand better how it behaves and what improvements and refinements should be made.

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Manufacturing Execution System as an Integration Backbone for Industry 4.0

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Abstract. Manufacturing Execution System (MES) has been applied to plan and manage production on the shop floor level. Some of its functions include monitoring output, quality control data, and operator productivity. It works between the automation layer and the administrative IT systems, enabling the vertical integration of information. Although MES has already been applied in manufacturing for many years, we argue that the MES is well-developed to play a central role in Industry 4.0 implementation efforts. Advanced connectivity has allowed the MES to gain more information from the shop floor entities. In this scenario, MES may be an integration backbone for Industry 4.0, connecting machines to the manufacturing control logic, collecting data, and providing information for decision making. This paper aims to discuss an updated view of MES's role in manufacturing as a fundamental enabler for data integration in Industry 4.0 environments. A pilot advanced MES case application in an Industry 4.0 manufacturing environment is developed and described. A learning factory has been selected for the pilot application in this research due to its flexibility to allow the necessary IT system changes. In the developed scenario, an MES is applied to control the manufacturing of a customized product. The MES receives the product configuration data from the ERP system, controls shop floor equipment, and manages operators' activities. Product data is gathered along the process. Based on this case application, current MES potential and limitations are explored.

Keywords: Manufacturing Execution System (MES) · Industry 4.0 · Product Data Management (PDM) · Product Lifecycle Management (PLM)

1 Introduction

Industry 4.0 is an initiative to transform industrial manufacturing through digitization and the application of new technologies [1–3]. The implementation of these new technologies is supported by data carried by the traditional IT systems – PLM (Product Lifecycle Management), ERP (Enterprise Resource Planning), and MES (Manufacturing Execution Systems) [4]. In this landscape, the MES has a critical role in how Industry 4.0 can

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be implemented. The MES is key to achieving the flexibility and integration envisioned in Industry 4.0 [5–8].

Typically, the MES doesn't have a single function but has many supporting, guiding, and tracking primary production activities [9, 10]. The MES is applied to oversee plant floor activities, for example, scheduling, data collection, and quality control. These systems are used to identify the optimal sequence planning considering the process constraints (e.g., time for setup and processing) and the workstations' available capacity. MES are also used to monitor output, consumable usage, and operator productivity. Therefore, the MES can provide the manufacturer with long-term trends on manufacturing efficiency by considering raw material consumption and the number of parts produced [11].

The MES works between the automation layer and the administrative IT systems like ERP [12]. The ERP is an enterprise-wide information system that integrates and manages business processes across the company [11]. The MES develops physical and logical links between ERP and manufacturing. It enables the information exchange between a company's organizational level and the systems on the shop floor. It also manages the bottom-up information flow, collecting shop floor information and analyzing it through mathematical techniques.

MES systems have been in place for many years as an important enabler for performance, quality, and agility in manufacturing [4, 9, 10]. Although the MES has already been applied in manufacturing for a long time, we argue that it is well-developed to assume a critical role in Industry 4.0 implementation efforts. Industry 4.0 is based on the integration of business, manufacturing processes, and value chain actors [1]. Industry 4.0 envisions a factory floor with autonomous and intelligent entities that are integrated and decentralized [13]. This will allow for a more flexible manufacturing process and the possibility for products to be customizable. Therefore, some of the technologies used are Cyber-Physical Systems (CPS) and the Internet of Things (IoT). Advanced CPS are autonomous systems that can make their own decisions based on real-time data capture, analytical results from machine learning algorithms, and past machine behavior [1]. In this Industry 4.0 scenario, MES may be currently seen as an integration backbone, connecting machines to the manufacturing control logic, collecting data, and providing information for decision making.

This paper aims to discuss an updated view of MES's role in manufacturing as a fundamental enabler for data integration in Industry 4.0 environments. A pilot advanced MES application in an Industry 4.0 manufacturing environment is implemented and described. Based on this application, current MES potential and limitations are explored.

The paper is structured into six sections. After the introduction of the research topic in Sect. 1, Sect. 2 discusses a brief understanding of Industry 4.0 and MES. Section 3 provides the research approach developed in the paper. Section 4 presents the MES scenario implementation at a Learning Factory. Section 5 provides a discussion of the results. Finally, the conclusion and an outlook on further research needs are discussed in Sect. 6.

2 MES in the Industry 4.0 Context

Industry 4.0 is a broad concept that encompasses several enhancements in manufacturing strategy and environments, including increased flexibility to support product customization [5, 14] and advanced connectivity [1, 15].

Production flexibility levels required by Industry 4.0 demand a decentralized MES configuration [4]. It will still be a single data structure, but it will allow decentralized data capture and processing by Cyber-Physical Systems [8, 16, 17].

Every CPS will need to have the intelligence to identify itself and connect to a centralized system, providing that system with its position and state. The associated computing power can be elsewhere [18, 19]. Information will be provided from each entity and relayed to the MES, where this information can be gathered and shared. This allows each product to have its unique transformation process, leading to the needed flexibility for product customization to be carried out [13].

As discussed on ISA-95, there are different levels of integration in the manufacturing system. The MES is positioned as the third level of integration, connecting the production and control environment and allowing the operations management [20]. Besides, as proposed in the MESA c-model, the MES should be responsible for collecting operations information over the different manufacturing systems and components [21].

Advanced connectivity has allowed the MES to gain more information from the shop floor entities [5–8, 13, 16, 22, 23]. This advanced connectivity means the MES does not require complex systems and interfaces on the operational front, so staff can instead use more adaptable interfaces that can be used more easily and remotely [13].

In this scenario, the MES is crucial to gather a broad range of manufacturing information, analyze it and relay it to the ERP. A continuous information flow between all elements demands both horizontal and vertical integration. Integration of data from different systems is also one of the pillars of Industry 4.0 [9]. Vertical integration allows information flow between CPS and the MES. All services provided by Cyber-Physical Systems should be considered. It ensures CPS makes decisions that comply with the rules set out by the manufacturer [13]. Thus, the activities on the factory floor can be visible, managed, and accurately measured. With the information gathered, optimum parameters can be determined to increase manufacturing efficiency and product quality. The collected information is also important to allow for horizontal integration. Horizontal integration enables the smart supply chain to be transparent as each element of the supply chain's status is visible.

Recent advances indicate that MES could also be integrated with a Digital Twin (DT) to allow further transparency in the manufacturing process. A Digital Twin deals with this physical/digital duet [24–27]. "A digital twin is a digital representation of an active unique product … that comprises its selected characteristics, properties, conditions, and behaviors by means of models, information, and data within a single or even across multiple life cycle phases" [28]. By integrating the MES with the shop floor, including the Digital Twin, this bilateral communication between the physical and digital objects can exist [8].

3 Experiment Setup

In this research, an advanced MES scenario for Industry 4.0 has been implemented and tested in a Learning Factory. Conducting the research on a Learning Factory enabled the necessary freedom to operate technical changes and enhancements on the IT systems and equipment. At the same time, the Learning Factory provided requirements and tradeoffs that mockup a real manufacturing setting.

The selected Learning Factory is located at a university school of engineering in Brazil. It demonstrates the assembly of a customizable skateboard in the context of Industry 4.0. Figure 1 shows the Learning Factory assembly line with five workstations, numbered in yellow. Each workstation is focused on specific assembly activities: 1) two trucks assembly to the skateboard deck; 2) four wheels assembly to the trucks and quality control; 3) skateboard shock absorber customization; 4) 3D printed options (e.g., rails) assembly and product delivery. Materials are supplied for the workstations with a milk-run cart specially designed for this purpose. Workstation 5 is used to disassemble products for material reuse for further testing procedures. Therefore, it is considered separately from the assembly workflow.

Fig. 1. Learning Factory overview with workstations for product assembly

Besides the assembly line, the Learning Factory also features a production cell equipped with two 3D printers for the production of low-volume and high variety skateboard accessories.

The Learning Factory sample skateboard product can be customized for each production order. The wheel colors can be chosen from a list of available alternatives. Wheel colors can be different for the front and back wheels. The shock absorber can be set on a scale between soft and rigid. This selection results in a torque adjustment on the skateboard truck. Accessories such as 3D printed rails and a connectivity box (for a smart connected product) are available. Figure 2 presents a schematic view of the product with its main configuration elements.

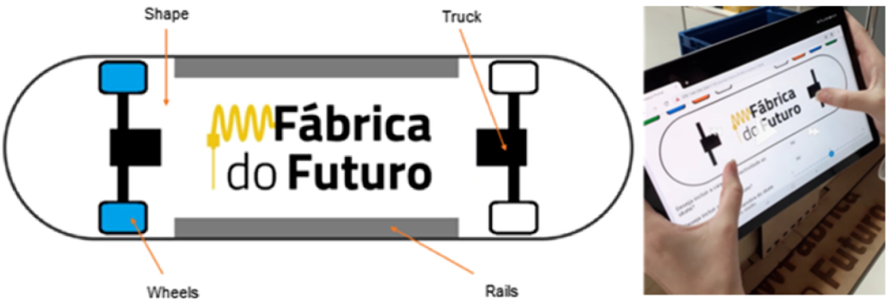

Fig. 2. Skateboard representation and its Product Configurator

The research involved implementing three central manufacturing IT systems: PLM, ERP, and MES. After that, different applications were developed at the individual MES level to show MES integration as the backbone for Industry 4.0.

The PLM, ERP, and MES were implemented on the university cloud services. The PLM system was implemented on a high-performance (8vCPU, 16 GB RAM) Virtual Machine (VM) running an SQL Server and structured on a relational database. The ERP system was implemented on a high-performance extra memory machine (8vGPU, 32 GB RAM) on a VM running SQL Server running a relational database on a progress environment. Finally, the MES system was implemented on a regular (2vCPU, 8 GB RAM) VM running SQL Server and having a relational database on a SQL Server environment [29].A Java-based Product Configurator (customization interface) was developed to receive the individualized customer request (Fig. 2). The Product Configurator was integrated with the ERP sales and product order module to receive customer orders.

The MES software already had a predefined integration script with the ERP system. This integration automatically captures the XML file from the ERP product order and converts it into the MES database format [29]. Thus, customized customer orders are placed on the Product Configurator interface, resulting in a production order in the ERP system, which is then transferred as an XML file to the MES.

At the Learning Factory, the MES is responsible for managing the assembly activities conducted at the workstation level. When the product assembly is concluded on workstation 4, the assembly data is reported to the ERP system, indicating that the production order has been completed and the product is ready to be delivered.

After implementing the PLM, ERP, and MES systems, three applications were developed and integrated into the MES. The first application integrates the MES with an image processing quality control device (MVISIA ESOS) on workstation 2. The second application connects the MES to the torque wrench device (Atlas Copco ETP STB33) on workstation 3. Finally, the third application connects the MES with a 3D printer (DDDrop EVO Twin) for the production of optional parts. All three applications have the MES data structure as the backbone for production information, as represented in Fig. 3.

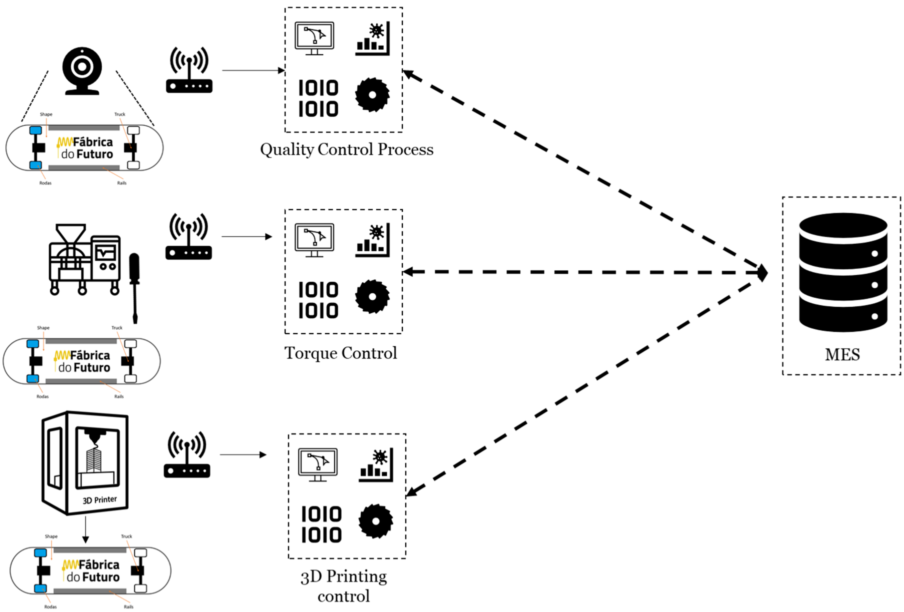

Fig. 3. MES connecting different CPS devices

Figure 3 presents a schematic overview of the implemented and tested solutions in this research. This picture shows three independent manufacturing and assembly equipment and applications that receive MES information. The information is order-specific and varies for each product being assembled. The information provided by the MES is needed to trigger the assembly according to the specific production order parameters. When an activity is concluded in a workstation, the order execution parameters (e.g., quality parameters) are sent as new information to the MES system database.

After the implementation, tests were conducted to assess the solution and support discussion on the MES role in Industry 4.0 manufacturing environments.

4 MES as an Industry 4.0 Backbone for Flexible Production

This section details the implemented MES scenario. Therefore, the production order process flow is described. A customized customer order is inputted into the Product Configurator, and a production order is created in the ERP System. Customizable parameters include wheel colors for front and back trucks, the torque applied to the shock absorber (soft to hard), and the optional items selection. The ERP system transmits the production order parameters to the MES via an XML file.

The configuration is sent through the MES to the first workstation, where the trucks are assembled to the skateboard deck. The MES controls a printer used to print a QR code order ID tag, which is attached to the product.

At the second workstation, wheels are added to the truck. The operator receives the information about the wheel color to be assembled on the MES screen. After the manual assembly is completed, an automated quality check is performed. A quality control camera is positioned on the top of this workstation. The quality control camera takes pictures and uses computer vision and machine learning to check if the wheels' positions and colors match the customer order. The computer vision camera information is compared to the MES configuration information, providing automated quality control. The operation can only be concluded in the MES if the quality is approved – Fig. 4 details the implementation.

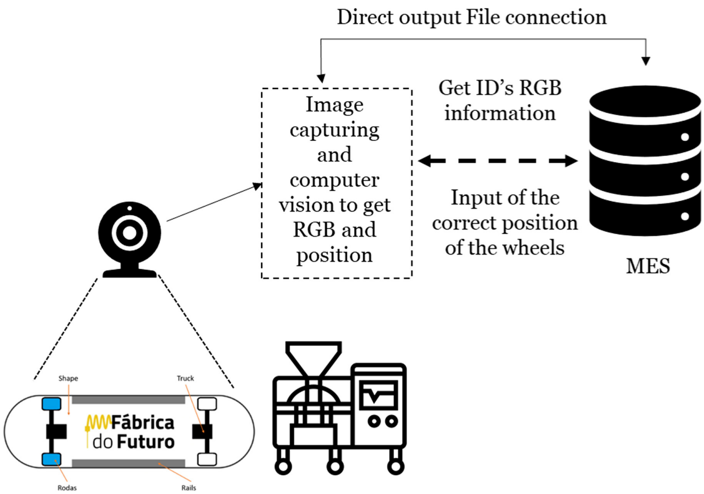

Fig. 4. Image recognition quality control integrated to MES

The camera positioned on the top of this workstation works on the connection. The camera is connected to the internal data network. The camera connects with the MES data structure to get the product configuration data based on the product ID. The camera then collects pictures of the assembly. The RGB of each wheel is identified with a computer vision algorithm. The identified colors are compared to the ones requested by the MES. All the data is remotely processed on the CPS. The MES provides the requested colors and receives the quality control information (approved/not approved). If there is a mismatch between the production order data and the assembly, the errors are pointed out for the operator, including wheel color and position. The quality control data (time, operator, inspection result, etc.) is registered in the MES for traceability. Figure 5 presents a screenshot of the implemented solution.

At the third workstation, a torque wrench is used, providing customized torque to the truck shock absorber. The torque is informed by the MES to the torque wrench controller. Then, the actuator transforms this information into the application. The actual torque is informed to the MES for information tracking. The integration follows a more traditional approach – Fig. 6 shows the implementation model – the torque is read at the MES database, and a serial communication is started with the controller.

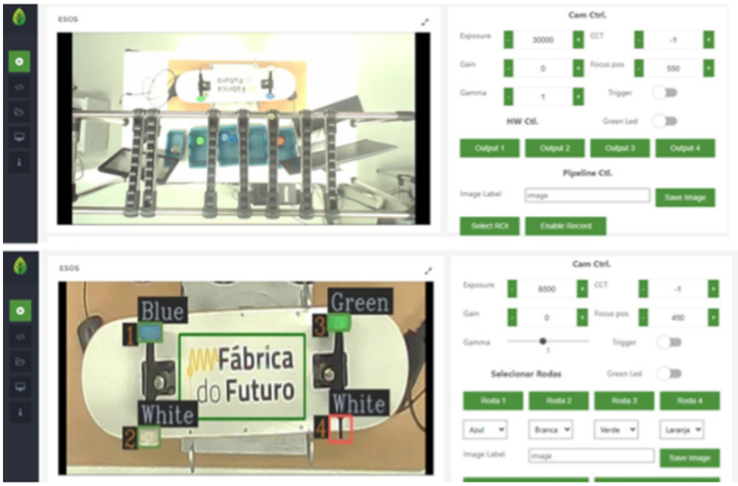

Fig. 5. Image recognition quality control implemented

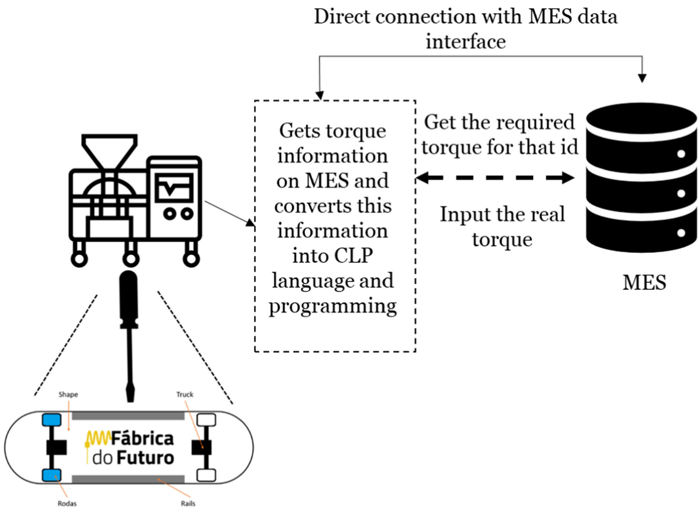

Fig. 6. Torque control system integrated to MES

Finally, at workstation 4, accessories can be applied as per the customer order. These accessories are produced using the two 3D printers available on the shop floor. As accessories are low volume and potentially high-variety items, additive manufacturing is suitable [30]. In the scenario, the 3D printers are started by the MES when a new customer order including 3D printed items is updated at the MES database. The MES also receives and registers progress information from the machines – Fig. 7 details the implementation model.

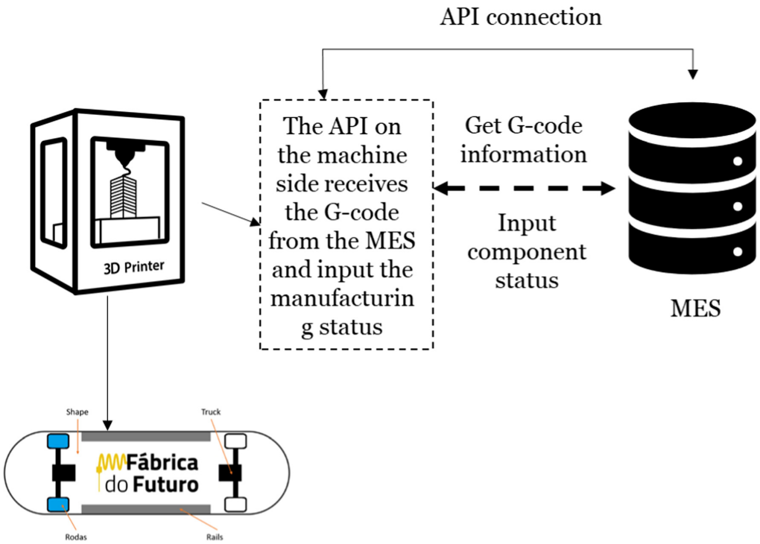

Fig. 7. 3D printing implementation model integrated to MES

The connection, in this case, is allowed by a python odbc connected with the MES and a Java API on the client-side of the 3D printer. The basic principle of the API is to send a request to the machine containing the G-file requested for the part's manufacturing. On this file, the machine's initial setup, as temperature, layer thickness, etc., is given to the machine. On the MES side, the API requests the manufacturing state to update the system's information. Finally, the part status is changed to ready after the machine indication and the production is updated.

The information flow on the implemented scenario has been represented in Fig. 8. It demonstrates that the MES has a central role in manufacturing. The MES connects the production information with the management systems while predicting and controlling the steps that need to be performed to complete the manufacturing process.

5 Discussion

In the Industry 4.0 MES scenario application presented, it was possible to identify two MES developments. First, even though MES continues to be the way to bridge data from the shop floor to the management levels, it now has a central role in manufacturing. The MES connects product information to manufacturing and management systems, enabling real-time decisions. Second, MES now represents an integration platform for different applications and manufacturing equipment at the production level. These applications are single connected nodes that receive data from the MES and sent new inputs for the system.

The MES possesses the central data structure in the shop floor and can, indeed, serve as the backbone for Industry 4.0 IT transformation. This vision has already been discussed in previous works [4, 8, 13, 16, 22, 23].

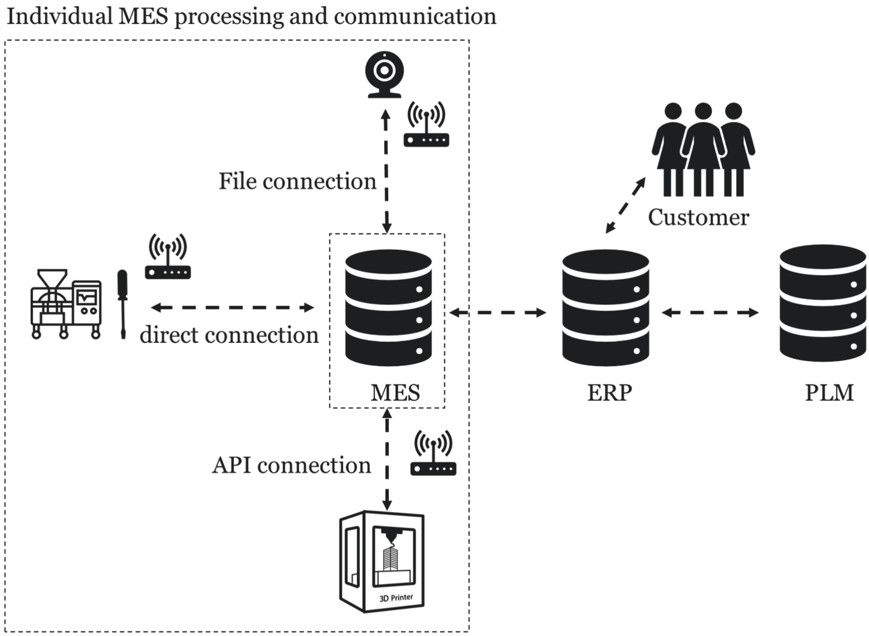

Fig. 8. Information flow

The MES position has been evolving from a manufacturing system that oversees the production and coordinates the manufacturing to integrating the data of different connected and distributed systems, becoming the backbone of the entire manufacturing environment [27].

Through this integration, the MES can help provide greater flexibility to allow for one-of-a-kind production [5–8]. This is demonstrated through the customizable elements (wheel colors, torque applied, optional items selection) in the implemented MES scenario. Therefore, this research expands previous efforts by demonstrating an implementation exploring the MES integration potential. In this research, the MES also connects decentralized manufacturing equipment. However, this integration is realized to a central decision-making logic. The MES evolution and role in a decentralized decision-making scenario remains open for further research.

6 Conclusion

This paper discusses an updated view of MES's role in manufacturing as a fundamental enabler for data integration in Industry 4.0 environments. The paper presents a pilot advanced MES application in a Learning Factory. The pilot application explores MES potential to link product and manufacturing data and equipment.

The implemented scenario demonstrates that MES may be a key enabler to Industry 4.0 initiatives in manufacturing. The tested application indicated that the MES enhanced flexibility for product customization. Moreover, it played a significant part in data collection and decision support. The studied MES application enabled integration between the individually connected equipment and management systems, connecting the shop floor with the ERP and supporting a continuous flow of information between the different control levels.

Besides, the MES must be prepared to connect with different types of information and protocols. It can be through an API, as in the 3D printer model, a direct connection, as in the torque wrench, a file exchange, as in the computer vision, or any other connection protocol. In this way, the MES works as a platform to connect various individual data processors to the whole manufacturing environment.

This research has limitations regarding the use of open-source platforms for integration and a Learning Factory scenario for implementation. At the implemented Learning Factory scenario, future steps may include integrating the information of multiple applications to test the distributed MES system's latency and robustness. This experiment will evaluate the capacity of distributed communication between systems and machines. The Learning Factory implementation may also be enhanced to explore the MES role in a decentralized decision-making scenario. Future research work may also assess the evolving MES role in the industry. Therefore, case studies of advanced MES adopters and even a survey research approach may be conducted.

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Challenges to Asset Information Requirements Development Supporting Digital Twin Creation

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Abstract. The creation of a digital twin of rail infrastructure assets places greater emphasis on requirements engineering, model-based delivery methods, and digital information management to support the creation of both physical and virtual deliverables. However, requirements engineering capabilities are latent in comparison to complex discrete manufacturing. In this paper, we explore requirements engineering practices in Australian rail infrastructure projects creating digital twins for asset management and operations. An investigation of the challenges encountered by project teams during the development of asset information requirements for physical and digital deliverables was conducted using an in-depth literature review together with semi-structured interviews with rail project delivery teams. Challenges to the maturity of requirements engineering were categorised according to their main characteristics. The process, technology and supply chain issues identified provide empirical evidence of the pain points faced by delivery teams in developing asset information requirements in support of the creation of a digital twin. Findings serve as a starting point for further research into the development of requirements engineering methods distinguished by systems-based approaches.

Keywords: Requirements engineering · Digital twin · Asset management · Systems engineering · Rail infrastructure

1 Introduction

During the creation of a digital twin, informational requirements supporting the delivery and operations of physical systems, their virtual replicas, and real-time behaviours must be developed [1]. There are different types of information requirements related to the delivery and operational phase of rail infrastructure. The release of the International Standard ISO 19650, Parts 1 and 2 have provided rail projects with much needed consistency in the terminology, concepts, and principles of information requirements and related processes. The standard describes each information requirement type and process relative to the project delivery phases; it includes: i) organisation information requirements (OIR), ii) asset information requirements (AIR), iii) project information requirements (PIR), and iv) exchange (or employer) information requirements (EIR) [2, 3].

The information requirements defining rail assets follow a similar development process as in discrete manufacturing and software development projects; in what is a series

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of interconnected activities encompassing requirements elicitation and description, documentation and decomposition, analysis and allocation, and validation. However, recent research demonstrates that requirements development practices are relatively immature in the construction industry [4]. In complex construction projects generally, and in particular those creating digital twins to support rail infrastructure asset management and operations, lack mature methodologies and integrated tool ecologies to support information requirements development activities. Whilst ISO 19650 (Parts 1 and 2) [2, 3], provides much needed guidance to building and civil engineering projects in this area, there remains a lack of implementation-ready requirements development methods supported by software that can help automate, integrate, trace and record asset information requirements across temporary project-based supply chains.

Against this backcloth, the authors explore contemporary requirements engineering practices in rail infrastructure projects relative to the development of physical and virtual (digital twin) deliverables, and examine the challenges encountered by project stakeholders. The research aim is to identify and categorise challenges in order to understand the barriers to the development of asset information requirements that ultimately impact on the creation of a digital twin. The paper proceeds in Sects. 2 and 3 with an overview of related literature. Section 4 describes the qualitative research methodology, and Sect. 5 presents the categories of challenges and discusses findings derived from interviews with rail infrastructure stakeholders. Section 6 concludes the paper with recommendations and discussion of open issues concerning systems approaches to requirements engineering and greater emphasis on co-engineering.

2 Digital Twin Creation and Requirements Development

The "Digital Twin" (DT) concept was first introduced by Grieves in 2003 [5]. Since then, definitions and explanations of the DT concept have been proposed and refined [5–8]. DT technologies were adopted in the spacecraft sector in 2010 and later in complex manufacturing sectors [9, 10]. NASA were pioneers of DT technologies for remote monitoring, controlling and running simulations of spacecraft from Earth [11]. DT applications in the aerospace, defence and nuclear sectors are often regarded as some of the most advanced due to higher demands for managing and optimising the performance of complex assets [1]. The development processes surrounding the physical asset and its virtual replica are described by Boeing using the classic V-model of the systems development lifecycle, mirroring the 'V' to create a "Diamond Model" [12]. With Model-based Engineering (MBE) as its foundations, the Diamond Model reflects the co-development processes of both the physical and virtual assets (see Fig. 1). The lower V reflects the classic systems engineering process of the physical system, while the mirror reflection of the V above represents the DTs modelling and simulation [12]. The Diamond Model takes the classic V-Model transformation of product functional requirements to physical systems that are ultimately delivered as a product or service solution and incorporates the DT pathway as separate but integrated activities. The inverted V represents the design and realisation of the behavioural simulations [12]. The design and development process of the virtual model correlate exactly to the development of the physical baseline. In other words, the virtual informs the physical during the design, development, simulation phases, and as IoT devices are used, the physical informs the virtual. This interplay is simultaneous along the lifecycle and between the physical systems and their DTs [12]. The creation pathway of a DT is therefore predicated on a lifecycle approach to requirements engineering and information management, highlighting the critical role of software interoperability.

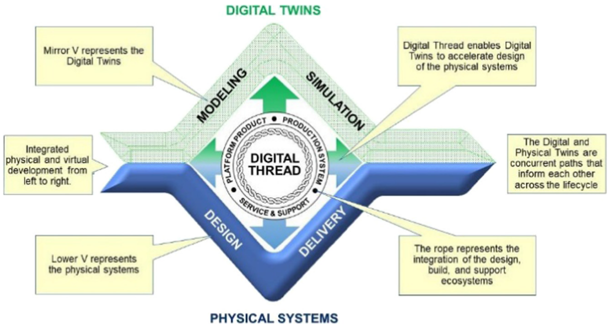

Fig. 1. MBE Diamond-Model [12]

In the built environment, the development of DTs are in the early stages, with few fully-realised examples [13]. The effective creation of a DT arguably demands object-based approaches to structured data requiring BIM model use. In a white paper on DTs in the built environment, the Institution of Engineering and Technology propose an industry-agnostic DT maturity spectrum with five maturity levels (Table 1) [14].

Table 1. Digital twin maturity spectrum defining principles and outline usage [14].

Maturity[1]	Defining principle	Outline usage
0	Reality capture (e.g., point cloud, drones, photogrammetry, or drawings/sketches)	– Brownfield (existing) as-built survey
1	2D map/system or 3D model (e.g., object-based, with no metadata or BIM)	– Design/asset optimisation and coordination
2	Connect model to persistent (static) data, metadata, and BIM Stage 2 (e.g., documents, drawings, asset management systems)	– 4D/5D simulation – Design/asset management – BIM Stage 2
3	Enrich with real-time data (e.g., from IoT, sensors)	– Operational efficiency
4	Two-way data integration and interaction	– Remote and immersive operations – Control the physical from digital
5	Autonomous operations and maintenance	– Complete self-governance with total oversight and transparency

[1] Logarithmic scale of complexity and connectedness.

Systems requirements engineering in digital twin creation is emphasised due to inherent product, process, and stakeholder complexities. Product complexity exists relative to the asset itself, its virtual replica and real-time behaviours. Process complexity is present in the interdependent activities supporting the elicitation, description, documentation, decomposition, analysis and allocating of AIRs. Stakeholders complexity exists relative to the presence, power and influence of project team members involved (or not) in information requirements development activities. The recent release of the ISO 19650 standard provides a step-change that can help address these complexities. ISO 19650 describes the processes supporting digital information management in the context of buildings and civil engineering works, including building information modelling (BIM) [2, 3]. Used in conjunction with the asset management standard ISO 55000, rail project teams are able to implement consistent and structured processes to support the identification of appropriate, relevant, and effective information requirements. The outcome of the information requirements elicitation and description activities starting with OIRs (the business case) is focused on the creation of AIRs, and ultimately the development of robust libraries of AIRs that can inform what data an organisation should be collecting and why it necessary throughout an asset's lifecycle. As a result, the EIRs supporting the creation of a DT can be identified.

In the built environment, to support requirements engineering processes, a range of software tools have seen steady increases in their application on AECO projects. A growing body of complex building and civil infrastructure projects are utilising tools to support requirements management, configuration and validation [4]. Adoption is largely driven by the need for AECO projects to identify and trace dependencies between requirements [15]. In other case studies on BIM-enabled building projects have investigated the effectiveness of requirements planning and management tools, including IBM Rational DOORS, dRofus, TRAM, ReqMan [16]. IBM Rational DOORS is a widely utilised tool in civil infrastructure projects, and in particular in rail infrastructure [20]. DOORS is an object-oriented requirement system supporting the capture, traceability, analysis, and management of requirements changes across the development lifecycle [17]. However, a drawback of the use of DOORS on rail infrastructure projects is its lack of support for automating the validation of requirements by linking to the 3D model. dRofus provides a centralised, data-driven platform supporting requirements traceability and change management, as well as client requirements capture and facility standards management [16]. Compared to IBM Rational DOORS, dRofus has limited requirements management capabilities that focus on the architectural and spatial elements of the building [4], however it does support validation by linking to the 3D model.

Yet, despite the use of requirements management software on AECO projects, the interactions between the myriad of interdependent requirements often go unchecked and as a result remain independent. Linking requirements management software with information contained in 3D models (or linked databases) to automate traceability and verification processes are therefore rare. Software companies and service providers from outside the built environment are introducing tools from aerospace and automotive sectors. Established requirements assurance and validation software supporting efficient requirements management and traceability processes have recently been introduced in rail infrastructure projects in Australia [18]. The use of software and validation services in rail infrastructure projects assumes that information requirements have been developed in accordance with an asset system hierarchy [19] and that the value of requirements assurance and validation processes extend beyond project delivery. Deficiencies in repeatable requirements development processes and availability of structured data also prohibit the value of systems approaches to requirements engineering in rail projects. Compounding these issues, is the lack of maturity in the co-engineering and collaborative information requirements development process supporting the physical and virtual assets.

3 Challenges to Information Requirements Development

Challenges to requirements development and related digital information management capabilities were investigated and categorised using three core areas of industry maturity, namely requirements development – i) Processes, ii) Technologies, iii) Supply Chain. By reviewing the AECO literature, the intention of the authors is to identify challenges specific to requirements engineering and related digital information management to understand their potential impact on the creation of DTs throughout project delivery. In total, 36 papers from AECO domains were identified and 19 papers were reviewed after eliminating papers that did not meet the search criteria. The search criteria restricted papers to those using model-based approaches to project delivery with DT or BIM based facilities management (FM) deliverables. Due to the limited scope of this paper, a summary of the most relevant findings is reported in Table 2.

Table 2. RE and related digital information management challenges

Year	Challenge	Source	Maturity classification
2010, 2016, 2019	Change of requirements/evolution of client needs	[20–22]	Process
2012	Highly distributed requirements development with different levels of abstraction	[23]	
2013, 2015, 2021	Incomplete information requirements documentation, decomposition, analysis, and allocation	[24–26]	
2014	Lack of common language supporting information requirements development processes	[27]	

(*continued*)

Table 2. (*continued*)

Year	Challenge	Source	Maturity classification
2015	Unstructured and late delivery of data and information to the FM phase of buildings	[28]	
2015, 2017	Lack of application of standards or guidelines supporting information requirements processes	[28–30]	
2013, 2015, 2018, 2019	Lack of interoperability	[25, 28, 31, 32]	Technology
2014, 2017	Heterogeneous data inputs and outputs (e.g., different levels of detail, formats, units, etc.)	[29, 30, 33, 34]	
2016, 2017, 2019	Limited software support for managing conflicting requirements	[20, 30, 35]	
2017, 2020	Multiple disconnects in the flow of information due to technology-based deficiencies	[29, 36]	
2018	Limitations to systems requirements engineering software configuration	[37]	
2018	Ongoing investment in requirements engineering software	[37]	
2012	High level of diversity of stakeholders across distributed requirements development process with different levels of abstraction used by different stakeholders	[23]	Supply chain
2013, 2015	Lack of clear roles and responsibilities, lack of contract and liability framework	[25, 28]	
2014	Missing links between requirements captured in the user requirements' document and their functional specification	[33]	

(*continued*)

Table 2. (*continued*)

Year	Challenge	Source	Maturity classification
2015, 2017, 2019	Missing stakeholders and lack of collaborative work amongst the team during early design phase	[29, 32, 38]	
2017, 2019	Lack of awareness/expertise of standards or guidelines supporting information requirements processes	[29, 30, 32]	
2018	Ongoing investment in training of requirements engineering software	[37]	

Table 2 summarises the three types of challenges, including those related to:

i. *Process maturity*: The continuous changes to AECO requirements and lack of adequate change management processes is one of the most well-documented challenges reported by researchers over the last decade [20–22, 34, 39]. Whilst this challenge is common to all project types – and is not unique to projects with DT or BIM based FM deliverables – the specification and allocation of OIRs combined with the consistent management of AIRs and EIRs throughout the project amplify traditional requirements change challenges. Other issues surround deficiencies in the requirements specification process resulting in unclear, incomplete [24] or conflicting requirements [20, 35], the lack of process standards [28–30], unstructured and late delivery of data and information to FM phases [28], and absence of a common language for AECO requirements [27].
ii. *Technology maturity*: Issues included errors or failures related to software interoperability [25, 28, 31, 32], deficiencies in common data input and output requirements [29, 30, 33, 34], limited software support for managing conflicting requirements [20, 30, 35], breaks in information flow due to a lack of platform enabled technologies [29, 36], and the lack of requirements engineering tool integrations and ongoing investment on requirements engineering software [37].
iii. *Supply chain maturity*: The spatial and organisational separation of stakeholders creates obvious challenges to collaboration and communication [23]. And there is a lack of clear roles and responsibilities, contract and liability framework for information requirements management [25, 28]. Missing links between high-level user requirements and their functional specification can as a result become amplified [33]. Further, early involvement of all stakeholders is essential for requirements elicitation, prioritisation, negotiation and communication. The absence of key stakeholders during the early design phase brings challenges to all activities in the requirements development process due to knock-on effects to downstream requirements-dependent tasks [29, 32, 38]. In terms of knowledge and expertise, there is a lack of

awareness and expertise of standards and guidelines supporting information requirements processes [28–30]. The ongoing investment on requirements engineering software training is also regarded as a supply chain wide challenge [37].

4 Information Requirements Development Case Study

Following the literature review, the research collected primary data to investigate the challenges encountered by project teams when developing and managing complex and interdependent information requirements.

4.1 Research Design and Method

A case study [40] approach was adopted, and data collection involved semi-structured interviews with industry experts in the rail infrastructure domain who have participated in public rail project.

The semi-structured interviews ensured that multiple topics surrounding the research problem could be covered. Key interview questions therefore included the following areas: (1) experience in managing requirements of physical asset and digital deliverable, (2) Current challenges to developing and managing requirements (both functional and digital). Ten participants were interviewed across five companies (see Table 3). Interviews took place between February 2020 to May 2020. Each interview took approximately one hour, and recordings were subsequently transcribed and verified.

Table 3. Interviewees

Organisation	Role	# Interviewees
Developer	Digital Engineering Director	1
	Senior Project Manager	1
	Engineering Lead	1
	Systems Architecture Principal Engineer	1
Consultant	Systems Engineer	2
	Digital Engineering Lead	2
	Rail Systems Engineer	2
Total participants interviewed		10

5 Case Study Findings

Interviews were transcribed and analysed using the same taxonomy as identified in literature review. Findings identified a variety of challenges relating to all three categories identified from the literature – that is: process, technology, and supply chain maturity challenges. Analysis also revealed insights related to the adoption of more integrated and systems-based approaches to requirements engineering. Due to the limited scope of this paper, a summary of findings is provided in each following sub-section.

5.1 Process Maturity

Process maturity refers specifically to requirements engineering related processes and the integration of those processes with traditional AECO project management processes. A number of significant challenges were identified by rail infrastructure interviewees, including i) lack of requirements change management processes, ii) lack of validation process supporting physical and virtual requirements, iii) delays in information requirements development process (elicitation and description and documentation and decomposition activities), iv) disconnection in the workflows that support system architecture and project level requirements, v) lack of process standards supporting AECO requirements development and management, and vi) lack of agreed and consistent requirement language.

Lack of requirements change management process. Change of requirements keeps happening during the development and delivery of rail infrastructure. To minimums delivery risk, it is important to inform those project level changes to network level. However, this process is lack at the moment as captured by the following responses from the Systems Architecture Principal Engineer.

> "…changes occur at the project level without informing the upper level – the network level – to evaluate the impact on the data of service that is expected at that given time in the future…"—Systems Architecture Principal Engineer.

Lack of validation process supporting physical and virtual requirements. In sectors such as aerospace and automotive industries, requirements validation – ensuring specified requirements meet the customer needs – is recognised as a critical activity in the requirements development process. A lack of robust requirements validation in rail infrastructure was highlighted by all rail interviewees.

> "The behaviours that came from the Defence sector, where there is a lot of rigor in validating the mathematical information, is not being shared in construction industry."—Systems Engineer.

Delays in information requirements development process. The information requirements should be recognised during early planning phase and then fed into the design phase. However, the reality on many rail infrastructure projects is that this occurs during the detailed design and even construction phases.

> "…The rail systems are so fragile and sensitive… This industry is always at risk of making decisions that have side effects and unknown emergent properties and consequences that are picked up for too late…"—Systems Engineer.
>
> "The current rail industry is very, kind of, physically focused. The digital twin should be developed in parallel with physical rail. But it's very difficult to get the focus from the key stakeholders on the information requirements at the early stages of development…because the maturity of the industry is actually quite low with regards to the sort of requirements definition up front to feed into the design. It's very much geared around detailed design." —Digital Engineering Lead.

Disconnection in the workflows that support system architecture and project level requirements. In rail infrastructure, network level requirements are performance based, and should guide the development of project level requirements. However, there is disconnect between the planning of the system architecture and the elicitation of project level requirements as captured by the following responses from the Systems Architecture Principal Engineer.

> "…There is disconnect between the planning of the system architecture and how requirements are not derived from a well-planned definition of the system network so as to inform and spill into a project level…"—Systems Architecture Principal Engineer.

Lack of process standards supporting AECO requirements development and management. The use of industry standards typically indicates the maturity level of the industry. In rail infrastructure, there is a lack industrial-wide standards and guidance supporting structured processes and the management of information requirements throughout the lifecycle of the asset.

> "…different projects adopt a digital engineering approach in different levels of maturity… there is a lack of standards or structured guidance… and consistency across these approaches is really important…"—Senior Project Manager.

> "…people require information at different levels [of detail] in terms of how the systems wide requirements map with the project requirements and the functional requirements…"—Senior Project Manager.

In addition to the challenges identified above, it was noted by interviewees that the elicitation and documentation of information requirements underpinning the creation of DT in rail infrastructure is a complex and lengthy process which brings with it challenges related to the need to utilise an agreed and consistent requirements language which was seen as lacking in contemporary practice.

Lack of agreed and consistent requirements language. Consistent requirement language supporting effective and efficient communication and collaboration among multiple stakeholders of a project was noted as lacking across the sector. The lack of a common or standard requirement language used across different rail infrastructure projects was lamented by those engineers with systems backgrounds. "…there is no common set of requirements that go down…"—Rail Systems Engineer.

5.2 Technology Maturity

Technology maturity challenges refer to technology artefacts and, including software tools, software integration, interoperability, and data exchange as well as hardware and network technologies. The technology maturity challenges identified by interviewees include: i) interoperability of requirements management software with digital modelling tool chain, ii) disconnected data and processes within the common data environment, and iii) lack of tools supporting automatic information requirements validation.

Interoperability of requirements management software and digital modelling tool chain. Requirements management tools like IBM DOORS were reported to be commonly used in rail infrastructure projects. However, the software was not commonly used to support requirements elicitation and configurations management, with these software functionalities being underutilised. Automation of requirements validation using a direct link with the 3D model was also absent. An integrated tool ecology was therefore noted by most participants as lacking.

> "They use DOORS to baseline the requirements in project. The problem is many people don't use DOORS to create requirements… they derive requirements from multiple sources, many requirements come out from the concepts of operations and the concepts of maintenance…"—Rail Systems Engineer.

Disconnected data and processes within the Common Data Environment. The Common Data Environment (CDE) provides a cloud-based platform for stakeholders to share geometric information as well as related asset information such as registers, schedules, contracts, reports and model information. According to the rail infrastructure experts interviewed, the design or purpose of CDEs is often not configured to support a through-life approach to digital information management as the scope of the CDE focuses on project delivery phases. The CDE therefore fails to take a lifecycle approach to requirements engineering and falls short in the management of information requirements beyond the handover and commission phase.

> "The primary CDE was ProjectWise… However, ProjectWise does not support Revit well from the point view of developing working progress models. So, they were using BIM 360 for the Revit models, and then also the 12D tool for the civil designs… so managing that sort of series of *different* CDEs, a connected data environment rather than a common one, meant that we have to fill in the gaps between each of those different systems…"—Digital Engineering Lead

Lack of tools supporting automatic information requirements validation. As a physical-focused industry, the validation of physical deliverables and their functional requirements was seen as an important part of rail infrastructure projects. However, the lack of formal validation tools (and processes) of the information requirements describing the digital deliverables (i.e., models/databases of physical assets and process behaviours) was noted. "There is a lack of verification and validation for simulation, and certification of modelling".—Systems Engineer

5.3 Supply Chain Maturity

Issues relating to the maturity of the supply chain and participating project stakeholders relative to their knowledge and levels of collaboration/participation. Supply chain maturity challenges therefore refer to project roles and responsibilities, culture and communication, and education and training. The three challenges noted by interviewees in this category surround the lack of a clear description of roles and responsibilities for information requirements development, lack of support from senior management, and lack of expertise in requirements development supporting DT creation.

Lack of a clear description of roles and responsibilities for information requirements development. It is essential to set up a clear roles and responsibilities for efficient and effective requirements management. However, so far in rail infrastructure, this role is not clearly set as captured by the following responses from multiple participants.

> "…There is a whole bunch of reviews over the design but the information itself, nothing. Obviously, there is no professional accountability… We suggest that there should be a role of information manager who is accountable for systems process, workflows and data structures…The information is a skill set which is current lacking in the industry".—Digital Engineering Lead.
>
> "…there is accountability from a company perspective which includes systems engineering. They've got their insurance and liabilities built in the contract. But when it comes to personal professional accountability, it's really lacking at the moment in a top-down driven way with transport to accredit the staff…"—Digital Engineering Lead.

Lack of support from senior management. Support from senior management was viewed as the foundation for the successful implementation of new processes and technologies related to information requirements development. A common complaint was therefore the lack of support from the senior management on rail infrastructure projects.

> "…they are not budgeting for the asset information management…and how that feeds into what ultimately will become asset information management system in the operational environment…"—Systems Engineer.

Lack of expertise in requirements development supporting DT creation. Having relevant expertise and a minimum a common understanding in rail infrastructure project teams was viewed as being critical to the successful implementation of information requirements processes, particularly those supporting the elicitation and documentation of AIRs and EIRs that underpin the creation of the DT. Moreover, the information requirements of a DT should be specified at the early stages of the project, ideally described as OIR and AIR, so that stakeholders are able to capture requirements in project contracts. However, the lack of knowledge and common understanding with regard to the requirement development, DT concept (and related terms such as digital engineering) was seen as a key barrier.

> "…it (requirements document) says nothing about who is going to own what level of data, what level of specificity, what kind of schema…it (requirements) is not very performance based, it is generally input based…"—Engineering Lead.
>
> "…There is no consistency of requirements development approach. The SE consultant usually sits in a conflicting position by providing the service of stakeholder engagement and providing business requirements specifications, while at later stage, they are nominated to manage those requirements…"—Rail Systems Engineer.

"…there is a misunderstanding with regards to this term digital engineering… they have completely different understanding of what the defence believe digital twin is…"—Systems Engineer.

6 Discussion

Three key areas of maturity have been identified as key to information requirements development to support the creation of DTs in rail infrastructure projects, namely i) process maturity (including process-based standards and protocols), ii) technology maturity, and iii) supply chain maturity. Within these three areas of maturity, 12 challenges are identified from the case study.

6.1 Mapping Challenges

In comparing the identified challenges, a number of challenges identified in the existing research literature mirror the responses of case study interviewees. Eight challenges can be correlated between the case study and literature survey findings, including: i) lack of requirements change management processes, ii) delays in information requirements development process, iii) disconnection in the workflows that support system architecture and project level requirements, iv) lack of process standards supporting AECO requirements development and management, v) lack of agreed and consistent requirement language, vi) interoperability of requirements management software with digital modelling tool chains, vii) lack of a clear description of roles and responsibilities for information requirements development, and viii) lack of expertise in requirements development supporting DT creation.

The remaining four challenges are unique to the rail infrastructure case study, namely: i) lack of validation processes supporting physical and virtual requirements, ii) lack of tools supporting automatic information requirements validation, iii) disconnected data and processes within the CDE, and iv) lack of support from senior management. Three of these challenges are specific to the creation of DT deliverables. The validation process and technology for both physical and virtual requirements is a challenge that is not represented in the literature. Whilst data and process disconnects in the CDE are documented in the literature [29, 36], the impact of these deficiencies in information flow on requirements engineering processes, tool chains and outputs have not been reported. The lack of support from senior management was largely reference to with regard to the client. Whilst this challenge was not identified by the authors in the requirements engineering literature reviewed, similar challenges are often raised in research investigations on BIM adoption on AECO projects [41, 42]. Our case study highlights a common situation, where the public agency, acting as the client, lacks experience in SE and requirements engineering relative to supporting effective and efficient information requirements development in the creation of DTs.

Conversely, 7 out of the 18 challenges identified in the literature survey were not reflected in the interviewee responses. These challenges all related to either technology maturity or supply chain maturity categories. One explanation for this may be due to the nature of the roles and responsibilities of the interviewees – where most were from management or systems engineering roles that were not actively involved in the use of software to support SE or requirements engineering processes.

To locate the challenges identified in the case study in the asset lifecycle, each challenge was mapped to corresponding phases using the 'Diamond Model', see Fig. 2.

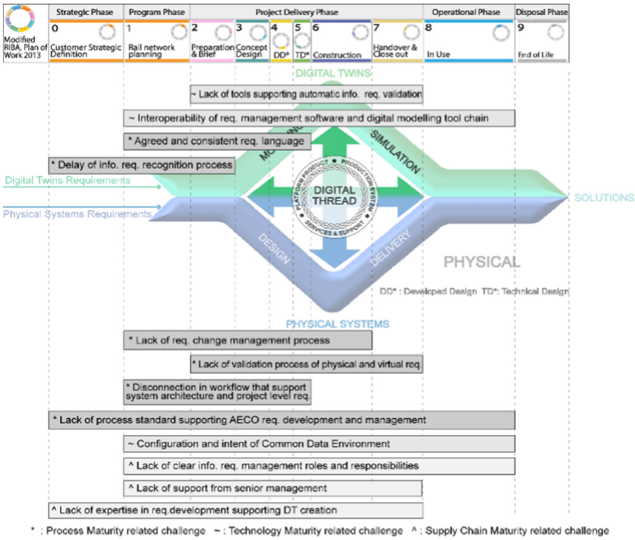

Fig. 2. Challenges to information requirements development supporting DT creation mapped to Diamond-Model development lifecycle [12]

The majority of challenges identified pertain to those commencing in the early phases of the project, including 'Customer Strategic Definition', 'Rail Network Planning', and 'Project Preparation and Brief Development'. The effects of the issues identified continue across the 'Concept Design', 'Developed Design' and 'Construction' phases with most continuing to effect 'Handover and Close Out' or 'Operational' phases. Challenges that involved both physical and virtual requirements are represented below the 'Diamond Model', while challenges specifically related to digital requirements engineering activities are mapped onto the reflected 'V' of the 'Diamond Model'. For validation related challenges, although this occurs during technical design phase, the setup of validation processes and supporting documents occur in the early planning phase.

In the creation of a DT, stakeholders are not only distributed, but also come from diverse disciplines, formalisms, and tools. Information requirements supporting both the physical and virtual deliverables must be shared and exchanged between multiple disciplines so as to build a common view of the targeted deliverables [43].

6.2 Recommendations and Supporting Research

Two deficiencies identified in both rail infrastructure case studies concern deficiencies in systems approaches and collaborative co-engineering practices. Firstly, our case study reflected a well-documented deficiency in the application of SE [44] and critically systems requirements engineering (SRE) methods [26]. Secondly, there exists a greater dependency on a co-engineering approach during the creation of complex and adaptive systems, where “co” requires the project team to work towards the DT deliverables as a common goal. Co-engineering therefore addresses both collaborative and concurrent engineering concepts. The impacts of the implementation of systems and co-engineering approaches can be identified at two levels; the organisation and project relative to the “mind-set” and sharing of the DT system objectives and vision. Thus, adopting systems and co-engineering approaches is identified as a key criterion for complex and adaptive systems when the lifetime of the asset extends over several decades. For rail infrastructure projects the co-engineering of information requirements is key to support the delivery of both physical and virtual assets with decades long lifespans. In adopting both systems and co-engineering approaches, SRE implementations are arguably better supported.

The key principles of SRE – including its holistic process-based approach, its focus on increasing interactivity across project teams, and validation of requirements against original system goals – are designed to overcome many of the challenges identified in the case study. The creation of DTs in rail infrastructure projects may therefore benefit from the application of SRE methods; from requirements elicitation and analysis to requirements prioritisation, and requirements communication and negotiation, and to requirements validation, change management and requirements traceability. Integrating SRE methods with model-based approaches using BIM during planning and early design stage presents a solution pathway for more effective support in DT creation.

Related research investigations have explored the role of SRE to support the specification of information requirements. Notably, [45] have used SRE to adapt and redefine the ‘Level of Detail’ concept, in order to provide more complete definitions of BIM model use in complex infrastructure projects. ‘Level of Detail (or LOD), together with the Level of Information (or LOI) are widely used data definition standards that describe geometric (LOD) and non-geometrical (LOI) information. To extend these concepts, [45] introduce ‘Level of Abstraction’ (LOA) to describe relevant objects for different types of BIM model use. The application of SRE was successfully implemented by [46]to support specific areas of BIM-enabled infrastructure projects focused on the specification of exchange information requirements. A drawback of the LOA method proposed by [46] concerns the need for clear classifications for the LOA, in terms of which LOA level is more (or less) ‘abstract’ than the other across different model uses. In addition to the complexity of this approach, the LOA definitions themselves do not include all disciplines, with structural engineering notably missing. Moreover, the focus of the paper is on the EIR and neglects the AIR processes that are linked to the BIM and DT use domain. The applicable phase of this approach starts after the BIM Preparation and Brief phase which is too late in the asset lifecycle.

6.3 Concluding Remarks

The findings in this paper provide empirical evidence of a number of process, technology and supply chain ‘pain points’ that are currently facing NSW and Victorian rail infrastructure projects in the creation of DTs. The findings serve as a starting point for further research into the creation of rail DTs and the potential role of SRE. Future research will focus on the examination of how the introduction of SRE capabilities can positively affect the creation of DTs in rail infrastructure.

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An Activity-Based Costing Model for Additive Manufacturing

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Abstract. Additive Manufacturing (AM) has received a high interest in various applications, especially Powder Bed Fusion (PBF) technology. As for any industrial process, cost is one of the most important key performance indicators where good estimation and management have a direct impact on the competitiveness of the enterprise. Therefore, a detailed analysis of the current AM processes cost is essential. This paper has two main contributions, firstly, a critical analysis of the existing cost models in PBF, and metal-based material AM technologies by illustrating their main cost drivers and formulas. Secondly, an Activity-Based Costing (ABC) model is proposed with the aim to cover all important characteristics of AM process. The main cost drivers in AM process are exploited in this model to support the quotation of new product at earlier stages of AM project negotiation. The proposed costing model is part of a global knowledge-based framework for decision aid in AM project.

Keywords: Cost model · Cost estimation · Cost drivers · Activity based costing · Additive manufacturing

1 Introduction

One of the main challenges for decision maker at early stages of AM project is estimating the cost, since it is usually a key point of negotiation [1–4]. Good cost estimation has a direct bearing on the competitiveness of a business of an enterprise because overestimation can result in loss of a business and goodwill market, and underestimation may lead toward financial losses in enterprise [5]. Thus, cost estimation Frameworks/models have an important role internally and externally when providing the quotation [6, 7]. Estimating the cost is a challenging task which needs a big amount of manufacturing data and knowledge connected to various design and manufacturing aspects: such as material, support, used machine, post-processing, and so on. Face to this complexity, there is recently a high demand of decision support tools and models able to identify the suitable strategy to optimize the global cost while keeping the same level of quality [8]. According to the Solid Freeform Fabrication (SFF) symposium held in Austin in 2014 [9], most of the experts agreed that future Additive Manufacturing (AM) systems should

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address functional metallic/multi-material and large-scale parts, allowing low operating cost, speed, and energy consumption. So, understanding the key factors impacting the cost of AM process is necessary for effective deployment and future uptake of high-quality standards [1]. Indeed, a detailed analysis of the current manufacturing cost and evaluation of the expected improvements reveal a cost reduction potential of about 60% in the next 5 years [10], which will significantly advance the market of AM.

In consequence, the costs incurred by AM attract the interest for different stakeholders (i.e., end users, technology developers, AM service providers, investors, etc.). Careful examining of additive manufacturing costs is important to compare additive manufacturing processes with traditional processes, and to identify the main cost drivers used at various steps of the additive manufacturing process [11].

Powder Bed Fusion (PBF) is one of the complex AM processes where thermal energy selectively fuses regions of powder bed to produce parts [12]. Generally, the process consists of: A thin layer of powder is spread by levelling roller or recoating blade, where a moving energy source (laser beam in case of Laser PBF machines that passes through a system of lenses and reflected by a mirror, used to control the laser beam spot movement on the X, Y planner, onto the platform surface [13]) melts or sinters the powder into successive cross-sections based on the CAD file. The platform goes down in a specific pitch based on the layer thickness, then the powder is spread for another layer over the solidified layer, to build the next one, until building a complete 3D component. The process may take place in a high vacuum chamber to avoid oxidation issues of metallic powders at high temperature, thus the build chamber is frequently filled with inert gases, argon in most cases [14]. Examples of PBF process are selective laser sintering (SLS), selective laser melting (SLM), direct metal laser sintering (DMLS), and electron beam melting (EBM) that uses electron beam as an energy source [15].

Despite the significant progress and technology advancement that have been made by PBF, performance in terms of speed, accuracy, process control and cost effectiveness still need to be improved [13]. This paper has two main contributions. The first one is a critical analysis of the existing cost estimation models in AM, focusing on the ones that are related to metallic materials, and PBF technologies. Then, based on this analysis, the second one is a cost model using Activity-Based Costing (ABC) approach, proposed for PBF laser-based technologies and metal materials, with the ambition to cover some limits of the existing AM cost estimation models. Also, this study represents the main associated cost drivers within the PBF technology process chain. The next section presents a detailed analysis of literature with the aim to identify the main cost drivers and most significant cost models. Then, Sect. 3 sets up the main foundations of the proposed costing framework, while Sect. 4 gives a brief illustration about the application of this framework in an industrial case study.

2 Literature Survey

2.1 Cost Classification Techniques

Cost is the amount that has to be paid to obtain an end product or service regardless of how much the company has gained or lost [16]. According to the Association for Advancement of Cost Engineering [17], cost estimation intends to determine the quantity and predict the costs of constructing a facility, manufacturing goods, or delivering a service. However, there are a wide range of classifications regarding cost estimation [3] based on several aspects like; approach type, granularity level, tools used, and even the application phase. According to Kadir et al. [18], different views of cost models could be categorized into different perspectives depending on the role of the person handling the cost issues like:

Manufacturing Perspective: (Task-based classification techniques) includes several phases of product development and manufacturing tasks, it can be grouped into design-oriented (e.g., part design, process planning), or process-oriented that covers cost elements in the production phase, direct and indirect costs (e.g., pre-processing, production (build job), and post processing).

Management Perspective: (Level-based techniques) covers a wide range of product costs that are associated with product lifecycle costing, design to cost reduction, remanufacturing and value engineering of the product. These techniques are divided into process-level (costs associated with production, similar to task-based), and system-level (that covers all costs throughout the product life cycle like; maintenance, inventory, etc.).

Financial/Accounting Perspective: (Method-based) uses a classical classification techniques of cost models based on the used methods and factors. These techniques are categorized into Qualitative (Intuitive techniques, Analogical techniques), and Quantitative (Parametric techniques, Analytical techniques) [5].

Intuitive techniques are primarily dependent on past experience (expert knowledge), where this experience can be applied either directly, or using different decision support systems, like (rules, decision tress, case-based, etc.) [5]. This approach is suitable at early stages like design, and conceptual stage [3]. Analogical techniques are based on the concept of deriving an estimate from actual information regarding similar real product [2], using historical cost data of products with known cost. Such techniques, like Regression analysis and Neural Networks, have the ability to define a relationship between variables and cost.

The Parametric techniques focus on the characteristics of the product without describing it completely [19] by using the cost estimation relationship that can be presented in mathematical equations, with variables that are associated effectively with cost drivers. The Analytical techniques separate a product into several units, operations, and activities, also the resources consumed during the product life cycle. They express the cost as a summation of all these components [5]. It is further classified into different categories (e.g., Operation-based, Feature-based, Tolerance-based, Activity-based, Break-down approach). These are easy and effective methods to apply.

2.2 Cost Estimation Models in AM

The intent of this section is to scrutinize the most relevant cost models defined about the AM "*focusing on the ones that are related to metallic materials, and Powder Bed Fusion PBF technologies more specifically*". In order to get an overview of the current propositions for cost estimation of AM, in particular the main cost drivers and the used techniques, as well as classify them according to management perspective, described previously, as shown in Table 1.

Process-Level Cost Models

Schroder et al. [20] used Time-driven ABC for the development of a business model which evaluates the process cost of AM technologies (FDM, SLA, SLS, EBM). Thus, their proposition of cost model is consolidated based on detailed sub-activities, and an overall of 77 input values are needed for a detailed cost calculation divided into process and order specific information's. Another Time-Driven ABC process-level cost model in AM is proposed by Barclift et al. [21]. They provide cost modelling for PBF by expanding the work of [22], and also defining a new financial depreciation model for reused metal powders using Sum-of-the-years digits depreciation. Their study concludes that the fixed material cost undervalued the cost of build jobs within a range of 13% and 75% for virgin Ti64 powder. The uncertainties in this model are the exact number of reuses permitted for each material alloy, also other cost elements related to quality assurance processes are not included. The work proposed by Cunningham et al. [1] incorporates the full process chain for Wire-Arc Additive Manufacturing (WAAM) in order to create a detailed cost model. The key cost drivers are identified using sensitivity analysis. The results of this work state that WAAM has a significant potential as cost-effective manufacturing approach compared to other AM technologies. Moreover, Facchini et al. [10], provide a cost model to compare the process cost due to production of batch of aerospace parts, adopting both WAAM and traditional machining technologies. Their proposition is using a parametric approach based on computational algorithms, taking into consideration overall manufacturing costs and Non-recurring Engineering NRE costs, which refer to the one-time cost to research, design, develop and test due to production of new parts. Four performance indicators of the process are identified to evaluate the cost of each phase of the process (e.g., setup, building job, part removal, etc.). Ruffo et al. [2] have proposed a cost model based on a parametric approach (as an analytical function identifies the cost estimation relationships) and an engineering approach (to find overall costs by the sum of elementary components used in each step of the production process) in the case of LS (Laser Sintering) manufacturing, as the relationships found are approximations based on statistics. The scope of this cost model is limited to the production process, including material cost as an indirect cost and (overheads, maintenance, capital equipment depreciation, labor, software, and hardware) costs as indirect costs assigned to the components on a machine working-time basis. So, this cost model has to be extended to cover a wider range of AM process chain.

The analogical approach was used in Rudolph et al. [23], and Chan et al. [24]. Rudolph et al. [23] develop an automated self-learning calculation cost model for SLM implemented within a web-based platform. The customer is able to upload the part geometrical data via online form. Then, the key characteristics (volume, surface and dimensions) are identified to obtain an offer calculation. Linear Regression is used to predict the capacity utilization and the build height in order to estimate build and material costs. The work is only focusing on a cost calculation of the build process including material and manufacturing costs. Chan et al. [24] propose a cost estimation framework using machine learning algorithms for dynamic clustering, LASSO and Elastic Net Regressions, so the production cost associated with a new job can be estimated based on similar cases in the past. Cost estimation process starts with extracting and calculating 17 different types of features from the process information in G-code which is generated from the submitted STL file. Those features are then forming the feature vector which will be used as an input of the predictive model. In this study there are some missing links to make effective cost estimation framework, where some cost elements like post-processing, labor cost, and overhead are not included.

System-Level Cost Models

Lindeman et al. [25] aim to provide a deep understanding of AM product lifecycle cost structure for laser-based technologies. The proposed tool is divided into two segments, the first maybe filled by engineer, and the second segment for experienced AM user. It used analytical network process method, multi criteria part classification, then Time-driven activity-based costing as a general method for the calculation, and a good means for allocating cause-based costs to allow the comparison of additive and traditional manufacturing methods. It also, evaluates the relevant factors for specific product, process, warehousing, and capital issues. The cost model is difficult to be implemented in industrial context because of the lack of knowledge about the processes and difficulties for companies to incorporate the lifecycle coasting approach.

Kamps et al. [26] carried out qualitative cost analysis incorporating life cycle assessment (LCA) on laser beam melting process. Two integrated models were suggested for cost and life cycle assessment in cradle-to-gate framework focusing on the industrial process sequence. An excel-based cost model is developed for cost calculation as well as build-up duration and argon demand based on company and machine specific data. Whereas the LCA model is based on key assumptions that simplify the model without threaten the calculation outcome significantly. The model needs more experimental measures to improve its accuracy. The results were based for gear production and only few costs were measured.

In summary, it is necessary to mention that each of the existing cost models has advantages and disadvantages, but no model meets all criteria satisfactorily, these criteria, among others: simplicity, genericity. For instance, part of the proposed models is limited to AM build process, while others are complex and difficult to implement. So, there is a need for a generic and simple cost model that covers cost elements in different phases of AM process and can be adopted in industrial practices.

Table 1. Comparison of main AM cost models

Cost model	Main cost drivers	System-level	Process-level	Used method/approach
Schroder et al. [20]	CAD preparation cost, operating cost (preparation process), material cost, machine cost, labour cost (production), post-processing cost, quality control process cost, administrative cost		✓	ABC (time-driven-ABC)

(*continued*)

Table 1. (*continued*)

Cost model	Main cost drivers	System-level	Process-level	Used method/approach
Rudolph et al. [23]	CAD preparation cost, set-up cost, operating cost, labour cost (production), production overhead, pricing mode cost, material cost, part removal cost, treatment cost, post-processing overhead		✓	Analytical, and analogical "linear regression"
Chan et al. [24]	Material cost, machine cost, production cost		✓	Analogical "ML algorithms, net regression"
Barclift et al. [21]	CAD preparation cost, operating cost (preparation process), set up cost, labour cost, material cost, machine cost, depreciation cost (powder feedstock), part removal cost, substrate process cost, post-processing cost		✓	ABC (time-driven)
Lindeman et al. [25]	Inventory cost, setup cost, material cost, machine cost, labour cost (production), depreciation cost, post-processing cost, part removal cost, production overhead, logistic cost, quality control cost	✓	✓	ABC (time-driven)
Facchini et al. [10]	CAD preparation cost, operating cost (preparation process), setup cost, labour cost, material cost, part removal cost		✓	Parametric (computational algorithm)
Kamps et al. [26]	CAD preparation cost, setup cost, material cost, machine cost, labour cost (production), depreciation cost, maintenance cost, electrical cost, gas cost, energy cost, production overhead, post-processing cost, part removal cost	✓	✓	Intuitive, analogical LCA life cycle assessment

(*continued*)

Table 1. (*continued*)

Cost model	Main cost drivers	System-level	Process-level	Used method/approach
Cunningham et al. [1]	Operating cost (preparation process), setup cost, material cost, machine cost, labour cost (production), part removal cost, post-processing cost, quality control cost, tooling cost, treatment cost		✓	ABC (time-driven)
Ruffo et al. [2]	Material cost, machine cost, production cost (build job), overhead cost		✓	Parametric, and engineering approaches

3 Proposed Cost Estimation Framework: An ABC Approach

3.1 ABC Method

Activity Based Costing ABC approach has been selected to be used, since it has gained the recognition as an easy and effective method, with better information for controlling capacity cost [16]. The cost estimation is prepared from the cost incurred by activities during manufacturing of the product [5]. ABC could provide the structuring support (the activity) to keep non-financial information such as defect rates (quality), throughput rates (effectiveness of the industrial process) and delivery time [7, 27]. It may help the companies to improve product design and manufacturing process, as well as classifying the activities to value-added and non-value added.

The following steps demonstrate the implementation of the ABC approach [28]; it starts with identifying the cost centers connected to the directly used resources, including human resources (designer, labour, etc.), and equipment/machines. Then it analyzes the overall cost (like overhead costs) associated with these cost centers, and it calculates their cost driver's rate. After that it is necessary to assign resources to each cost center, and to determine cost center rates based in the resource cost drivers. Later, the method allows identifying the activities that take place in the product development process, and defining activity driver(s) for each one. Finally, the achievement is finding the total cost of each activity based on the cost-centre resources for each activity, using cost center rate multiplied by the amount of the drivers consumed by each activity (see Fig. 1).

3.2 Main Cost Drivers

The activities of the PBF production process chain were identified according to the major production processes involved that represent the scope of this cost model. One of the main purposes of cost modeling is to identify the factors affecting the cost during various processes of AM which are called cost drivers. Thus, before starting with the equations of the cost model, the main cost drivers within the process chain – that are needed in order to estimate the product cost – are illustrated in Fig. 2.

It is also important to consider the various interdependent aspects like; product characteristics, customer specifications, machine/material types, and manufacturing process parameters, in terms of their correlation with the main cost drivers therefore to increase the robustness of cost investigation.

Build time is one of the most essential factors to estimate the cost of AM. Certain machine/material combination have strong impact on build time. Also, part characteristics, and requirements (part volume, part features, part quality), and manufacturing parameters (hatching and contour percentage, layer thickness, scanning speed, build height, support required) affect the build time. The estimation of build time is beyond the scope of this paper. However, several software packages exist for estimating the build time like (Materialise-Magics, EOSprint, AddUp Manager, etc.). Besides, several works

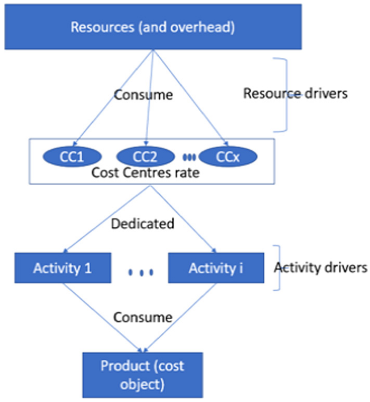


Fig. 1. Activity-based costing approach implementation, adapted from [28].

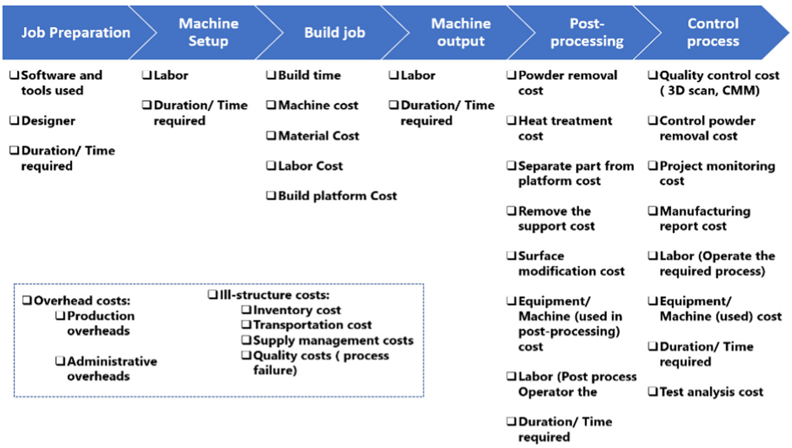


Fig. 2. Main cost drivers in PBF process chain.

have been caried out for estimating the build time using Machine learning techniques like [29–31].

Machine/equipment cost is also to be taken into account, especially AM machine cost due to the high purchase price of AM machines. This cost is indicated as hourly rate for running the machine (cost/hour). It is based on the purchase price of AM system, service year, and other maintenance expenses associated with such system. Specific machine component like build platform has a separate cost because in some cases, it might have a significant effect on the cost of AM products, this type of cost is based on the dimension "mainly the thickness" of the platform, platform material type, and platform state if it is new or has been already used before for several builds.

Material cost has to be considered carefully because the cost of AM metal material is significantly high compared to raw material used for traditional manufacturing. Two things have to be considered in determining this cost. On one hand, the material price per kilogram which is based on the material type, material supplier, and material state (new or reused). On the other hand, the quantity of the consumed material which is related to the total volume of part, other test parts "that might be included in the build job", support structure, number of parts, and the material waste that includes both material loss during the build process and trapped material within build parts.

Labor cost is related to the labor needed to execute a task or activity (designer, AM operator, post-processing operator, etc.) such as job preparations, machine output, post-processing, and control process. This cost is indicated as an hourly rate cost.

Post-processing and quality control costs may take up to 50% of the final product cost [25]. They both depend on the customer requirements, part characteristics, customer activity sector (function of the product), required labor, used technique, used machine/equipment, and the duration/time needed for the activity, which are the most related factors for these costs. Post-processing costs are the sum up of all necessary post-processing operations after AM machine output, (e.g., powder removal, separation of the part from the platform, support removal, machining process, and heat treatment, etc.). On the other hand, quality control cost is the cost of different steps needed to assure and evaluate the various aspects to achieve part quality, and product requirements (e.g., 3D scan, CMM, Tomography, Microstructural evaluation, Metallurgical test, etc.). Indeed, it is substantial to mention that these processes have to be considered beforehand the manufacturing. In specific situations, some of these processes are carried out by subcontractors.

Overhead costs are assigned to the operations of AM system and categorized into: Production overheads, like building rent, support equipment, or energy costs; Administrative overheads that are related to computer equipment, communication, and software license costs. Some cost models (e.g., [2, 25]), have included overhead costs as indirect costs along the machine cost, by taking the annualized overhead costs over the machine working time per year. Ill-structured costs are the hidden costs in the supply chain [11] such as, inventory, transportation, supply chain management (purchasing, operation, distribution, integration), and quality (in terms of process failure during machine operation and part rejection) costs. These costs are difficult to consider and not well understood due to the limited knowledge and data in the accounting practices [9]. However, AM has a positive potentiality in reducing these costs compared to conventional manufacturing technologies, because of its ability to manufacture parts on demand, produce an entire product in the same build at once, and reduce the link in supply chain by bringing the manufacturers closer to consumers.

3.3 Cost Calculation for AM

In this section part of the proposed cost model equations are presented. The estimation of AM final product cost is carried out by identifying at first the main needed activities to realize the product, then the cost centers associated with these activities and their drivers. In most of the activities the main drivers are the duration/time required to achieve the activity. So, this cost estimation model could be also included as a Time-Driven ABC.

$$\text{CAD/CAM preparation cost} = T_{\text{CAD/CAD prep}} * (C_{\text{Designer}} + C_{\text{WS}}) \tag{1}$$

$T_{\text{CAD/CAD prep}}$: the time required for creating support, simulation, etc. (h)
C_{Designer}: The Designer hourly rate (€/h)
C_{WS}: The cost rate of using workstation (including software and computer) €/h

$$\text{Machine set} - \text{up cost} = (T_{\text{setup}} + T_{\text{mat.change}}) * C_{\text{op}} \tag{2}$$

T_{setup}: the time required to prepare and setup the build job (h)
$T_{\text{mat.change}}$: the time required to change the material and clean dispenser (h)
C_{op}: AM operator hourly rate (€/h)

$$\text{Build job cost} = C_{\text{Build machine}} + C_{\text{production}-\text{stop}} \tag{3}$$

$$C_{\text{Build machine}} = T_{\text{Build}} * C_{\text{AM}-\text{Machine}} \tag{4}$$

$C_{\text{Build machine}}$: the cost for operating AM machine (€)
$C_{\text{production-stop}}$: the cost of stopping the production (not failures), but to fill the dispenser, empty the re-coater (mainly related to manual tasks) (€)
T_{Build}: the time for building the entire job for specific project (h)
$C_{\text{AM-Machine}}$: AM machine hourly rate (€/h)

$$C_{\text{Build material}} = M_{\text{material}} * C_{\text{material}} \tag{5}$$

$$M_{\text{material}} = (V_{\text{Build}} * P_{\text{melted}-\text{density}}) + M_{\text{waste}} \tag{6}$$

$C_{\text{Build material}}$: the cost of used powder in AM builds job process (€)
M_{material}: mass of used material in build job (kg)
C_{material}: the commercial price of the used powder (€/kg)
V_{Build}: total build volume for specific project (mm3)
$P_{\text{melted-density}}$: powder melted density (around "Powder density/0.6") (kg/mm3)

M_{waste}: powder loss during AM builds job (kg)

$$\text{Machine output cost} = T_{rem} * C_{op} \tag{7}$$

T_{rem}: the total time required to remove the entire build, and cleaning (h)

$$\text{Powder removal cost} = T_{PR} * (C_{op} + C_{PR\,machine} \tag{8}$$

T_{PR}: the time required for automatic powder removing (h)
$C_{PR\,machine}$: hourly cost rate for powder removing machine or equipment (€/h)

$$C_{PR\,(Material\,trapped)} = M_{material\,PR} * C_{material} \tag{9}$$

$C_{PR\,(Material\,trapped)}$: the cost of powder lost during the powder removal process, which is the trapped powder within the build parts (€)
$M_{material\,PR}$: mass of lost powder during powder removing process (kg)

$$\text{Separate parts from platform} = (C_{Sep\,mach} * T_{Sep\,mach}) + (C_{Sep\,op} * T_{Sep\,op}) \tag{10}$$

$C_{Sep\,mach}$: hourly rate cost for the used machine (e.g., EDM, Saw) (€/h)
$T_{Sep\,mach}$: the time/duration for the separation machine (h)
$C_{Sep\,op}$: hourly rate cost for the separation process operator (€/h)
$T_{Sep\,op}$: the time/duration for the operator (input, remove, monitor) (h)

Other costs related to post-process activities are also included in the cost estimation model like; heat treatment, support removal, surface finishing, and machining. They are mainly based on the time/duration to realize the activity, post-process operator hourly rate, and used machine/equipment cost rate. Different quality control activities are included as well, parts of these equations are presented below in (11,12, and 13).

$$\text{Project Monitoring cost} = T_{follow\,up} * C_{project\,leader} \tag{11}$$

$T_{follow\,up}$: the total time needed to trace and monitor specific project (h)
$C_{project\,leader}$: project leader hourly rate (€/h)

$$\text{Creating Manufacturing Report cost} = T_{M.rep} * C_{project\,leader} \tag{12}$$

$T_{M.rep}$: total time required to create the manufacturing report (based on the level of this report, and customer specifications) (h)

$$\text{Control Check} = T_{QC} * (C_{QC\,tool} + C_{QC\,op}) \tag{13}$$

T_{QC}: time required to realize the control check (h)
$C_{QC\,tool}$: hourly rate for the used tool/or machine (e.g., 3D scan, CMM) (€/h)
$C_{QC\,op}$: quality control operator hourly rate (€/h)

Thus, the final equation to estimate the cost of a product is shown below;

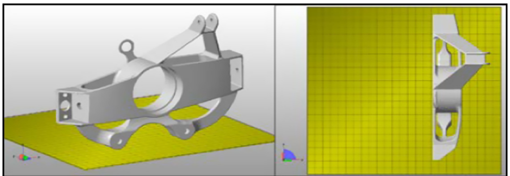
$$\text{Final Product cost} = \text{Total material cost} + \text{B. Platform cost} + \sum \text{Activity cost} \quad (14)$$

$$\text{Total material cost} = C_{\text{Build material}} + C_{\text{PR(Material trapped)}} + C_{\text{Psq}} \quad (15)$$

Total material cost: the total material required for a specific project (€)
B. Platform cost: the cost for using a specific build platform (€)
C_{Psq}: the cost of the powder sample needed for powder test analysis, if required (€)
$\sum$Activity cost: the summation of the required activities costs (€)

4 Case Study

To illustrate the application of the proposed cost model, one part designed and produced by laser-based PBF has been selected from [21], see Fig. 3. This part was built using EOS Titanium Ti64 material, and manufactured by EOS M280 DMLS machine. The cost will be estimated following the carried-out process presented in [21]; the process starts with CAD/CAM preparation by importing the STL file into Materialise Magics software, and Machine setup for the build job, then AM process. Once the build job is completed the entire build is removed. Next, heat treatment and wire EDM (subcontracted processes) are applied. Finally, the required post-processing in terms of support removal and other mechanical process are carried out by the operator. Using the cost model constants from [21], the costs for producing the part are estimated using the proposed cost model equations, and compared with the ones estimated in [21], as presented in Table 2. The costs are different in both machine setup, and machine output activities because in the proposed model the machine hourly rate cost is not included in these activities, only operator cost rate is included. Material cost includes the fused material to build the part (based on build volume), as well as the powder loss during the build process and the trapped powder inside the build (we assume the same quantity of powder loss from [21]).



Geometry	G_1
N_i	1
V_{part} (cm^3)	175
$V_{supports}$ (cm^3)	412
$V_{total}(cm^3)$	587
$A_{con}(cm^2)$	69
Bounding Box (mm)	74 x 218 x 172

Fig. 3. Automotive upright, source [21]

Table 2. Compare the estimated costs

Cost elements	Estimated costs ($)	Costs from [21] ($)
CAD/CAM preparation cost	630	630
Machine setup cost	550	850
Build job (C build machine) cost	3850	3850
Machine output	330	510
Heat treatment cost	Stress-relief “Subcontracted” 350	350
Separate parts from platform cost	Wire EDM “Subcontracted” 200	200
Post process cost	480	480
Material cost	2652	2652

5 Discussion and Limitation

In comparison with the current propositions for cost estimation in AM (as shown in Table 1), this model is considered as a process level cost model, using ABC approach, in which it has been developed based on an exhaustive review of these propositions, as well as several discussions with the industrial partners. This is done in order to overcome the missing cost elements in previous cost models, and to present the main AM cost drivers as well as their correlation with customer specifications and product characteristics.

The cost model equations cover a wider range of cost elements within AM process chain. In the previous models, the costs for following and creating the manufacturing report for a specific project were not mentioned. In reality, these costs might be significant for complex projects that required, for example, a number of subcontracted activities. Other costs were also highlighted in this paper which are related to control check process (e.g., 3D scan), and to the needed test analysis such as: powder test, metallurgical test, tensile test, etc. The cost for the used build platform was also included since it can vary based on its dimensions and material type. For instance, in some project the customer asks for a specific build platform. Moreover, in this model the quantity of the consumed material was based on several aspects along the part volume such as: the associated test parts, powder loss within the build process, powder trapped inside the part channels, and the powder quantity used of test analysis in some cases.

The cost estimation model could serve as a basic element in two important applications. First it can be adopted in real industrial practices and linked to expert knowledge using different approaches (e.g., rule-based) to support the estimation of cost at early stages. Second, it can be used to track the incurred cost of each activity and its related factors toward a full cost traceability model.

On the contrary, this cost model did not consider the state of the used powder (if it is new, recycled, or mixed). Therefore, the material price is treated as an input for the model, based on the commercial selling price from the supplier regardless the state of the powder. In addition, the model is limited to PBF metal laser-based application. However, the use of this cost model in different applications could be achieved after some updates and modifications. Finally, Costs for build failure and re-design or engineering of pre-existing part were not captured in this model.

6 Conclusion and Perspective

In this work several cost models in the field of AM have been reviewed, and a cost model using Activity-Based Costing approach is developed. At first, the main Cost Drivers within the PBF process chain have been presented and explained. After that, generic cost estimation equations using ABC are proposed that cover several cost elements like post process, quality control and assurance processes, test analysis process, powder loss, build platform, etc. A case study was presented using Ti64 material part produced by EOS M280 DMLS, in order to clarify the employment of cost model equations. The cost model has been tested with one of our industrial partners in order to estimate the cost based on customer specifications, using developed Business Rules (know-how knowledge) that link customer specifications and product characteristics to cost model inputs and main cost drivers. The proposed cost model is a key step on an ongoing work concerning the development of a knowledge-based decision aid system dedicated to support the whole value chain associated to additive manufacturing project. Several future improvements on this model could be carried out, by further investigation of overhead and Il-structured costs (such as those associated with build failure, build rent, energy consumption, and administrative overhead), on the other hand extending the model by considering other associated costs with product lifecycle from product concept until the disposal of the product.

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Industry 4.0 for PLM in Pandemics: Towards a Smart Digital Agile PLM

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Abstract. Product Lifecycle Management (PLM) is a business strategy, aiming to streamline the flow of information about products and related processes throughout the whole product Lifecycle such that the right information in the right context at the right time can be made available. Currently, the COVID-19 pandemic meant major improvements to the way service companies operate, changing the schedule and activities of their workers. The introduction of Industry 4.0 also launched emerging technology that could promote certain operations, thus alleviating the consequences of COVID-19. The aim of this research is to, first, investigate how this pandemic has impacted the product lifecycle, and secondly, explore how industry 4.0 technologies can address these challenges by proposing a Digital Smart Agile PLM framework.

Keywords: Product lifecycle management · Industry 4.0 · COVID-19

1 Introduction

Crisis have always allowed human organizations to progress by building on the lessons of the past. The Coronavirus pandemic is no exception. COVID-19 is "the" global crisis of our time and the biggest challenge we have faced since World War II. But the pandemic is much more than a health crisis, it is also an unprecedented socio-economic crisis putting pressure on each of the countries it affects. It has devastating social, economic and political impacts that will leave deep scars slow to fade.

For manufacturers, the health crisis has revealed the value of a lean, resilient Product Lifecycle Management, promoting responsiveness to withstand such shocks, or even become more efficient in normal times. Every product has a lifecycle from ideation to disposal. It is triggered from the design phase, runs through the phases of manufacturing, usage and recovery or disposal at the end of its life, thus creating a loop [1].

Physical products are becoming smarter because of the increased number of product embedded information devices (PEIDs) [2] and their real-time processing capabilities [3]. Indeed, the increasing use of PEIDs provides the data needed for intelligence.

The idea behind Product Lifecycle Management (PLM) in regard to data analytics is pretty simple. It's all about collecting and managing the information and processes

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related to all stages of product lifecycle. PLM can then be thought of as the information age manifestation of the cobbler model that focuses a company on its value chain and seeks to reintegrate people, processes, resources and information [4].

The efficiency of these processes can still be greatly improved. Anything that increases visibility into the reality of operations provides data, which can be used to improve these same operations. In this sense, it is important to be able to act with an actor who knows how to work on the visibility of the product lifecycle. Thus, it must be done in a secure environment for the actors, where we don't share everything with everyone.

Today, in the era of digital transformation imposed on all areas of industry, the standards have never been higher. How to adopt a global efficient approach while meeting the needs of customers? Industry 4.0 technologies are here for the rescue. Industry 4.0 factories have machines supported by wireless connectivity and sensors. These sensors are connected to a system that can visualise and monitor the entire production line and can also make its own decisions [5]. This was always considered as a disadvantage in using industry 4.0 technologies as it decreases human to human interaction. In the current situation, it has become a reason to adopt these autonomous ways of working.

The aim of this paper is to introduce industry 4.0 as a way of efficiently managing the product lifecycle in this pandemic and also the after pandemic. The rest of the paper will be structured as follows: after introductory remarks, Sect. 2 presents a standard PLM model based on a review of other models, thus illustrating the relationship between PLM and SCM. Section 3 will recognize the position of PLM in this pandemic, highlighting the constraints it applies on products in supply chains. Section 4 proposes a framework to overcome pandemic constraints using industry 4.0 technologies. Concluding remarks and some potential-work suggestions will be given in the last section.

2 Towards a Standard PLM Model

2.1 The Proposed Model

Leonardo Da Vinchi said – "Simplicity is the ultimate sophistication". It is very true. To find simple and clear PLM definition is hard. So, how to do it anyway? Depends to whom you are talking to, engineers; managers; contractors; suppliers; customers, PLM means different things. All of them have a different perspective on PLM. But ultimately, it is about how to organize product development, manufacturing and support in the way that will make your product a first class citizen [6] that fulfills all its intended functions in an intelligent way.

The term 'lifecycle' generally indicates the whole set of phases, which could be recognized as independent stages to be passed/followed/performed by a product, from 'its cradle to its grave' [4]. Adopting an easy-to-use model, product lifecycle can be defined by three main phases: The Beginning Of Life (BOL), the Middle Of Life (MOL), and the End Of Life (EOL). In literature, many researchers agreed to this categorization of the product lifecycle, but not with the same definition.

Stark [7], Terzi et al. [4], and Kiritsis et al. [8] considered:

- In the BOL phase, the product concept is generated and subsequently physically realised. It includes design (product design, process design and plant design) and manufacturing (production of the artefacts and warehousing).
- In the MOL phase, the product is in the hands of the final customer, i.e. product user and/or some service providers, e.g. maintenance actors and logistic providers. It includes distribution, use, and support (in terms of repair and maintenance).
- The EOL is the phase where products are collected, disassembled, refurbished, recycled, reassembled, reused or disposed. It can be said that EOL starts from the time when the product no longer satisfies its users (initial purchaser, second hand owner).

Li et al. [9] had other considerations regarding the product lifecycle stages:

- BOL is the period in which the product concept is generated, designed, and subsequently physically realized. It includes design (product design, marketing) and production (procurement, product manufacturing, and equipment management).
- MOL is the period when products are distributed, used and maintained by customers or engineers. It includes logistics (warehouse management, transport), utility (customer service, support), and maintenance (corrective/preventive maintenance).
- EOL products are either recycled by manufacturers or disposed by customers.

We can see that Li et al. [9] considered warehouse management as part of the MOL phase unlike Stark [7], Terzi et al. [4], and Kiritsis et al. [8] in which it was considered as part of the BOL phase. Li et al. [9] referred to the procurement process which involves choosing the right supplier for raw materials and delivering them to the production firm. By means, the different blocks of the product supply chain are highlighted.

Bouhaddou et al. [10] had a more detailed perspective where they considered that:

- BOL phase includes Requirements' definition (customer requirements, feasibility study), Product development (design, prototyping, and testing).
- MOL phase includes Production (manufacturing, assembling, and quality control), distribution (storage, transportation and delivery), Use of the product by the customer (product usage and consumption, maintenance, and support).
- EOL includes dismiss, disposal and recycling.

We estimate that Bouhaddou et al. [10] considered BOL as the phase where the product is still a prototype not ready to be used by end users, MOL is the phase where the product is ready to be used and consumed.

In Fig. 1, we propose a model where we consider:

BOL as the phase where the product is still in the hands of the company. It includes Requirements' definition (Customer requirements, environmental requirements, feasibility study), product development (Marketing, product design, prototype, test), and production (procurement, manufacturing/quality control & packaging). We exclude warehousing and distribution from the BOL phase as we estimate some organizations subcontract these activities, and we want to keep the model a standard one.

MOL as the phase where the product in no longer in the territory of the enterprisee and is ready to be consumed by customers. It includes Logistics (warehousing, sales and distribution/return), utility (customer service, product support), and maintenance (preventive and corrective maintenance).

EOL as the phase where the product is no longer usable or do not satisfy the customers' need and should be either retired or recycled (partially or totally re-manufactured, re-used).

Our model is based on a combination of different perspectives. We want to keep it standard so that it can fit, with some additional specifications if needed, every company in the industrial sector.

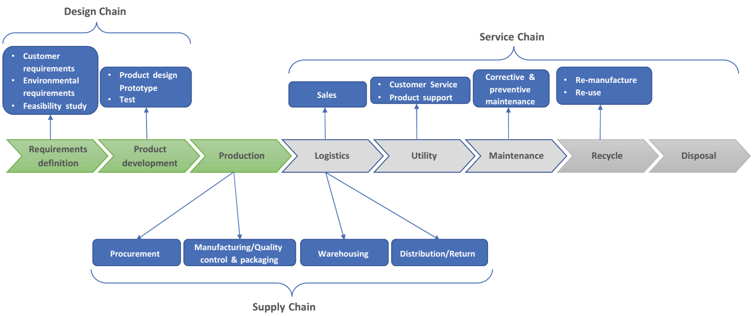

Fig. 1. The proposed PLM model

2.2 PLM and SCM: HOW?

Instant gratification has become the norm. Customers want products delivered yesterday and are ready for the next product iteration shortly thereafter. The concept-to-delivery process in today's product manufacturing business is extraordinarily complex and fast paced. In order to respond to rapidly changing trends and meet customer expectations, companies must constantly strive to reduce product development time and increase speed to market. That's a key reason why faster time to market continues to be the number one benefit that companies hope for from their PLM investments.

But PLM alone will not deliver the expected results. Lead time, cost management, product quality, and access to raw materials force sourcing organizations into tough decisions sometimes at odds with the goals of customer-centricity.

We have identified the three chains that constitute the product lifecycle as shown in Fig. 1. We are talking about:

The design chain where a prototype of the desired product is achieved, and the first tests are performed. It includes requirements definition and product development.

The supply chain where the product is being manufactured, stored, sold and distributed based on the prototype.

The service chain where extra assistance is given to consumers regarding products. Along this chain, not only product support and maintenance activities are offered whenever needed but also disposal and recycle actions are being taken care of.

We can see here that the supply chain is a component of the product lifecycle. It is an essential chain and better management of it implies better product lifecycle management.

Indeed, if we are not able to predict the customers demand and deliver them the desired product as described, the work done along the design chain will not be visible to final customers. There will be also no service chain as there is no product to be used or maintained. Therefore, a company, through its supply chain, must be able to answer the design chain results/outputs and present a ready-to-use input to the service chain.

To do so, Companies must be able to give customers/consumers the right products in the most resource-effective manner, without sacrificing quality or service. If the supplier, manufacturing, and post-sales support networks are being stressed to the breaking point, if the products require excessive inventories to maintain service levels, or if costs and complexity throughout the product supply chain need to be reduced [11], then smart supply chain and product life cycle management acting together is required. Indeed, by understanding how product lifecycles in industry —and within a company — work and integrate with supply chain, managers are better equipped to optimize their supply chain accordingly, saving money and achieving customer satisfaction.

In the following, we are studying the impact of the pandemic on the product' supply chain. We conserve studying it in the design and service chains for the coming works.

3 Post-pandemic Product Supply Chain

In "The World is Flat" (2007), his acclaimed study on the globalization of the economy, Thomas Friedman recounts a visit to an auto parts manufacturer in China, where a sign suspended above the production line displayed the following proverb: "Every morning in Africa, when the gazelle wakes up: she knows that if she wants to survive, she must run faster than the fastest lion. Every morning in Africa, when the lion wakes up: he knows that if he does not want to starve, he must run faster than the slower gazelle. Lion or gazelle, it doesn't matter, when the sun rises, it is better to start running".[1]

In 2020, as the coronavirus pandemic disrupted the global activity, this Darwinian conception of competition deserves our reflection. Speed is of the essence, and companies that want to stay ahead of their competitors and survive must closely monitor the impact of the crisis and adapt quickly.

But the pandemic could also lead to deeper changes in the globalized economic models that Friedman described in his book. By drawing attention to weaknesses in supply chains, the crisis has led some international companies to place more emphasis on inventory capacity than operational efficiency, at least in the short term.

This crisis underlines the more pressing need than ever to be reactive to change. It also shows that when a crisis affects several regions, sectors and assets at the same time, it is extremely useful to be able to collaborate with other specialists.

In this context, according to experts, the integration of internet technologies, robotization and the need to have the most up-to-date and reliable data flows possible in the industry will make it possible to gain flexibility and agility to manage the various phases linked to products lifecycle.

[1] Thomas Friedman, 'The World is Flat: The globalized world in the twenty-first century', Penguin, 2007.

Thus, mastering the information related to these different phases is more essential than ever in the context of this 4th industrial revolution. The company will therefore need to have software that allows it to track this information.

Companies were already on the way to digitalizing PLM processes before the pandemic. If companies were planning on doing so gradually, then the pandemic has intensified and accelerated it. It has reinforced many trends that will enable companies to carry on their businesses despite social distancing and travel restrictions. As flexibility, productivity and efficiency are basic requirements in this era, digitalization and the automation solutions will maintain their performance levels and more. COVID may not have uncovered new challenges, but it has increased the urgency of pre-existing ones. Where brands and retailers originally expected to have 5–10 years to shift their retail and sourcing strategies, that timeline has now shifted to 5–10 weeks.

Based on our literature review, we summarized the constraints imposed by the pandemic on the product supply chain and classified them in Table 1 as follows:

$$\text{Failure of supplies and uncertainty in raw material supply} \tag{C1}$$

$$\text{Maintain deficient machines} \tag{C2}$$

$$\text{Manage infection risks in plants} \tag{C3}$$

$$\text{Ensuring workforce capacity to assemble, store and ship products} \tag{C4}$$

$$\text{Loose collaboration} \tag{C5}$$

$$\text{Congested ports} \tag{C6}$$

$$\text{Integrate customer specific requirements} \tag{C7}$$

$$\text{Optimize decision} - \text{making} \tag{C8}$$

$$\text{continuous optimized production} \tag{C9}$$

$$\text{Manage process and data complexity} \tag{C10}$$

The international demand for raw materials [12] which are exported by Africa is weakening [13], national productions which require imported inputs sometimes suffer from the breakdown of production and supply chains.

In this context, a survey [14] was carried on by Saratech Inc., an engineering organization specialized in helping customers develop better products by implementing PLM softwares and new technologies. It was conducted among a range of company sizes, during Q3 2020 with data analysis and insights extrapolation conducted in Q4 2020. Respondents of the survey, as shown in Fig. 2, came from various industries; for example,

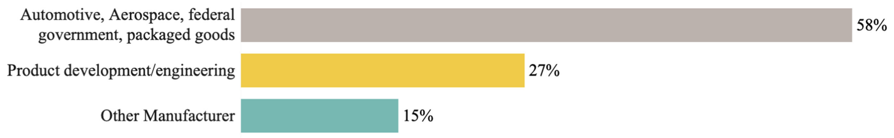

Fig. 2. Respondents of the Saratech Inc. survey

27% labeled their industry as Product Development/Engineering, and 15% came from industries described as "Other Manufacturer." Respondents also included automotive, aerospace, federal government, packaged goods, and other industries/verticals.

The study aimed to closely examine how organizations are adapting during the COVID-19 pandemic. It investigates how these organizations are actively transforming their supply chains and democratizing production capabilities.

To examine the potential influence of the pandemic on sourcing parts, the respondents answered, "How has the pandemic changed sourcing parts?". 65.3% of respondents reported that nothing has changed, and it was business as usual. 16.9% of respondents stated they have started to look at new ways to insource parts instead of outsourcing. 15.1% of respondents said they have pivoted and are using new technologies.

Table 1. Constraint of the product supply chain.

Constraint	Procurement	Production	Warehousing	Distribution
C1- import raw materials	X			
C2- reduce workforce & manage plants		X	X	
C3- maintain deficient machines		X	X	
C4- manage infection risks in plants		X	X	
C5- loose collaboration	X	X	X	X
C6- congested ports	X			X
C7- integrate customer specific requirements	X	X		X
C8- optimize decision-making	X	X	X	X
C9- continuous optimized production		X		
C10- manage complexity	X	X	X	X

According to this study, fewer companies were impacted by the pandemic in terms of raw materials required for manufacturing. Companies managed to find alternative solutions to overcome this challenge. On the contrary, in another context, during the pandemic, people were trapped in their homes and their expenditure on services such as transport has fallen, while smartphones, home furnishings and many other items have risen. This meant a huge number of cargo ships floating in the sea, in conjunction with the need for urgency for supplies and protection gears to combat the pandemic. The congestion was aggravated by Covid's work schedule constraint and separation. Nevertheless, industry 4.0 technologies are promising in assisting companies to overcome these challenges by providing alternative solutions, the according knowledge and skills.

The post COVID era opens an opportunity window for sustainable business transition [15], and need to make supply and production systems more resilient [16]. COVID-19 has infected people in several countries around the world, spreading to all continents. With this spread has come serious effects on the industry. All companies' leaders were concerned about how it will affect their sales, success metrics and most critically how would they minimize employees' interaction to fit into the new precautionary measures.

Companies should think about putting together a committed cross-functional unit. A cross-functional team will organize the efforts of various business divisions, track and provide the requisite information to senior management for more contact with staff, clients, and stakeholders. It's past time to assess vital responsibilities and main positions, as well as form a team of temporary replacements in the event of a force majeure situation, since there is a greater chance that certain workers may be unable to work due to quarantine or sickness.

Under different situations, businesses should create an efficient management decision-making mechanism. It should determine how it will guarantee the wellbeing of workers who are required to be at work and are unable to work remotely (e.g., shop assistants, cashiers, drivers, etc.). Companies are re-evaluating their strategies for ensuring proper occupational sanitation, providing disinfectants, and so on.

COVID-19 places a burden on the workforce as it tries to adapt to the current industrial process regime. To ensure social distancing at work, various reforms have been made, including improvements in manufacturing processes and, as well as standard operating procedures. This adds to the pressure on workers to meet their productivity goals when the current regime necessitates more time. Therefore, an optimal and real inventory and work allocation is required for the different phases of the pandemic [12].

Beside constraints that impact product supply chain processes directly, others have been faced once the product is ready to be delivered to clients. First, there would be no way to present what we have to offer to clients and interested parties if there are no more trade shows, in-house exhibits, or conferences. It was clear right away that something different, a new form of case, needed to be developed. It had a massive impact. The second choice is a home office. The word has been around for a long time, but only a few businesses have made it a reality.

While pandemic has made it clear that human to human interaction should be minimized, home office was adopted as the new way of working. The word has been around for a long time, but only few businesses have made it a reality. Home office working style had emerged to be adopted by supply chains stakeholders, and it is now a reality.

The Covid-19 crisis challenges a very hierarchical managerial culture based largely on "Command and Control". While it is obviously too early to say what organizational changes will take place over time, it invites, or even forces, a price for physical and psychological distance in traditional management. It will accelerate management by objectives to the detriment of micromanagement, reinforce the importance of local management, more able to manage and raise local issues for rapid adaptation.

The health crisis calls for finding other means to ensure the cohesion of the social body, the organizer of collective intelligence in a world where remote work will be structurally more important. Questions of identity, mission and "what are we doing together?" will arise even more sharply. The technological infrastructure of firms will need to be strengthened thus, allowing remote access and collaborative work.

Consequently, PLM in collaboration with industry 4.0 technologies may be the most important piece in the architecture when companies strive for:

- Engineering collaboration for designing smart products
- Vertical integration to implement flexible and reconfigurable smart factories
- Horizontal integration to implement smart processes on extended enterprise.

4 Industry 4.0 to the Rescue of PLM

4.1 Industry 4.0 Answering Pandemic Constraints

The COVID-19 pandemic has caused lockdowns around the world, disrupted the way we work and live, and caused economic repercussions not seen since the end of World War II. The COVID-19 pandemic is fast becoming a litmus test for businesses. Its consequences could not be anticipated. To overcome them, all that matters is the ability to react quickly and adapt immediately. Moreover, in an age when smartphones, laptops, IoT, AI and other technologies are part of everyday life, increasing agility by dispensing with essential digital innovations is mission impossible.

The pandemic has demonstrated that responding to the current and evolving demands as fast and flexibly as possible is more critical than ever. In recent months, various manufacturing industries have faced a variety of challenges. Some industries, such as food and pharmaceuticals, had to rapidly scale up demand. Others, such as manufacturing and aviation industry, were forced to cut down or even cease operations. Some have even started producing other products to sustain the crisis and avoid ceasing their operations. Elavarasan and Pugazhendhi [17] have even enumerated the world's leading manufacturing companies' activity before and during COVID-19 as shown in Table 2.

Table 2. Manufacturing Industries before and during pandemic [17]

Companies	Domain	Manufacturing products	
		Before Pandemic	During Pandemic
Ford	Automotive Industry	Vehicles	Modified respirator and ventilators
Tesla - Gigafactory	Automotive Industry	PV cells	Ventilators
Airbus	Aerospace Industry	Aircraft products	Ventilators
Mercedes-AMG High Performance Powertrains	Automotive Industry	Formula 1 engines	Continuous positive airway pressure (CPAP) machines
Dyson	Tech company	Vacuum cleaners and hand dryers	Ventilators
Ineos	Chemical company	Oil, gas, plastics Chemicals and other products	Hand sanitizer and other healthcare products
Gucci	Fashion	Luxury clothing	Masks
Zara	Fashion	Aparel	Surgical masks
Bacardi	Alcohol based company	Rum	Hand sanitizers
Eight Oaks Farm	Distillery	Liquor	Disinfectant
LVMH and L'Oreal	Fashion	Face creams and perfumes	Medical disinfectants and sanitizer gels

There is a requirement for the introduction of various advance technologies to tackle various problems and constraints related to this viral pandemic [5]. Industry 4.0 technologies, as illustrated in Fig. 3, have the capability of providing better digital solutions for our daily lives during this crisis [18–20] in many ways.

First, the cloud has taken on an extreme dynamic. Without it, the infrastructure for everything is missing. Distributed working worldwide is not new, but it has been greatly accelerated. The majority of businesses are conservative. Because of where the data is stored. Where is my engineering job, my drawing? There are still some major corporations that say, "My records should remain in my building!".

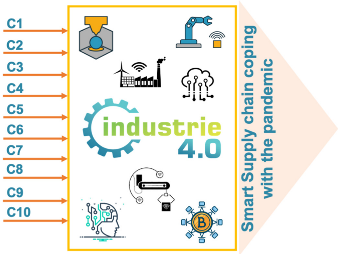

Fig. 3. Industry 4.0 as a response to pandemic constraints

Decentralized devices, such as those used in the home office, are, of course, driving cloud adoption. Otherwise, no one can operate on the same object from different locations. The Cloud is on its way. That being said, companies' conservative perspective must be respected. Their valuables, technical knowledge, and patents should not be left lying around. Many people are also unsure whether or not they can fully embrace cloud computing. One thing is sure, for the time being, anything that is in progress and contains private expertise should be kept locally. A good alternative would be to consider storing metadata in the cloud and storing data locally. This hybrid way of storing will ensure quick access to master data and metadata, as well as protection of their valuables. Corona is accelerating cloud-based distributed development worldwide. There will be a lot of activity, especially in end products with connected applications.

In addition, thanks to digital and automation of processes that can be adopted while personal access to premises is limited, certain facilities can continue to run. Machinery may also be operated remotely, commissioned, maintained or repaired. Engineers could "remotely" access a computer, system, device, or a machine and provide the same instructions as they actually stood beside the machine. Siemens, for example, offers these kinds of assistance. They use remote virtual reality to supervise desperately needed service work to support one of their clients whose company is closed to their service.

In particular, industrial 3D printing has demonstrated its utility in the crisis as it offers quick, scalable and dispersed alternatives to materials which are so desperately needed. For example, Siemens has opened her Additive Manufacturing Network to hospitals and health organizations shortly after the onset of the pandemic. Hospitals, physicians and other organizations have been able to send their medical equipment replacement parts desperately needed to third-party printing designers and 3D printing providers, thereby solving bottlenecks rapidly and without any administrative burdens.

Furthermore, thanks to Internet of Thing and Artificial intelligence (AI), a solution was developed which alerts manufacturers against the risk of infection in their facilities. It is a smart mix of modeling applications, small handheld monitoring systems and communications technologies. A Siemens production factory in Houston, Texas, already uses this functionality [21]. It will be used to refine the manufacturing processes remotely in order to make the workplace safer. The machine monitors the distances between employees and, in cases of danger, issues a warning. Companies can also install hotspots in their factories and monitor communications with infected employees.

Accordingly, there are some companies and plants that had always been endowed with a recognizable degree of autonomy and digitalization that they were capable to face the current circumstances. For instance, the Siemens plant in Amberg is among these companies and has a degree of automation is between 75% and 80% [22]. Consequently, their efficiency had only a slight decline which they were quickly able to catch up while reorganizing their procedures to fit the new sanitary precautions.

Companies managing their own supply chains and those outsourcing to third-party logistics providers manage a massive flow of freight, goods and products on a daily basis whilst at the same time creating vast data sets especially due to the shift to e-commerce during the pandemic. Millions of shipments are tracked daily from origin to destination, indicating information such as content, weight, size, location, route, etc., of each individual shipment, across large numbers of networks [23]. It is this data tracking, providing the big data, which contains huge value which needs to be exploited [24].

Visibility is an essential necessity of tracking products in an end-to-end manner throughout the supply chain. Gartner Research [25] reported that virtually no company is able to, or will be able to, provide end-to-end supply chain visibility in the near future.

What is needed, according to Kiritsis [26], is a closed-loop PLM system that will allow all the actors who play a role during the lifecycle of a product (managers, designers, service and maintenance operators, recyclers, etc.) to track, manage and control product information at any phase of its lifecycle (design, manufacturing, MOL and EOL), at any time and any place in the world.

Although there are a lot of information flows and inter-organisational workflows, the business operations in closed-loop PLM are based on the interactions among three organisations: PLM agent, PLM system, and Product. The PLM agent can gather product lifecycle information from each product at a fast speed with a mobile device like a personal digital assistant or a laptop computer with a Product Embedded Information Device (PEID) reader. It sends information gathered at distribution sites to a PLM system through the internet. The PLM system provides lifecycle information or knowledge created by PLM agents whenever requested by individuals or organisations [26].

Through advanced analytics, it is becoming possible to provide real-time visibility across the supply chain in addition to improving distribution processes performance [24]. With this improved visibility, companies will be able to track the movements of shipments and products from the time the shipment is released until it arrives at its destination. Tracking systems will generate alerts if shipments stay at certain nodes longer than expected and prompt transportation managers to contact the freight firms involved and explore the matter to ensure timely delivery [27]. The system will be freed from the use of human labour normally deployed for handling and inspection. Lower safety stock inventory levels are expected as the products move more swiftly through inspection points. With increased information visibility throughout the supply chain, managers will be better able to respond to problematic and exception-handling cases.

To summarize, Cloud computing will allow centralized data access, Additive manufacturing will support simulation and prototyping in the design phase as well as in supplying with necessary raw materials. IoT will give a thorough insight into how the product is being used during its lifecycle and illustrate certain components which are not of importance in terms of usage. In addition, customers require special and fast user interfaces which can be improved in conjunction with the Industrial Internet of Things (IIoT) rather than workflow-based commitments. One of the key fields is perhaps the capacity to predictively and prescriptively track and maintain, remotely or physically factories and plants. Consequently, product preferences will change with the interactive technology. Useful, autonomous and productive experience for users is to be expected.

Regardless of individual features, the PLM market is evolving quickly, and suppliers of tech solutions need to evolve solutions that address emerging demands in order to stay competitive. The biggest driving force is digitalization and Industry 4.0. Those businesses today are forced to be digital in one way or another for survival matters.

In addition, existing companies will need to combine the latest digitized approaches with what is already existing in the PLM package. The challenge is to find strategies for seamless and timely transformation coupled with the change management initiative.

4.2 The Smart Digital Agile PLM Framework

Having healed its wounds, the manufacturing industry must incorporate new work habits that will undoubtedly continue for years to come. It should rely on a PLM that is:

- Remotely operated and impact resistant.
- Operating closed offices, in a network.
- Integrating security, authentication and cloud functions for remote working.
- Allowing a product to be divided into sub-assemblies that can be addressed independently, in order to operate in degraded and parallel mode, if necessary. This induces system engineering, the definition of interfaces between subsystems and mature data. But also, to structure this data to limit the dependence between disciplines (mechanics, software, electronic), and this on the different phases of the life cycle.

In order to achieve the aforementioned characteristics, companies need to operate in a crosslinked manner. In Fig. 4, each chain of the product lifecycle will be using outputs and constraints of other chains relying considerably on the emerging technologies.

In fact, the basis for progress in digital transformations is the high product data quality and the focus is on digital models for product design, product supply and service chains. They are important prerequisites for digitally optimized processes in the era of Industry 4.0. These digital models should be available at all levels of product life. They offer a comprehensively realistic visual snapshot of a machine control system that is a digital twin. It allows the designer to fully and effortlessly move his engineering method

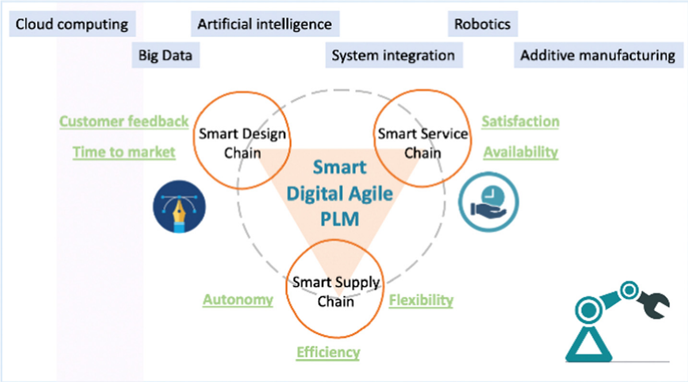

Fig. 4. The Smart Digital Agile PLM framework

into the virtual universe. It is no longer important to work on actual hardware designs. Product development will be agile, thus only the final steps would be carried out in the real world, allowing the ecosystem to connect evolve and transform to stay competitive.

PLM in the era of industry 4.0 will be endowed of collaborative design, tapping into the creativity outside the company walls. It will engage communities and customers earlier, deeper and more often. Feedbacks will be taken into considerations on the fly as flexible manufacturing capabilities will be developed and connected services will be delivered. In accordance with this, the value proposition of the products will be extended, thus insights into how the products are performing and being used will be gained. Using these tools, we will have the essential building blocks of a resilient PLM.

5 Conclusion and Future Research Directions

The health crisis has taught businesses how essential it is to know how to adapt quickly whether in terms of production, sourcing or even distribution. Observing what is happening in parallel in the world, given the developments in information and mobile technology, there is no doubt that we find ourselves in the era of intelligence.

Companies in many sectors are making efforts to move from ‘gut-feel’ decision-making to accurate data-driven insight to achieve effective business decision making. By adopting a more sustainable model, it is possible to ensure business continuity, even in the event of an unexpected and massive change in demand.

Supply chain (SC) managers need to get involved in the product development process to enable both product and process innovation. The experience of the weeks when the economy came to a screeching halt and the period of recovery should be a source of reflection and teaching for researchers and policy makers. The product lifecycle perspective becomes more important because it provides a holistic view across disparate enterprise silos to provide a coordinated response to the customer. Integration of product lifecycle and SC management can provide fresh perspectives and critical insights that are often missed due to the extreme fragmentation of functions within the firm.

Thus, supply chain professionals need to embrace these developments to remain efficient, effective and competitive. Anticipating sales volumes, customer preferences for products and optimizing work schedules are few examples where proper analysis of product data has the power to help succeed and overcome the current challenges.

The objective of this paper was to expose industry 4.0 as a rescuer of product lifecycle management (PLM) in this pandemic, having the potential of changing and impacting companies in a big way. A standard PLM model was elaborated following a review of existing PLM models. The link between PLM and SCM was outlined and the position of PLM in this pandemic was recognized, highlighting the constraints it applied on products in supply chains. Then how industry 4.0 would address these challenges was presented and finally a smart digital PLM framework was proposed.

Along this study, we have noticed that companies lack the possibility to access product related information letting managers face the difficulty of linking together the available data and drive decisions. Therefore, we propose to investigate how to have a single point of product and process information access across multiple domains, projects, partners, suppliers and systems through the use of industry 4.0 (I4.0) technologies.

In this paper, the research mainly focused on how industry 4.0 is rescuing PLM through enumerating constraints linked to the product supply chain only. As future research direction, we propose to investigate constraints along the product lifecycle and go through each I4.0 technology to explore their opportunities and challenges for PLM.

Furthermore, the main innovation in the 4th industrial revolution is the implementation of Cyber-Physical Systems (CPS) to establish the global value creation networks. PLM enables companies to take full advantage of IT combined with CPS to make the processes highly intelligent. We propose to design a CPS combining feedback data from product usage and sending it back to constructor to take it into consideration for future advances allowing much more agility and flexibility along the product lifecycle.

Finally, most studies and proposed models concern manufacturing phase of the lifecycle. Little efforts have been devoted to the logistics (warehousing and distribution/return) phase. We propose to cover this phase so as to provide more traceability and visibility on the product while delivering it to sale points or to final costumers.

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Towards a New Society: Solving the Dilemma Between Society 5.0 and Industry 5.0

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Abstract. Along with the technology development, new theoretical concepts are born continuously. Nowadays, given the challenges societies are facing (e.g., climate change, digitalization), an agreement on the meaning of concepts we want to build our societies on has never been more crucial. We have been living in Industry 4.0, and a new society is now approaching, grounded in two new conceptual perspectives: Society 5.0 and Industry 5.0. The level of common ground shared by these two new terms is not clear. On the one hand, they might be referred as synonyms, whereas on the other some differences are evident, as Society 5.0 seems to be related more to the human sphere, while Industry 5.0 seems to be more industrial-centered. A clarification is deemed mandatory. Therefore, the present article consists in a literature review, with the aim of clarifying which are the main commonalities and differences between Society 5.0 and Industry 5.0. 170 potentially relevant articles were found on Scopus, and 40 were analyzed by the authors, based on criteria such as language, relevance, and type of publication. For each article, the definition of Society 5.0 and Industry 5.0 was identified and analyzed. Finally, the definitions were compared and conclusions on the predominance of similarities over differences between the two concepts were drawn. With the present work, the authors took stock of the actual society, and give final indications on which studies are needed in the future.

Keywords: Society 5.0 · Industry 5.0 · Human · Technologies · Innovation

1 Introduction

With the constant improvement of technology, humanity has always had to adapt continuously to build a better society with cutting-edge industrial production processes. Humanity is now facing the Era of Industry 4.0 and the results of the adoption of the new technology provided by it will be shown no earlier than 2020–2025 [1].

In the last period, to be precisely in 2016, the concept of Society 5.0 was born. In 2016, the Japanese Government coined the concept of 'Society 5.0' as future society that Japan should aspire to. It follows the hunting society (Society 1.0), agricultural society (Society 2.0), industrial society (Society 3.0), and information society (Society 4.0). Society 5.0 is expected to achieve a high degree of convergence between cyberspace

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(virtual space) and physical space (real space). While Industry 4.0 is dealing with the future of industry, Society 5.0 focuses on a more Human-centered society [2].

The concept of Society 5.0 aims to create a smart society, in which the integration of cyberspace and the real world using state-of-the-art technologies helps different sectors, countries, and regions to cooperate with each other in such a way as to achieve the goals of sustainable development [3].

Society 5.0 is a new type of society where innovation in science and technology occupies a prominent place, with the aim of balancing social and societal issues that need to be solved, while ensuring economic development [4].

Together with Society 5.0, the term Industry 5.0 was coined. Industry 5.0 was firstly introduced on December 1st, 2015, in an article published by Michael Rada with the reference to the social network LinkedIn. Industry 5.0 is the efficient use of machines and people labor in a synergistic environment [5].

In the past industrial revolutions, Industry 1.0 introduced waterpower and steam power, Industry 2.0 introduced mass production system enabled through electrical power, Industry 3.0 created significant advancement through digital and electronic devices, and Industry 4.0 provided significant applications by using the cyber system, artificial intelligence (AI), Internet of Things (IoT), and other advanced technologies [6].

Industry 5.0 refers to the integration of physical and virtual space to solve not only production problems, but also the social ones. Indeed, all advanced information technologies, artificial intelligence, augmented reality and robots are used in everyday life, industry, healthcare, and other areas of human activity [1].

The term of Industry 4.0 was firstly introduced in 2011 by the German Government with the aim to achieve a high degree of technology improvement. At the same time, in America, the concept of Smart Manufacturing was born, which is described as the German Industry 4.0. The two terms, Industry 4.0 and Smart Manufacturing, have the same characteristics, but they were born in two different countries.

This literature review is poised to understand and clarify if the two new concepts, Society 5.0 and Industry 5.0, have the same characteristics in order to avoid managing the two terms differently in the future, similarly to what happened for Industry 4.0 and Smart Factory. In fact, the meanings of Society 5.0 and Industry 5.0 could be misled, with the former seeming more human-centered and the latter more industrial and centered on processes.

Therefore, the authors provide an analysis of several characteristics of Society 5.0 and Industry 5.0. In particular, five categories were defined: "Definition" (i.e., how the two concepts are defined), "Focus" (i.e., why we need to change Society or Industry), "Enabler" (i.e., which technologies or factors have a direct impact on the development of the two perspectives), "Benefits" (i.e., which are the benefit of the two concepts), and "Barriers" (i.e., which limits hinder the technological progress).

The article is divided into four sections. First, the methodology through which the literature review was conducted will be illustrated. Secondly, the results pertaining differences and commonalities between Society 5.0 and Industry 5.0 along the abovementioned categories will be presented. Thirdly, the results will be interpreted, and some conclusions on the overlap between Society 5.0 and Industry 5.0 will be drawn. Finally, the authors will provide indications on future research directions.

2 Methodology

As anticipated in the introduction, the article consists in a literature review. Thus, the purpose of the present work is to critically evaluate important literature in a specific field meticulously (i.e., Society 5.0 and Industry 5.0). Indeed, this article is not just listing the contents found in the literature, but it focuses the attention on which methods the studies used. The methods through which this purpose was achieved will be illustrated for the sake of transparency and repeatability.

Firstly, two key research questions were strictly related to the definition of Society 5.0 and Industry 5.0 (i.e., "What is Society 5.0?" and "What is Industry 5.0?"). Furthermore, two additional key questions aimed at investigating the barriers/challenges for the development of both concepts (i.e., "Which are the barriers of Society 5.0?" and "Which are the barriers of Industry 5.0?"). In contrast, the authors added two more questions in order to point out which benefits could emerge with the realization of the two concepts (i.e., "Which are the benefits of Society 5.0?" and "Which are the benefits of Industry 5.0?"). Finally, the last two key research questions regarded the enabling technology/resources capable to create such concepts, (i.e., "Who and which enablers permits to reach Society 5.0?" and "Who and which enablers permits to reach Industry 5.0?").

In order to obtain the articles and expand the literature, the research was conducted using Scopus as database. Future research will include other important search engines (e.g., Web of Science, IEEE Xplores, Taylor and Francis, Emeralds). The key words researched were "Society 5.0", "Industry 5.0", "Society 5.0" AND "Industry 5.0", "Society 5.0" AND "Enabler", "Industry 5.0" AND "Enabler".

The total amount of articles found using these key words were 170. A significant percentage of the articles found were "Conference papers". This is understandable, since these two concepts were born very recently. The authors tried to consider more journal articles, since they pass through a rigorous review analysis before being published in a journal and for this reason are more reliable. The total number of articles found were 39 (19 using "Society 5.0" key word and 20 using "Industry 5.0" key word). Amongst these 39 articles, only 34 were considered useful for this study. The others were excluded because of linguistic barriers (i.e., languages unknown to the authors) or because they were irrelevant to the purpose of the present study. No timeframe was specified in the criteria of the research and the first article found was published in 2018, with the majority of the other articles published in 2020 and 2021. Most of the articles were written by scholars and academics from Asian university, followed by American and European scholars and academics.

2.1 Analysis

The analysis conducted is poised to understand the main concepts regarding "Society 5.0" and "Industry 5.0" described in each article. The authors extrapolated the relevant information needed from all the articles considered. This was done in order to compare the main concepts of all the articles and, consequently, to find commonalities and differences.

The authors organized all the information in several main categories in order to critically evaluate them. The categories defined by the authors were the following:

– the *Definition* of Society/Industry 5.0 was extrapolated in order to understand the idea behind the concepts.
– *Main focus* of the two concepts (e.g., human, machines, technologies, social issues).
– *Enablers* concerned the factors which could permit to achieve the technological development.
– *Nationality focus*, regarded the possibility for the implementation of Society/Industry 5.0 to be cultural-specific (i.e., developed in a specific region or with some cultural constraints).
– *Benefits* included any advantage that each concept could bring to humankind and industrial development.
– *Differences* and *Commonalities* between Society/Industry 5.0 and Industry 4.0 were also defined.
– *Barriers and challenges* which could hinder the transition to Society 5.0 and Industry 5.0.
– *Maturity level* of the concept.

This article considers only five categories from those mentioned before: "Definition", "Focus", "Enablers", "Benefits", and "Barriers". The other categories will be analyzed in future studies.

3 Results

This section is divided into six subsections describing the type of research design and all the categories abovementioned. The subsections are as follows: 3.1 "Type of studies", 3.2 "Definition of Society 5.0", 3.3 "Definition of Industry 5.0", 3.4 "Focus", 3.5 "Enablers", 3.6 "Benefits", and 3.7 "Barriers".

3.1 Type of Studies

Articles Related to Society 5.0. The total number of articles found on Scopus using the key word "Society 5.0" were 19, but only 17 were useful to the study. Amongst these 17 articles, 13 were literature reviews and the remaining were experimental, analysis and survey research. The main topics of all the articles were related to understand the positive effects of technological development to optimize and improve the healthcare system [7, 8], to solve social issues [9], to improve the quality of education [4, 10], to create a sustainable environment [2, 11–14], and to understand how a high-tech environment can influence the working conditions [15]. All the articles considered were published in the time frame 2019–2021.

Articles Related to Industry 5.0. The total number of articles found on Scopus using the key word "Industry 5.0" were 20, but only 17 were useful to this study. Amongst these 20 articles, 9 were literature reviews, 1 experimental study, 3 case studies and 4 survey research. The topics of the articles were related to the analysis of improvements that could be generated by Industry 5.0 to the healthcare system [6, 16], how the technology development could optimize the industrial sector [1, 17–25], in which way the marketing sector could benefit from the Industry 5.0 revolution [26], the level of education needed with the realization of the new concept [27], and the impact of the new perspective on the supply chain segment [28]. The articles were published in the time frame 2018–2021.

3.2 Definition of Society 5.0

In order to understand the commonalities amongst all the articles, the authors collected and analyzed the definitions of Society 5.0 (Table 1).

Table 1. This table contains all the definitions of Society 5.0.

Author(s), Year	Article	Definition
Sarfraz et al. 2020	Is covid-19 pushing us to the fifth industrial revolution (Society 5.0)?	Bridge human/machine
Liliasari et al. 2019	Innovative chemistry education: An alternative course models in the disruption era	Integration between physical space and cyberspace
Cook et al. 2021	Insight into the millennial mind-set: Impact of 4IR and Society 5.0 on the real estate, construction and other industries	Extension of networks, increased digitisation and connectedness
Sołtysik-Piorunkiewicz and Zdonek, 2021	How Society 5.0 and Industry 4.0 Ideas Shape the Open Data Performance Expectancy	Integration between physical space and cyberspace
Wolniak and Skotnicka-Zasadzien, 2021	Improvement of Services for People with Disabilities by Public Administration in Silesian Province Poland	Integration between digital and real space
Fachrunnisa et al. 2020	Spiritual welfare creation for knowledge workers in society 5.0 a conceptual model	Social resolution between virtual and actual world through harmony
Polat and Erkollar, 2021	Industry 4.0 VS society 5.0	Aims to use all advanced technologies on behalf of social life of society

(*continued*)

Table 1. (*continued*)

Author(s), Year	Article	Definition
Hysa et al. 2021	Social Media Usage by Different Generations as a Tool for Sustainable Tourism Marketing in Society 5.0 Idea	Integration between physical space and cyberspace
Udin et al. 2021	Developing Interactive Mobile Mathematics Inquiry to Enhance Students' Mathematics Problem-solving Skill	Sinergy between human and technology
Carayannis et al. 2021	Known Unknowns in an Era of Technological and Viral Disruptions—Implications for Theory, Policy, and Practice	Bridge human/machine and integration between physical space and cyberspace and human/robot interaction
Nomura and Miyata, 2020	Digitization of the approach to food and nutrition respecting individual health values	Data-driven society
DeWit et al. 2020	An integrated approach to sustainable development, National Resilience, and COVID-19 responses: The case of Japan	Integration between physical space and cyberspace
Gurjanov et al. 2020	The smart city technology in the super-intellectual Society 5.0	Integration between physical space and cyberspace
Kojio, 2020	Sustainable Workplace in Kyoto – 'Kyo-sei' in Society 5.0	Integration between physical space and cyberspace

From the analysis of all the definitions it seems evident that Society 5.0 is perceived as an environment in which there is the integration between the physical and cyber space. Furthermore, in each article there is a particular label with which Society 5.0 is defined. In the articles [7, 12, 14, 29, 30] this new concept is labelled as "Super-smart Society", in the articles [2, 8, 9, 11, 14, 29, 31, 32] Society 5.0 is defined as "Human-centered Society", in the article [33] the new concept is defined as the "Era of Digital Society", and in the articles [4, 12, 34] Society 5.0 is described as based on knowledge and it is defined as "Society of Intelligence" or "Superintelligent/Superintellectual Society".

It is evident from the literature that the main focus of Society 5.0 was the human. In particular, the aim of Society 5.0 is to solve various social and economic challenges through technology development [35].

3.3 Definition of Industry 5.0

In order to understand the commonalities amongst all the articles, the authors collected and analyzed the definitions of Industry 5.0.

The definitions of Industry 5.0 are similar to those related to Society 5.0. In most of the articles the characteristic of Industry 5.0 is the interaction between human and machines, as in the Society 5.0 with the integration of real (human) and cyber (machine) space. Unlike for Society 5.0, in the articles related to Industry 5.0, there were few labels which identified the Industry 5.0 concept. Only in 3 articles there was the presence of a specific label: in the article [6] Industry 5.0 is referring to a "Smart factory"; in the article [26] there is a conceptualization of Industry 5.0 as a "Society founded on super smart people"; and in the article [27] Industry 5.0 is called "Super smart society" (Table 2).

3.4 Focus

This section presents the key points on which both Society 5.0 and Industry 5.0 concepts are built, highlighting the common characteristics and the expressions frequently used.

Society 5.0. From the analysis it is evident that Society 5.0 is poised to create new values and solve social problems through advanced technologies [36], indeed 8 out of 17 articles focused on the benefit to solve social issues by transforming the actual Society into the new Society 5.0. Other important key points frequently used in the articles were "Economic development", "Sustainable development", and "Increase efficiency".

Industry 5.0. In the articles related to Industry 5.0, the most important key points for the technology development were: first of all, "Company sustainability", because, in contrast to Industry 4.0 which focused on production, Industry 5.0 provides a perfect solution to save the environment with the use of advanced digital technologies [18, 32]**.** Another relevant point was that the integration of new technologies with humans can change the production focus, shifting from a "mass production" process to a "mass personalization" process with the consequent benefit on "value co-creation" by means of customer involvement [25]. Other terms on which most of the articles focused were "Increase efficiency", "Increase safety" and "Reduce waste" within the company boundaries. Furthermore, there were few articles regarding "Social value".

3.5 Enablers

Society 5.0. In order to transform the actual society into Society 5.0, there is the need to improve and develop new technologies. Indeed, in most of the articles it was emphasized that "Artificial Intelligence", "Internet of Things", and "Robots", with the support of "Big Data", could facilitate the transition towards the new society. Society 5.0 is the society where advanced IT technologies (Internet of Things, Artificial Intelligence, Robots) are aggressively used in peoples' life, industry, health care, and other provinces of activity not for the progress, but for the advantage and convenience of each person [37].

Table 2. This table contains all the definitions of Industry 5.0.

Author(s), Year	Article	Definition
Gopalakrishna Pillai et al. 2021	COVID-19 and hospitality 5.0: Redefining hospitality operations	Human cyber physical system
Carayannis et al. 2021	Known Unknowns in an Era of Technological and Viral Disruptions—Implications for Theory, Policy, and Practice	Renewed human centric industrial architype
Carayannis et al. 2021	Smart Environments and Techno-centric and Human-Centric Innovations for Industry and Society 5.0: A Quintuple Helix Innovation System View Towards Smart, Sustainable, and Inclusive Solutions	Renewed human centered/human centric industrial paradigm
Javaid et al. 2020	Industry 5.0: Potential applications in COVID-19	Smart factories
Javaid and Haleem, 2020	Critical components of Industry 5.0 towards a successful adoption in the field of manufacturing	Cooperation between human beings and machines to meet customer requirements
Carayannis et al. 2020	Towards Fusion Energy in the Industry 5.0 and Society 5.0 Context: Call for a Global Commission for Urgent Action on Fusion Energy	Renewed human centered/human centric industrial paradigm
Dewi et al. 2020	Purchase Intention of Green Products Following an Environmentally Friendly Marketing Campaign: Results of a Survey of Instagram Followers of InnisfreeIndonesia	Society as containing super smart people
Özdemir and Hekim, 2018	Birth of Industry 5.0: Making Sense of Big Data with Artificial Intelligence, "The Internet of Things" and Next-Generation Technology Policy	Evolutionary, incremental advancement that builds on the concept and practices of Industry 4.0

(*continued*)

Table 2. (*continued*)

Author(s), Year	Article	Definition
Wasono Mihardjo et al. 2019	Boosting the Firm Transformation in Industry 5.0: Experience-Agility Innovation Model	Smart community, collaboration between people and smart technologies to take over on repetitive tasks integrating human creativity
Nahavandi, 2019	Industry 5.0—A Human-Centric Solution	Robots are intertwined with the human brain
Jan et al. 2020	A Lightweight Mutual Authentication and Privacy-preservation Scheme for Intelligent Wearable Devices in Industrial-CPS	The digitalization, automation and data exchange of industrial processes
Martynov et al. 2019	Information Technology as the Basis for Transformation into a Digital Society and Industry 5.0	The efficient use of machines and people labor in a synergistic environment
Martynov et al. 2019	The Use of Artificial Intelligence in Modern Educational Technologies in the Transition to a Smart Society	Super smart society
Pathak et al. 2019	Fifth revolution: Applied AI & human intelligence with cyber physical systems	Emphasize interaction between humans and machines

Industry 5.0. The enablers of Industry 5.0 were similar to those of Society 5.0. The frequent expressions were “Big Data”, “IoT”, “Artificial Intelligence”, and “Robots”. Other expressions used in few articles were “Automation” and “Blockchain”. IoT in industry 5.0 (as, indeed, in Industry 4.0) should not be the technology for the sake of technology, but it should be aimed at improving the quality of human life [38]**.**

3.6 Benefits

Society 5.0. It was evident that the benefits were human-centered. Indeed, most of the articles highlighted the positive impact of the future transition on humanity. The goal of Society 5.0 is to create a society centered on the human being, where both economic development and the resolution of challenges of social issues are achieved and people can enjoy a high quality of life, life to the full, fully active and comfortable [37]. Another important benefit is to make life easier for the increasing elderly population [30].

Industry 5.0 In most of the articles it was highlighted that the transition towards Industry 5.0 could have a positive impact on the involvement of Human’s creativity. The rise of the fifth revolution tends to a new human machine symbiosis, which distributes work in humans and machines. This partnership between human and machines allows human to concentrate on more creative work enhancing creativity and critical thinking skills, and machines should be left for mundane tasks [18, 25].

3.7 Barriers

Society 5.0. What was found in the articles it was not particularly helpful for the study, since only few of them described which barriers could prevent the realization of Society 5.0. From the limited information extrapolated from the articles, it was evident that the lack of funding, adequate managerial measures (e.g., healthcare sector) and skilled technological support were potential limitation for the successful application of technological tools of Society 5.0 [7]. other obstacles to establish and harmonically develop the Society 5.0 were the low level of civilian activity, which prevented the progressive ideas new economic model implementation in all places, and business absence of desire to support financially the technologies of clear social application [34].

Industry 5.0. For Industry 4.0 the barriers were related to "Ethical issues", "Skilled Worker", "Cost", and the delay of Industry 4.0 concepts development. Autonomously controlling production lines require a great deal of artificial intelligence applied in the software agents operating in the factory. This created concerns about how autonomous systems can incorporate ethical principles, and that ethical behavior in autonomous systems must be subject to verification and validation [23]. Fifth revolution demands high skilled people and robots working together to create personalized products, services and experiences [25].

4 Discussion

Society has always adapted to the exponential technology development. In the last few years, new definitions of society and industry emerged, such as Society 5.0 and Industry 5.0.

This study consisted in a literature review, and it is poised to find commonalities and differences between the two definitions. Industry 5.0 was firstly introduced in 2015 by Michael Rada [5], whereas Society 5.0 in 2016 by the Japanese Government [2]. The current work researched articles only on Scopus, and the articles found were published no prior to 2018. This consists in a limit, and future research will include other search engines.

From the literature is evident that Society 5.0 and Industry 5.0 are defined as the integration between real space (composed by humans) and cyber space (composed by machine). Indeed, both highlight the importance of human-machine interaction. Furthermore, both Society 5.0 and Industry 5.0 refer to a "Smart Society", meaning that the two concepts are human-centered. Both are built on the same technologies, "IoT", "Artificial Intelligence", "Robots", "Big data", and the focus is to increase sustainability, to increase efficiency and to involve more the human in the production process, to, on the one hand, foster human's creativity and on the other, to shift from a mass production to a mass personalization which could cover all customer satisfaction gaps with a consequent improvement of people's lives.

Part of the current debate refers to the potential overlap between Industry 5.0 and Industry 4.0. In this regard, the authors propose that, although the concepts are indeed interlaced, they can be differentiated. As represented in Fig. 1, Industry 4.0 is the typical factory that is more machine-oriented and does not give an important role to the human worker (i.e., smaller industry icon in Fig. 1). Industry 5.0 includes Industry 4.0, with the difference that it is more human-focused because there is the need to reintegrate the human's creativity throughout the whole industrial process (i.e., bigger industry in Fig. 1). Both the concepts are embedded in Society 5.0, which can be defined as an environment in which everything is connected, characterized by a human-centered perspective (i.e., circle in Fig. 1).

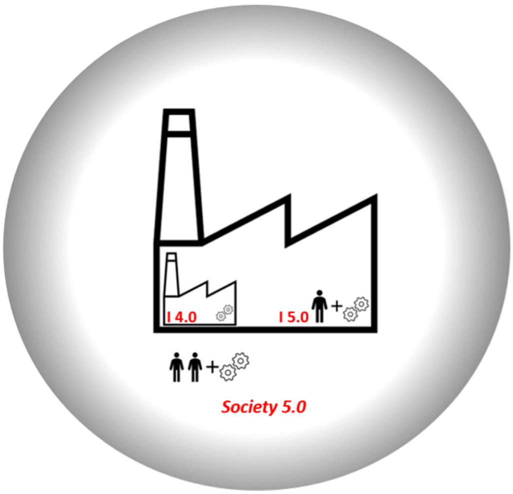

Fig. 1. Visual representation of the concepts of Industry 4.0, Industry 5.0 and Society 5.0. The smallest one is the representation of Industry 4.0 with the focus on the gear (machine). Industry 4.0 is embedded in the Industry 5.0 concept which shifts the attention towards the Human involvement (importance of creativity). The last one is the representation of Society 5.0 which embeds all the perspectives into society.

5 Future Research

Society 5.0 and Industry 5.0 are newborn concepts; therefore, it is necessary to run more studies in order to improve our knowledge. What is particularly necessary is to design studies on the pros and cons of the two concepts, in order to make more visible and evident that the two terminologies are referring to the same concept, and in particular Society 5.0 is more human-centric embedding the Industry 5.0 perspective as well. Furthermore, what should be investigated is the cost to make all these efforts, because in all the articles found there was not any information about implementation cost which is the first constraint an innovative solution has to deal with. What is impeding the actual society to shift towards Society 5.0/Industry 5.0 is the fact that Industry 4.0 will be able to show its results and achievements no earlier than 2020–2025 [1, 32]. Since the actual society is in the time interval 2020–2025, and the main achievements of Industry 4.0 are occurring now, there is the urgency to find a new perspective [39].

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Toward an Adaptive Approach to Implement Predictive Maintenance in Metallurgical Industry SMEs Through IoT and AI

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Abstract. Industrial actors are striving to transition to Industry 4.0 in order to enhance their production capacities, reduce costs and increase benefits. Their aim is to maintain competitive edges over their competitors in the global market. While this new paradigm introduced many technologies to improve manufacturing in general and machinery maintenance in particular, its implementation can be very challenging for SMEs due to hurdles such as limited financial leeway and lack of adaptability to their business operating environment specificities. This paper presents a conceptual approach to implement predictive maintenance while ensuring adaptability and cost-effectiveness by taking into account business related legacy data in the design phase, in order to provide SMEs with a simplified access to smart factory principles.

Keywords: Industry 4.0 · Predictive maintenance · Wireless sensor network · Self-adaptability · Manufacturing · IoT · AI · SME

1 Introduction

Every production system element is bound to degrade over time and/or usage and eventually experience failure when it fails short to accomplish its suitable role or to be up to an expected standard. To make up for this, actions can be accomplished to either retain it in or restore it to a state in which it can accomplish its suitable role, those actions are labeled as maintenance [1]. As such, maintenance can be of the utmost importance especially when failure can have disastrous consequences such as impaired or halted production, delivery delay, etc. This can be clearly seen in the manufacturing industry where maintaining industrial equipment can cost as much as 30% of the overall facility operating costs and 60 to 75% of the machine lifecycle cost [2]. Expenditure is necessary when the production system is one of the main value-adding components and hence maximizing machine up-time is one of the main concerns of such facilities.

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Among maintenance strategies, predictive maintenance is one of the key notions of implementing a smart factory. Unlike corrective maintenance, its goal is to address the breakdown before happening by predicting just in time failure situations resulting in reduced repair costs [4]. Predictive maintenance also strives to minimize machine downtime compared to preventive maintenance which schedules maintenance operations at regular intervals even when they might not be needed, which can increase failure rate in regards to the bathtub curve [5]. While this objective can be hard to achieve, industry 4.0 (I4.0) approaches managed to shorten the gap between the theory and its implementation through the association of many concepts such as Industrial Internet of Things (IIoT), Cyber-Physical Production Systems (CPPS), Artificial Intelligence (AI) and so on [15].

For SMEs, although predictive maintenance (PdM) has several benefits making it an important prospect for any industrial actor seeking to improve its performance, reliability and cost-benefits ratio, it can also be very hard to attain due to many hurdles. In fact, while PdM can cut as much as a 65% reduction in maintenance costs, it was also shown that the adoption of this approach can be very costly with an initial expenditure that many SMEs cannot afford [6]. While bigger factories can afford to experiment with the associated technologies of PdM in order to find the suitable approach fitting their situation the most through extensive sensing or R&D investments, small manufacturing companies can find it harder to implement. Also, the legacy machinery in these kinds of factories tend to be quite old, meaning that it is equipped with little to no data collection sensors and have a higher mean failure rate [16]. At this point, one can enquire about a way to ensure a smooth uplift for SMEs thriving to transition from classic maintenance strategies such as corrective maintenance (CM) or even preventive maintenance (PM) to PdM while being in sync with the company needs and issues, making it worthwhile in term of cost to benefits and motivating an upstart toward this fundamental axis of the smart factory. This can prove itself even more necessary when being applied to make-to-order (MTO) metal working factories where the machine nominal functioning states can be hard to characterize in comparison to mass production factory types where the machine functioning modes are repetitive, making failure or near failure states easier to encompass [17].

A widespread data-driven approach starts from gathering operational parameters widely-used as failure indicators (such as vibration, ultrasonic information, fluid analysis and so on) from the shop-floor, uncorrelated to the business processes (BP), and then trying to diagnose the machinery failures. Our paper's goal is to give a more end-to-end approach starting from a business oriented data analysis to determine the failure states and propose a wireless sensor network (WNS) adapted to the data coverage gap to fulfill in order to have the right sensing approach, while also providing a decision model minimizing the resources needed to detect and prevent failures. The WSN has to be able to self-adapt and reorganize itself depending on the likeliest failure state linked to each production and usage scenario determined in the initial BP and production data (PD) analysis to make the sensing less invasive and accurately designed, knowing that wireless monitoring in manufacturing plants can be challenging in term of transmission [7], organization, architecture [8] and self-adaptation [9].

Hence, to answer the question: "How to design and implement a predictive maintenance strategy in a SME metalworking manufacturing environment through a relevant cost-effective and self-adaptive decision support system without facing the hurdle of massive monitoring?", the first step of the approach would be to identify the main recurrent failure modes and their characteristics from an analysis of business processes and non-compliances (NCs) history and determine the gaps in data coverage. Next is, after a machine decomposition and components/failure criticality analysis, devising an appropriate WSN in order to fill that gap and monitor the production processes. After that comes the creation of a decision support system for maintenance to minimize the targeted failures. Last is to evaluate the model comprised of the decision support system and the WSN and adapt it according to the targets at each machine and production mode.

While the approach is thought to be global and can be applied to any type of industry in which material transformation of the product are at stake, our implementation scope will be limited to the manufacturing metalworking SMEs, taking as an example of a possible implementation the maintenance strategy of Tardy SAS in the metallurgical industry.

The paper will be structured as follows: Sect. 2 will be dedicated to the related work, Sect. 3 will introduce the general framework proposed in this paper while Sect. 4 introduces a conceptual implementation of the approach. Finally, Sect. 5 will conclude this paper and introduce further research directions.

2 Related Work

The literature has emphasized the importance of this approach regarding the adaptation of methodologies to the SMEs' operating conditions. As such, Masood et al. [10] presents a study in which current I4.0 approaches (including smart maintenance) are found to be mainly developed for or by large firms making them disconnected from the needs of SMEs despite the fact that they represent 90% of registered companies in Europe. The paper further states that the current proposed approaches offer limited links to SMEs requirements for technological investments and hence mismatch their needs, making them unable to fully confront the main issues in the I4.0 deployment for SMEs such as financial/technical resources limitation, the cause being mainly the abundance of technologies SMEs need to be aware of as well as the difficulty to assess their varying environment and needs.

This issue can be verified by Diez-Olivan et al. [11] with a review of numerous data-driven approaches to descriptive/predictive/prescriptive prognostic models based on heterogeneous data sources using data-fusion technics as well as the widely used methods for each, but none adapted to SMEs or tackling their issues. A similar approach can be seen with Diez-Olivan et al. [12] where a set of operational features (such as humidity, temperature, fuel pressure…) is used in a novel machine learning approach combining constrained k-means clustering, fuzzy modeling and LOF-based score to provide a fault detection and prediction strategy for an engine.

Orellana et al. [13] confirms the difficulty for SMEs and specifically MTO-based factories to get to second phase of I4.0 where the enterprise is able to integrate and digitize its machinery and intern processes and make the data available and visible, and that is mainly because of the prohibitive cost of replacing legacy machines with newer ones where the technology for data acquisition is already available. The approach presented in this paper is based on defining management indicators and then identifying the data-coverage gap before selecting the appropriate sensors to fill it, along with the underlying IT network to support it. This strategy, in a general sense, is similar to the one presented in this paper although the latter encompasses more than just management data and emphasized on production data such as NC in the failures analysis. Also, the case study presented in the paper isn't clear about the bridge between the chosen KPIs and the data covering choice. Another paper, by Sezer et al. [14], approaches the question of cost in an I4.0 enabled maintenance approach for SMEs but the study focuses on the reduction cost of the material tools and technologies used rather than on the choice of these tools and where it comes from in term of cost-effectiveness. In addition, although the data coverage approach is a classic operational parametric study, the model also includes a link (while faint) with product data and NC by using one of the characteristics of the product (roughness) to highlight the quality production.

Finally, Pertselakis et al. [3] addresses one of the issues discussed in this paper, and that is the fact that predictive maintenance is seen as a strategy relying on performing condition monitoring through sensor data and that most research work focus on sensorial data while neglecting the knowledge already present in legacy systems. The paper proposes a combination of legacy-data extracted knowledge and sensor data stream along with recent machine learning techniques for predictive maintenance. While the study covers a part of the issue at hand, and that being the integration of other types of data other than sensor based ones, it does not cover the motivations behind the choice of the eventual sensors as a lever for a more adapted and cost-effective PdM system.

3 Supporting Axis and Framework

Further along this section will be presented some key notions regarding the proposed framework and implementation.

3.1 Control Levels

The road toward preventive maintenance, in the context of I4.0, and toward the smart factory principles can be decomposed into three consecutive steps, each one relying on the previous to achieve a better overall integration of the production processes as well as an efficient operating:

- Diagnosis: maintenance aims to detect and solve machinery failures, to do so it is important to be able to identify the problem. This identification not only comprises of the problem description, but also all the patterns and relevant context involved. It can be seen as the data-information transition in the DIKW pyramid. The generated insight can then be used to assert the machinery health status at each time.
- Prognosis: the next step in term of usage and complexity is, from the diagnosis made on historical data, to be able to predict the next health status of the monitored machine. By doing so, one can expect to be able to move from preventive maintenance to predictive maintenance and hence reduce unnecessary costs in term of intervention, spare parts or lost uptime. In the DIKW pyramid, this can be assimilated to the information-knowledge transition.

- Prescription: Through knowledge accumulation, the maintenance system can be expected to not only predict the occurrence of each failure mode and its characterization but can also, with regards to business data (schedules, clients' orders …) and production data (machinery load, health status …) propose recommended course of actions optimizing the production operations such as modifying the maintenance plan, rerouting products and so on. In the DIKW pyramid, this part can be compared to the knowledge-wisdom transition.

3.2 Legacy Data

One of the main axes of this approach is the use of different business data as an input for the framework. Those data can consist of:

- Business process data in the form of a dynamic cartography, which can be attained through a static cartography supplemented with an implementation through web services or BP engines. This data source provides us with the necessary information on what is going on in the factory, who's in charge of which part of a closed/pending/planned process and so on. This part will supplement the prescription level with the necessary context as well as an output for its recommendation.
- Production data, through the ERP and other integrated tools. This can provide us with client's/supplier's orders, shop-floor operations scheduling, costs and other management-level KPIs.
- Shop-floor data: shifts, machinery workloads, uptime, maintenance planning, etc.
- Quality control data: NC occurrences with a complete context regarding the issue, the production operations that led to it, when, on which production line and with which configuration and environment, the resulting impact and proposed treatment (salvaged/scrapped) … At Tardy SAS, the main manufacturing NC can be classified by main families:

  - Dimension measurements NC
  - Shape defect NC
  - Centricity defect NC
  - Tool marks NC

3.3 Failure Causes

The characterization of failure modes required for predictive maintenance can prove itself to be an arduous task in the conditions where the machinery park consists of many decades old second-hand or overhauled machines, especially in the metal-working industry SMEs.

Furthermore, the classic sensor data-driven approach requires a large dataset of instances where the machinery experienced each failure mode and eventually because of all the probable causes, which can be difficult start for an SME with a high early expenditure and no added-value in the acquisition considerable waiting time. It can be even more difficult when the SMEs is of the MTO type, since customized work comes with customized operations for the machine and results in different operating profiles, conditions, parameters …

The said approach also captures only but a number of operational parameters (temperature, vibrations …) with no certainty as to if those aspects will be related to the failures or not in term of significance, relevance, variability and so on.

To address this issue, this paper proposed to start from the failure modes that can be noticed through two types of causes:

- Special causes: unusual variations in the process for which an identifiable reason can be determined and which make the system go out of control such as tool wear or overheating. Here the system being the machine in an extensive way, which can include a part of its environment such as a clamping board for a milling machine and so on.
- Common causes: usual variations in the system process which are inherent to it and to its operating behavior. For example, it can include systematic kinematic drifts of the legacy machine.

Depending on the data analysis, failure mode characterization and the links with the NC events, the maintenance plan can be adapted or revised to include notions such as imperfect repair or minimal repair, in an attempt to boost the metalworking system reliability.

3.4 General Framework

The general approach can be given by the following framework in which the starting point would be the business oriented legacy data such as BP, NC history, ERP and production resources (Fig. 1).

Next would be, through the legacy data, an analysis of the failure modes, their characterization as well their criticality regarding the resulting NC. The diagnosis, providing us with the maintenance target issues, enables to ascertain the data coverage gap between what is currently monitored and what needs to be monitored which guides us to the WSN design and implementation to fill that gap. The monitoring sensors data, along with the legacy data, can then feed a suitably constructed decision support model with IA frameworks depending on the state of the art performance as well as application compatibility. The system can next be evaluated in term of accuracy metrics with the objective of maximizing the level of control it can provide on the maintenance (diagnosis/prognosis/prescription), while also self-adapting to the various operating instances at hand (various products and usage profiles, each with the probable resulting NC and causes …).

The feedback loop is activated when the evaluation is not deemed to be of a satisfying resilience, resilience that can be defined through the same evaluation metrics discussed before (accuracy, maintenance capacity, self-adaptability, data coverage …), and, by determining the missing requirements, activates a self-adaptation which can lead to a reorganization of the sensing and/or the decision to further add new monitoring capacity.

This can be performed in an incremental way until convergence and/or satisfaction, making it well adapted and justified in term of expenses and deployment efforts to

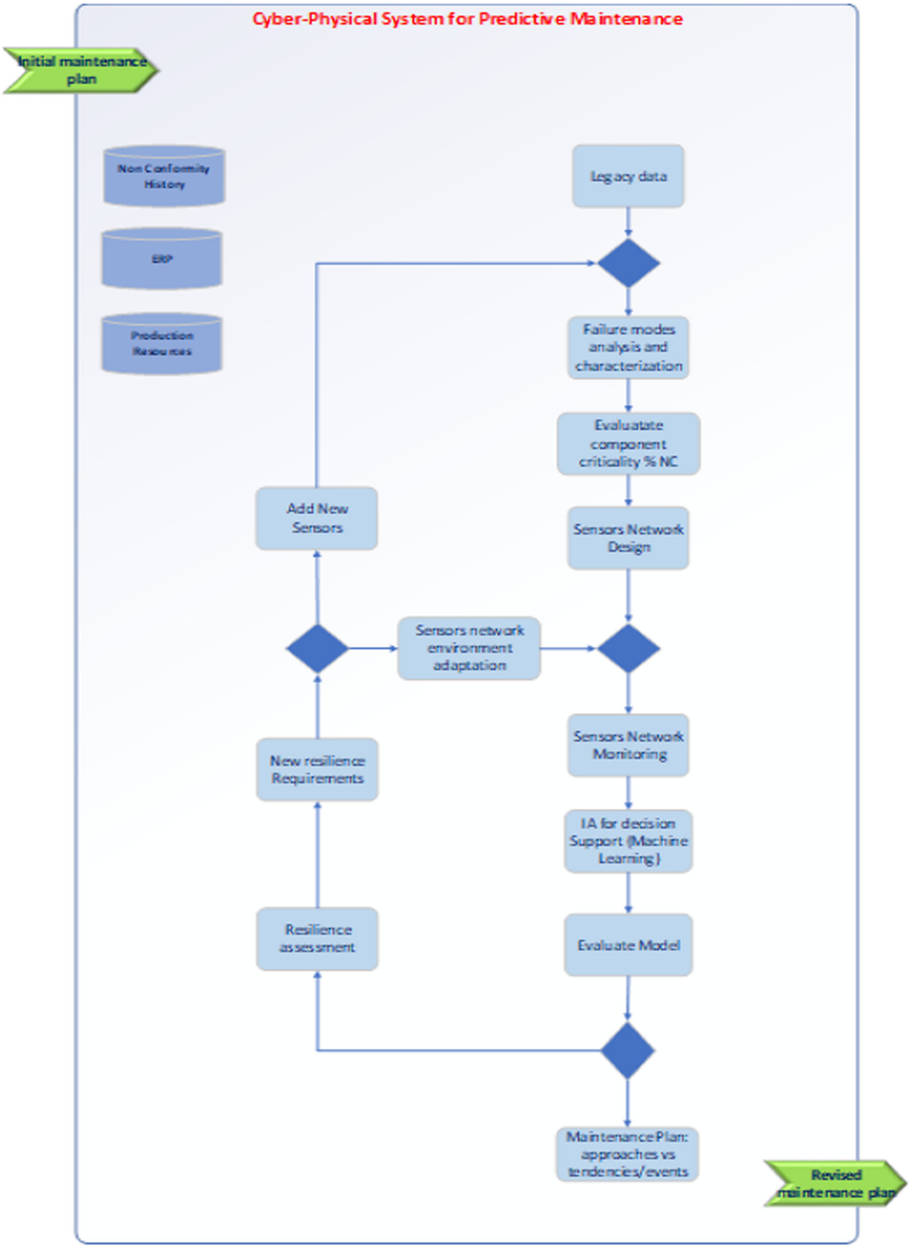

Fig. 1. General framework

accompany a SME early industry 4.0 uplift as well as more likely to produce immediate added value since the approach is designed to be directly correlated to the issues at hand.

Initialization. The initialization phase can be seen as follows:

- Perform an analysis of the data sources at hand to get a clear classification of failure modes in regards to the product, type of operation, machine, environment, workload and so on.
- Execute a machine decomposition reliability analysis to link each failure mode with the relevant components and operating patterns.
- Identify the needs in term of monitoring and data.
- Determine the data coverage gap hindering the course of action or the acquisition phase.

Design and Implementation. The next phase relates to the following blocks:

- Produce a WSN to cover for this lack in accordance with the monitoring strategy.
- Design a decision support system with the help of sensing data and AI with:
  - Pattern recognition and health management for diagnosis.
  - ANN/ML, probabilistic models and fuzzy logic for prognosis
  - Optimization algorithms, semi-supervised learning, knowledge-based system for prescription.

Assessment and Adaptability. As for the last blocks:

- Assess the relevance of the decision support system as well as the WSN depending on the advancing through the predictive maintenance capacities (failure modes characterization/detection/minimizing recommendations).
- Devise a self-adaptability strategy to improve the model performance depending on the various operating scenarios.
- Adapt the system configuration accordingly (reorganizing the WSN, adding more sensors …) whenever needed.
- Loop back for continuous improvements.

4 Implementation

In this paper the implementation part will focus on the initialization as well as the first step of the design.

4.1 Initialization

First of all, a classification of the quality control data and the NC history provided us with the main NCs encountered in the shop floor. This classification was further validated with the other data sources previously cited in order to take into account for BP bottlenecks, production data for the criticality analysis in term of costs and clients' orders. The result can be classified into 3 main categories:

- Tool issues: cutting tool wear, breakage, jamming, heating, bluntness, vibration, deviation and so on. This can concern all types of tools such either milling inserts, drills, taps, dies … This accounts for roughly 49% of the critical NC issues in the shop floor.

- Material deformation: the transformation processes involve fixing raw parts in order to proceed with the material removal. Depending on the process, the part drawings, the production and operations sequence, the raw will need to be locked down with different angles, positions and intensity. If the clamping is too tight or wrongly positioned, this will result in raw deformation during the cutting with a risk of tool breakage when drilling or right after, making the produced piece outside of tolerance limits. Conversely, if the clamping is not tight enough or wrongly positioned, the raw can slightly move or vibrate throughout the material removal process. If this issue can be well treated when working with mass produced pieces where the process is the same, it can be tricky for a MTO SME where every work piece can more or less be considered as a new process. In addition to quality issues, this problem is closely related to the machine safety in terms of tools, spindle and clamping table and claws. This accounts for 27% of the critical issues encountered in the shop floor.
- Other problems: such as machine tool assembly errors, breakdowns, kinematic drifting and so on account for the rest.
- When compared with workload, machines uptime and maintenance history provided by shop floor data, two machine tools were isolated as potential candidates for the WSN design, both being used for 5-axis machining:
- Colgar fv200
- DMU210P

4.2 Design and Implementation

In terms of WSN initial design proposal, the following data sources were chosen for monitoring:

- Cutting forces: either through numerical control signals or through external sensors such as strain gauges, piezoelectric force sensors, load measuring cells …
- Power consumption: mainly regarding the spindle. Can be acquired through the numerical control signals or power sensors/transducers.
- Tool motion sensors.
- Vibrations: monitored through accelerometers.
- Acoustic emissions
- Temperature: for the spindle and the contact area between the tool and machined work piece. This can be achieved through sensors such as infrared cameras, pyrometers, temperature probes, thermocouples …

The chosen components have to respect constraints such as:

- Costs: usage, setup and maintenance.
- Minimal to no interferences with the machine or the production processes such as additional restraints in terms of machine motion, workspace or processing operations.
- Ability to be positioned as close as possible to the cutting operation's area.
- Robustness towards the environment (shards, cooling liquid, noise …)
- Relevant characteristics to acquire the necessary data in term of precision, resolution, bandwidth, sensitivity …

The WSN, as well as internal numerical control signals, is expected to provide a sufficient data coverage to feed the decision support system and further advance in the implementation. In order to do so, many models and configurations have to be thoroughly tested first in a controlled laboratory environment for the connectivity and organization then placed onto the machine tools for the data acquisition part.

5 Conclusion

The methodology presented in this paper gives a general framework for manufacturing SMEs to approach the predictive maintenance in an I4.0 perimeter and provide an uplift towards smart factory implementation.

The strength of this approach is to start from an extensive panel of legacy data to design the predictive maintenance system with an implementation leading to immediate added value for the target audience. Therefore, it provides time for data acquisition and further investments in order to gradually upgrade the maintenance approach in a cost-effective and adapted way.

For future work, we aim to implement this framework in a real-life use case to accompany Tardy SAS in its industry 4.0 uplift. We can also aim for a more holistic approach to include quality control, another crucial axis of the smart industry, and its eventual relationship with the predictive maintenance, making use of the I4.0 bricks laid before (WSN, AI…). Finally, we can make use of both approaches to circle back to the static actual BP cartography and strive for a more dynamic approach, aiming for the "automatic production" axis of industry 4.0.

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