# Lean Engineering and Lean Information Management Make Data Flow in Plant Engineering Processes

Sabrina Karch[1(✉)], Johannes Prior[2], Anton Strahilov[1], Arndt Lüder[3,4], and Bernd Kuhlenkötter[2]

[1] let's dev GmbH & Co. KG, Alter Schlachthof 33, 76131 Karlsruhe, Germany
sabrina.karch@letsdev.de
[2] Chair of Production Systems, Ruhr-Universität Bochum, Universitätsstr. 150, 44801 Bochum, Germany
[3] Chair of Production Systems and Automation, Otto-v.-Guericke Universität, Universitätspl. 2, 39106 Magdeburg, Germany
[4] Center of Digital Production, Seestadtstr. 27/TOP 19, 1220 Wien, Austria

**Abstract.** The plant engineering process is characterized by high complexity, diverse interfaces and multidisciplinary processes. Today, there is still no standardized reference process architecture. A proven procedure is to use and adapt existing planning documents with certain similarities to a new project. This involves lots of effort not only in the design phase but much more in the semantic adaptation, resulting from redesign and reprogramming. Due to these challenges and the increasing importance of data as gold of digital age, a continuous flow of data and information is becoming even more important in plant engineering. Creating a solid base of engineering and operation data free of waste supports effectiveness and efficiency during the entire product life cycle. A new approach is to design general and configurable production modules. Just as virtual commissioning brings considerable time and quality benefits, the design of defined process steps in advance of a customer order is intended to bring forward some of the tasks, standardize multidisciplinary work and unify the data base. The aim of this paper is to present the lean-based concept of configurable production modules. Thereby, a focus is especially on lean information management to achieve an effective as well as an efficient plant engineering process and to create the requirements for a lean production process. The concept of configurable production modules is applied to the example of the plant design process of automated production plants for hydrogen electrolyzers.

**Keywords:** Lean information management · Data flow · Lean engineering · Configurable production modules


M. Liewald et al. (Eds.): WGP 2022, LNPE, pp. 664–676, 2023.
https://doi.org/10.1007/978-3-031-18318-8_66

## 1 Introduction

Optimizing the factors of time, costs, quality and individuality (flexibility) is a significant competitive advantage of manufacturing companies in the digital age [1], beginning already in the production engineering phase of the production life cycle. The effectivity and efficiency in the engineering phase of automated production systems and the information engineering affects the entire life cycle of a production system [2].

Automatization and digitalization of components, as well as processes, enable a significant increase in productivity, simplify data collection [3] as the "gold of the modern age" [4] and are the basis of cyber-physical production systems, with the aim of self-organized, real-time production of customized products [2, 5]. Digitalization seeks to manage complexity, redesigns process flow as well as generates new products, services, or business models [5], for example digital twins.

Lean is a renowned system idea to focus on effectivity, efficiency and reduce complexity through a customer-centered approach and the reduction of waste in value streams [6, 7]. "Design instead of re-design!" and teamwork of product development and production engineering are the nursery of lean processes [6].

The triad of automation, lean and digitization has an inseparable correlation and offers varied fields of action in context of engineering of production systems. Optimization in the engineering can be addressed to the planning process itself (e.g., lead time of information) and also to the processes to be planned (e.g., cycle time of plants).

The purpose of the paper is to use respective strength of each discipline as a basis to identify levers for reducing complexity in the planning process, establish the conditions for an efficient production system and to confirm the importance of a lean information flow from the beginning of a product life cycle. All activities follow the vision of generating plant engineering at the push of a button. The purpose is further specified in two research questions.

- How can the application of lean-aligned and predefined, configurable production modules and templates optimize the plant engineering process?
- How can the focus on lean information flow support effectivity and efficiency from the beginning of a product life cycle?

First, basics and state-of-the-art of the engineering process are discussed, using the example of plant engineering, followed by digitization and the significance of lean engineering and lean information management. Based on this literature-centered study of today's processes, fields of action are derived and presented in the main part. First levers are considered using the example of plant engineering for hydrogen electrolyzers within the sub-project FertiRob of the BMBF lead project H2Giga. Finally, a summary and an outlook for further work is given.

## 2 Data Flow in a Plant Engineering Process

The production engineering and especially the plant engineering is a significant phase of the product life cycle of the production system [8]. This phase is usually divided into several sub-phases, in which layout, process flow, mechanics, electronics and software of the system are designed (Fig. 1) [9].

The arrangement of the plant in a production building as well as the value stream are detailed with 2D layouts and process descriptions in plant layout and process design.

In mechanical design, the detailed 3D geometric model of the production system is created respectively fixed with all corresponding mechanical design data and process restrictions for the following sub-phases. Some of these mechanical design data are 3D geometry models, 2D drawings, bill of materials (BOMs), process animations as native simulations or videos, layout plans, simulation models for virtual engineering, documentation, production process descriptions, offline robot programs, etc.

Starting from the BOMs, all parts and components, integrated into the production systems, serve as input to start the next sub-phase of electronical/fluidic design. In this, electrical data is created and important electrical decisions are made that have a major impact on the production system. In this process, an initial restriction of the available production data from the system is made because of the selected electrical components, such as electrical drivers, pneumatic drivers, various sensors and safety components.

In addition, the electrical components restrict the accuracy of the available data on the one hand and the frequency in which the data can be taken from the components via the communication technology on the other hand, e.g., ProfNet, Profibus, OPC UA, etc. on the other hand [2].

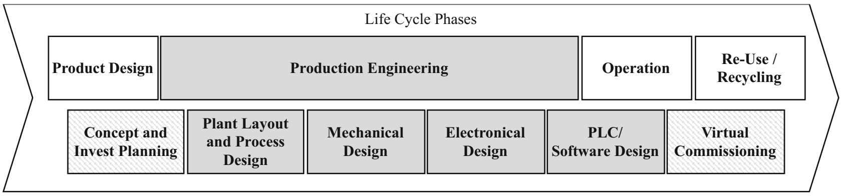


**Fig. 1.** Phases in production system engineering, in reference to [2]

With the finishing of the electrical/fluidic design, the PLC/software design phase begins. In this phase, the software (control program) of the production system is created. During this, a next important design and decision step is done, which is relevant for the evaluability of the data provided by the electrical components. The PLC is the hub that communicates with all electrical components and has access to all existing data in a frequency between 10 and 100 ms. In these sub-phases, important decisions are made for the system, which have significant effects on the subsequent design, functionalities, service life as well as the production quality of the product achieved during the operation of the system. A subsequent change is possible but usually associated with significant time and cost [2].

On the one hand, this results in enormous engineering data, which is usually not changed after the construction and commissioning of a production system and on the other hand, continuous system data is created during operation, such as error messages, style statuses, quality data, motion sequences, individual sensor data, etc. Depending on the recording rates, such recorded system data can reach large dimensions during system operation.

To merge and test all sub-phase, data without taking the risk of damaging the real plant as well as persons, the Virtual Commissioning (VC) is preferred as an ahead phase before the real commissioning [10, 11]. VC is therefore the first opportunity to check all data for logical errors and consistency as well as to perform the first checks on the data generated from the running system.

The simulation model required for VC is referred to as the mechatronic plant model in [12] and can be subdivided into the two sub-models, the extended 3D geometry model and the behavior model. The extended 3D geometry model includes the 3D geometry of the plants with mechanics, kinematics, part transport, sensors, and interfaces. This sub-model represents the plant mechanics for VC. The behavior model, in turn, is needed so that the mechatronic plant model can react to control outputs during VC in the same way as the real plant, pass information to other components and set appropriate control outputs [12].

Both sub-models are used as the basis for the digital twin of production plants. Among other things, the digital twin is used as the digital twin of the running production plant. In this case, the real PLC outputs are used. The output signals of the digital twin are not transmitted to the PLC. So, no PLC input signals of the real plant are manipulated.

In [13] an example of the file size of the behavior model and the generated run data is presented. The example shows that the required storage space for the behavior model, which consists of 106 individual behavior models, is only 8 MB, but for 8 h of running as a digital twin of the running real plant, it generates about 1 billion values with a data size of 11 GB at a sampling rate of 50 ms. This generated data directly depends on the number of input and output signals and the signal type, e.g., Boolean, Integer, Reals, etc. The file size depends on the used data format. In the example above, the behavior models were used as FMUs (10 electrical drives, 16 industrial robot, 80 pneumatic drives), according to the Functional Mock-Up Interface (FMI) [14, 15].

Based on expert discussions from the plant engineering industry, the biggest challenge is, which data to include and store during the development phase of a plant to achieve meaningful data recording during operation without collecting non-sincere, e.g., data over years of operation or, even worse, without recording data, which is of enormous importance. As a rule, experts decide in most cases to record and store all available data as a precaution. However, this creates a huge waste of data.

## 3 Digitalization and the Significance of Data

The importance of data in the digital age is expressed in headlines such as gold, raw material, the fuel of digital transformation or infinitely valuable.

Making data available became a “piece of cake”, the challenge remains processing data for the right purpose, at the right time for the right people [16]. This aspect is even more important in a production environment, because “Manufacturing generates more data than any other sector of the economy. (…) More data than healthcare, more data than retail, finance. When we talk to manufacturers, they mostly throw away the data. Where they keep it, they don’t know what to do” [17]. Even if generating data is a cost-effective process, the focus is on mastering the triad of data, information and knowledge and specific recommendations for action. Customer benefits, company benefits and above all resource efficiency are the guiding principles [5, 18].

In [19] it is brought to the point: "More recently, the digital era allows us to deal with lots of information, arising from sensors, CPS, IoT, and social networks. The challenge is to understand how to use these technologies to build on the fundamentals of lean thinking and create even more value and to improve industrial productivity".

## 4 Lean and a New Type of Waste

### 4.1 The Decisive Contribution of Lean

Efficiency is a masterpiece of lean, although the significance of lean in the digital age is a matter of debate. Representatives of the diversity of opinions are "Introducing Lean as a philosophy throughout the company with the traditional tools is dead, the Lean philosophy is alive" [5] or "Lean is the basis for digitalization and for "Industry 4.0". Waste must be eliminated before processes are automated and digitalized. Lean is therefore a prerequisite and basis for further progress" [6]. Lean arrived in the digital age.

If the system idea of lean is at the centre of attention, lean can still make a decisive contribution (Fig. 2). This aspect is summarized by Womack and Jones in lean thinking with the key messages: specify value from the end customer's perspective, identify value streams and stabilize them by eliminating waste, create a value flow, let customer pull value, and pursue perfection through continuous reduction of waste [7]. The essential role of people and leadership is also emphasized in lean enterprises [6, 20].

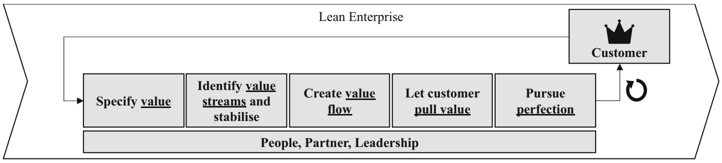


**Fig. 2.** System idea of lean, in reference to [6, 20, 21]

The reduction of waste in production or literally in all business processes is seen as the key principle of lean. Waste, or Muda in Japanese, means "to toil" or "pointless effort" and is any activity that does not add value to the customer's needs. It is found in overproduction, inventory, overprocessing, transport, waiting, movement/motion, defects, and unused intellect/skills in the production context [6, 20, 22]. In addition to waste, variability and inflexibility are also considered to be loss factors [6].

### 4.2 Waste in Engineering Processes

In the context of engineering, Muda arise in the planning processes itself and also in the processes to be planned, the later series production and affects engineering data as well as operation data (Fig. 3). Waste in the engineering process can be eliminated by taking the following levers into account, which finally lead to a reduction of the order throughput time [6].

- Reduced interfaces or at least the need for coordination and iteration loops.
- Structured data management and information exchange.
- Eliminated unnecessary work steps.

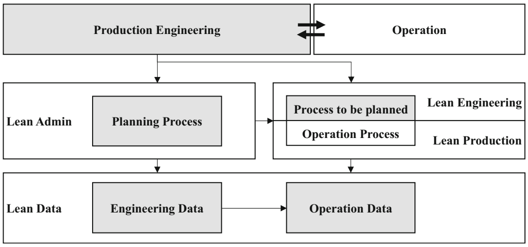


**Fig. 3.** Waste in engineering and data flow

The elimination of waste has its origin in product design and production planning with more potential influence than in ongoing production. Lean engineering provides planning principles, which can be applied to different types of workplaces and aim to create lean production processes [6].

- Ergonomic Workplace Design: Flow of horizontal material transport, work area with a best point area arranged in a radius of 80 cm, material supply always at the same place, position, and orientation (pick-optimized), and no set-up times of tools and machines.
- Machine Design: Machines' orientation in-depth and in an alignment reduces walking distances and required space.
- One-Piece Flow: A flow orientation of a layout or a cell is always the most important target, to reduce the lead time and stocks between stations.
- Human and Machine: The cooperation of machine and employee is to be designed in such a way that one employee can handle several machines and do not have to wait for the machine.
- Material Provision: Material is providing in the process with the help of chutes, rails, conveyors or hoppers, prepared in the smallest possible containers or units and the delivery schedule is organized via a Kanban system.
- Capacity: In the context of plant engineering, oversizing machine capacities can be defined as an additional type of waste [23].

If these principles are not already taken into consideration in the engineering, waste in automated production occurs as overproduction through lot sizes, overprocessing through production planning specifications or transport of goods through layouts without flow orientation [6].

### 4.3 Waste in the Information Flow

In addition to the traditional understanding of Muda, waste in relation to data has to be discussed to the increasing operationalization of industry 4.0 and usage of digital tools. It is generally agreed that the simple collection of data does not add value. The meaning of waste in the context of data and information is not finally defined.

In the sense of lean, the collection of data rather can be seen as an apparent performance, non-value-adding but necessary activity, which should be reduced to a minimum [6]. Waste in the information flow is less obvious and not immediately visible. There can be found parallels between lean thinking and waste in information management and defined as “the additional actions and any inactivity that arise as a consequence of not providing the information consumer immediate access to an adequate amount of appropriate, accurate and up-to-date information” [24].

The decision support is given priority and composed of the idea of a 5 C model in [16]: “Connection (sensor and networks), Cloud (data on-demand and anytime), Content (correlation and meaning), Community (sharing and social), and Customization (personalization and value)”.

Alieva et al. propose to define a new form of waste, “Digital Muda”, which can be found in uncollected, (partially) unprocessed or misinterpreted data in the production process also in the context of decision making [26].

A further literature review on the transfer of waste to information logistics can be found in [25]. Information logistics plans, manages, executes, controls, stores and prepares cross-process data flows with the purpose of decision support [27]. Meudt et al. set up a systematic approach to identify waste in information logistics according to the eight types of waste and the focus on brownfield processes (Fig. 4). The properties of information flow are considered, such as immateriality, compressibility, expandability and fast transportability. The model is based on the triad of data, information and knowledge and transfers these to data collection, data processing and data analysis [25].

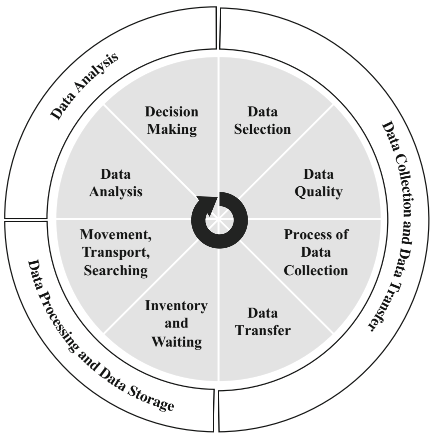


**Fig. 4.** A systematic approach to identify waste in information logistics, in reference to [25]

# 5 Fields of Action to a Systematic Reduction of Waste in Plant Engineering

## 5.1 Vision of Lean Aligned, Configurable Production Modules

In order to be able to transfer the lean data approach, the idea of template-based production modules is introduced. These modules aim to reduce complexity in plant engineering by creating pre-defined engineering artifacts in advance of a customer order.

The functionalities of individual components of the production cells, e.g., robot grippers, conveyor belts or sensors, are encapsulated, so that a distinction can be made between internal data, e.g., material or bearing of a conveyor belt, and user-specific engineering data, e.g., dimensions of a conveyer belt.

The idea follows a procedure model for project tasks as well as the project-independent activities of plant engineering, in particular the development of a continuous data model, reuse of artifacts, a standardized description language and the definition of reference models to describe knowledge formally [28, 29].

The approach uses a configurator [29], templates and a set of configuration rules to manage, for example, right of access, interdependencies of changes or configure customer orders. Project experiences are taken over in the knowledge management for further development of the standard based on previous configurations and best practices.

In the lean admin context, the implementation of configurable production modules increases efficiency in plant engineering in the first step by:

- Stakeholder [2] and interface management to reduce the need for clarification and iteration loops,
- Standardization as a starting point to document the knowledge of previous engineering activities, reduce redundancy of data and raise the quality of engineering artifacts and,
- Reduction of the order throughput time in particular through the predefined engineering artifacts.

In particular, the possibility of user-specific data exchange in the engineering chain through the encapsulation of functionalities establishes the conditions for a pull-oriented lean data implementation.

The production modules and as a result, the processes to be planned, follow the restrictions of lean engineering. Figure 5 demonstrates a draft of a configurable production module in the context of a production process to be automated for hydrogen electrolyzers. The shape of the casing is often comparable to a control cabinet, why the accessibility is focused on one side.

With the help of predefined templates and only a few data (variable and not variable), the parameters and the size of the plant can be customized and scaled, e.g., dimensions and positions of production cell, conveyors or robots. In addition, robot trajectories can already be pre-designed in a robot simulation program, depending on the variables of the product specific design. The template, especially if it is based on a neutral data exchange format, enables a lean information engineering and eliminates waste in information logistics starting with data selection and quality.

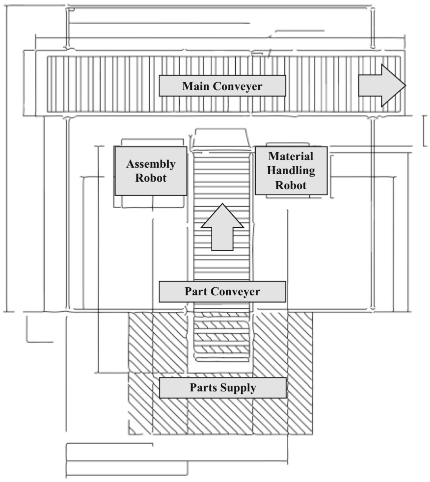


**Fig. 5.** Draft of a template-based configurable production module

The customer-specific scalability is to prevent waste due to under- or oversizing of the plant and eliminate waste in the movement of robots. The configurable production modules also ensure flexibility to arrange the plants according to diverse target layouts in a flow without stocks and in an optimized machine orientation.

A challenge is still to find an optimum of production modules considering variance and variability in product and process, not to risk a systematic under- or oversizing of plants, overproduction as the most critical form of waste, a lot of setups or waiting time in the process. Also, the number of different predefined production modules has to remain clear and manageable.

In the context of lean information management, the templates specify data requirements, processing and analysis as well as reduce data waste. The approach of configurable production modules is the baseline for a continuous data flow.

## 5.2 Levers to Create Lean Data Flow from the Beginning of a Lifecycle

Value in plant engineering results from the engineering artifacts as well as from the engineering data. Table 1 provides an overview of Data Muda Potentials in the context of plant engineering, derived from the current processes and considering the findings on lean information management and Digital Muda. The potentials can have different characteristics in relation to their maturity level and vary from Data Muda Potential not recognized to recognized and actions installed, running, or working.

A first indication is done to the effects on engineering processes or processes to be planned as well as to the superordinated category of waste according to [25]. All Data Muda Potentials impact the engineering processes, the impact on the processes to be planned is not always obvious at the first sight. Also, the range and intensity of Muda are indicated but have to be evaluated in detail.

**Table 1.** Data muda potential in plant engineering

| | Data Muda Potentials | Affects | | Waste [25] | | | Subject field [29] | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Engineering Process | Engineering Artifacts | Data Collection | Data Processing | Data Analysis | workflow | Methods | Tools | OrganizationaStructur | Economics |
| Upstream Processes | Communication and coordination between engineering and product design or other stakeholders [2], such as maintenance. | x | x | x | x | x | x | x | x | x | x |
| | Input data/information does not correspond to the needs of engineering (e.g. digital product twin). | x | | x | | | (x) | (x) | | (x) | |
| | Documentation of requirements and questions. The same topics are discussed several times with same or even different results. | x | | x | | | | x | | | |
| Mechanical Design | Variety of native data up to engineering results are created and processed in numerous tools. | x | | x | x | x | | | x | | |
| | Data is only used for specific tasks or in specific tools and has no relevance for next process step. | x | | x | x | x | | | x | | |
| | Data is transferred with data/information loss due to transformation of file formats, e.g. CAD drawing to PDF. | x | | x | x | | | x | x | | |
| Electronical Design | Data availability and accuracy through selection of electrical components e.g. pneumatic drivers or sensors. | x | x | x | | | | | (x) | | |
| | Frequency of data collection from the components by the communication technology, e.g. OPC UA. | x | x | | x | | | | (x) | | |
| Software Design | Evaluability in PLC programming (input and output signals). | x | x | x | x | | | | (x) | | |
| | Frequency (between 10 and 100 ms) of evaluation. | x | x | x | x | | | | (x) | | |
| | Influence of the system onto the running process, e.g. production quality. | x | x | x | x | | | | (x) | | |
| Virtual Commissioning (VC) | Interaction of robot programme and control programme is not confirmed until VC. | x | x | x | | | | | (x) | | |
| | Waste in simulation model as a basis for digital twin, transfers waste immediately to digital twin, e.g. library elements. | x | x | x | x | x | | | x | | |
| | Conclusions about performance of the system (oversizing/undersizing) will not be transparent until VC. | x | x | x | | | (x) | | | | |
| General topics in Engieering | Transparency of data and information flow and corresponding sources and sinks. | x | | x | | | | | x | | |
| | Push of data and information without focussing on selected needs of the user. | x | | | x | | x | | x | x | |
| | Changes from downstream process steps do not flow back in a structured or needs-oriented way. | x | | x | x | | x | | | | |
| | Selected data formats influence file sizes. | x | | x | | | | x | | | |
| | Loss of information through the use of unsuitable media/tools for transfer e.g. email. | x | | | x | | | x | | | |
| | Information to all persons and to right persons. | x | | x | | | x | | | x | |
| | Responsibility or acess rigth. | x | | x | x | x | x | | | x | |
| | Handling of data during its life cycle (generation to deletion). | x | x | x | x | | x | | | x | |
| | Optimum of overall process in context of the multidisziplinary engineering. | x | x | x | x | x | | | | x | |
| | Data requirements from Simultaneous Engineering (e.g. work statuses, versioning, missing or changed information). | x | | x | | | x | x | x | x | |
| Commissioning and Series Production | Recording and processing of plant data e.g. error messages. | x | x | x | x | | x | | | | |
| | Collection of relevant data during series production is not planded in plant enginering. | x | x | x | | | (x) | | | (x) | |
| Re-Use and Recycling | Data do not correspond to the needs of reuse and recycling (analogy: product design influences reuse). | x | x | x | x | x | (x) | | | (x) | |

x: applicable, (x): partially applicable

In the context of plant engineering, the state-of-the-art target status for engineering organizations including technical, organizational and economic aspects is described in [29]. The assignment of the Data Muda Potentials to the defined topics gives a hint to the current situation and also an initial indication of starting points for eliminating waste. These findings lead to further key questions and the following research activities.

- How does pull of data from customer or decision-maker influence data waste?
- How does data waste, in particular, data processing and analyzing, depend on repetitive (e.g., KPIs) or irregular decision needs (variability)?
- How can data waste in specific engineering tasks be identified, measured (qualitative or quantitative) and rated according to the influences as well as the effort benefit ratio (reference model)?
- How should data waste be considered in the context of data economics, innovation with not conclusively defined customer value, or Big Data and AI applications (flexibility)?
- How can the lean paradigm Genchi Gembutsu, “go to the place of value creation” [6], be rethought in the context of data and information flow?

## 6 Summary and Outlook

In this paper, an overview of the data flow in plant engineering processes is given in the context of the increasing importance of data and information in the digital age. Lean is proven to give orientation to establish effective and efficient solutions and processes in information flow, plant engineering as well as engineering artifacts in a multidisciplinary environment. A first approach to reduce complexity and addresses lean data is presented with the templated-based configurable production module (research question I). The next step is to finalize and evaluate the modules concept especially focusing on data waste. In addition, the value stream-oriented arrangement in the layout and the control concept with a vision of one-piece flow have to elaborate.

The Data Muda Potentials in plant engineering are elaborated in the context of current processes. Specific levers and key questions to eliminate data waste and increase effectivity and efficiency are defined (research question II). Following research activities are dedicated to how data waste in specific engineering tasks can be identified, measured (qualitative or quantitative) and rated according to the influences as well as the effort benefit ratio and finally eliminated.

**Acknowledgment.** Parts of this work were supported by the Federal Ministry of Education and Research (BMBF) within the research project H2Giga – FertiRob.

## References

1. Wiegand, B.: Der Weg aus der Digitalisierungsfalle: Mit Lean Management erfolgreich in die Industrie 4.0, 1st edn. Springer Fachmedien Wiesbaden, Wiesbaden (2018)
2. Biffl, S., Lüder, A., Gerhard, D. (eds.): Multi-Disciplinary Engineering for Cyber-Physical Production Systems: Data Models and Software Solutions for Handling Complex Engineering Projects. Springer, Cham (2017)
3. Burggräf, P., Schuh, G.: Fabrikplanung: Handbuch Produktion und Management, vol. 4. Springer Berlin Heidelberg, Berlin, Heidelberg (2021)
4. Webseite der Bundesregierung | Startseite, Rede von Bundeskanzlerin Merkel beim Publishers’ Summit des Verbands Deutscher Zeitschriftenverleger (VDZ) am 2. November 2015. [Online]. Available: https://www.bundesregierung.de/breg-de/aktuelles/rede-von-bundeskanzlerin-merkel-beim-publishers-summit-des-verbands-deutscher-zeitschriftenverleger-vdz-am-2-november-2015-390088. Accessed 23 Apr 2022

5. Kieviet, A.: Digitalisierung der Wertschöpfung: Auswirkung auf das Lean Management. In: Künzel, H. (ed.) Erfolgsfaktor Serie, Erfolgsfaktor lean management 2.0: Wettbewerbsfhige verschlankung auf. [Place of publication not identified]: Gabler, pp. 41–59 (2016)
6. Bertagnolli, F.: Lean Management. Springer Fachmedien Wiesbaden, Wiesbaden (2022)
7. Womack, J.P., Jones, D.T.: Lean Thinking - Ballast abwerfen, Unternehmensgewinn steigern. Campus Verlag, Frankfurt/New York (2013)
8. Drescher, B., Stich, P., Kiefer, J., Strahilov, A., Reinhart, G.: Physikbasierte Simulation im Anlagenentstehungsprozess – Einsatzpotenziale bei der Entwicklung automatisierter Montageanlagen im Automobilbau pp. 271–281 (2013)
9. Groover, P.: Automation, Production Systems, and Computer-Integrated Manufacturing
10. Kiefer, J.: Mechatronikorientierte Planung automatisierter Fertigungszellen im Bereich Karosserierohbau. LFT, Univ, Saarbrücken. [Online]. Available: http://nbn-resolving.de/urn:nbn:de:bsz:291-scidok-14686 (2007)
11. Wünsch, G.: Methoden für die virtuelle Inbetriebnahme automatisierter Produktionssysteme. H. Utz, München (2008)
12. Kiefer, J., Ollinger, L., Bergert, M.: Virtuelle Inbetriebnahme - Standardisierte Verhaltensmodellierung mechatronischer Betriebsmittel im automobilen Karosserierohbau **07**, 40–46 (2009)
13. Strahilov, A., (ed.): Digitaler Schatten von Produktionsanlagen als Big Data Quelle – Herausforderungen & Potential. Big Data Technologien in der Produktion von der Datenerfassung bis zur Prozessoptimierung (2017)
14. Süß, S., Hauf, D., Strahilov, A., Diedrich, C.: Standardized classification and interfaces of complex behaviour models in virtual commissioning. Procedia CIRP **52**, 24–29 (2016). https://doi.org/10.1016/j.procir.2016.07.049
15. Functional Mock-up Interface. [Online]. Available: https://fmi-standard.org/. Accessed 3 May 2022
16. Lee, J., Lapira, E., Bagheri, B., Kao, H.: Recent advances and trends in predictive manufacturing systems in big data environment. Manuf. Lett. **1**(1), 38–41 (2013). https://doi.org/10.1016/j.mfglet.2013.09.005
17. "The digital-manufacturing revolution: How it could unfold," McKinsey & Company, 10 Jan 2015. https://www.mckinsey.com/business-functions/operations/our-insights/the-digital-manufacturing-revolution-how-it-could-unfold. Accessed 23 Apr 2022
18. Kieviet, A.: Lean Digital Transformation: Geschäftsmodelle transformieren, Kundenmehrwerte steigern und Effizienz erhöhen. Springer Berlin Heidelberg; Springer Gabler, Berlin, Heidelberg. [Online]. Available: https://ebookcentral.proquest.com/lib/kxp/detail.action?docID=5741612 (2019)
19. Cattaneo, L., Rossi, M., Negri, E., Powell, D., Terzi, S.: Lean thinking in the digital era. In: Ríos, J., Bernard, A., Bouras, A., Foufou, S., (eds.) IFIP Advances in Information and Communication Technology, vol. 517, Product Lifecycle Management and Industry of the Future: 14th IFIP WG 5.1 International Conference, PLM 2017, Seville, Spain, 10–12 July 2017: Revised Selected Papers. Springer, Cham, pp. 371–381 (2017)
20. Liker, J.K., Braun, A.: Der Toyota Weg: 14 Managementprinzipien des weltweit erfolgreichsten Automobilkonzerns, 8th edn. FBV, München. [Online]. Available: http://site.ebrary.com/lib/hsalbsig/docDetail.action?docID=10684046 (2013)
21. Womack, J.P., Jones, D.T.: Lean Thinking: Ballast abwerfen, Unternehmensgewinn steigern, 3rd edn. Campus Verlag, Frankfurt am Main. [Online]. Available: http://swb.eblib.com/patron/FullRecord.aspx?p=1219872 (2013)
22. Ohno, T.: Das Toyota Produktionssystem. Campus Verlag (1993)
23. Takeda, H.: The Synchronized production system – going beyond just-in-time through Kaizen. Kogan Page (2006)

24. Hicks, B.J.: Lean information management: understanding and eliminating waste. Int. J. Inf. Manage. **27**(4), 233–249 (2007). https://doi.org/10.1016/j.ijinfomgt.2006.12.001
25. Meudt, T., Leipoldt, C., Metternich, J.: Der neue Blick auf Verschwendungen im Kontext von Industrie 4.0. Zeitschrift für wirtschaftlichen Fabrikbetrieb **111**(11), 754–758 (2016). https://doi.org/10.3139/104.111617
26. Alieva, J., Haartman, R.: Digital Muda - the new form of waste by industry 4.0. OSCM: An Int. J. 269–278 (2020). https://doi.org/10.31387/oscm0420268
27. Winter, R., Schmaltz, M., Dinter, B., Bucher, T.: Das St. Galler Konzept der Informationslogistik. In: Töpfer, J., Winter, R. (eds.) Active enterprise intelligence: Unternehmensweite Informationslogistik als Basis einer wertorientierten Unternehmenssteuerung. Springer, Berlin, pp. 43–58 (2008)
28. Unverdorben, S.: Architecture framework concept for definition of system architectures based on reference architectures within the domain manufacturing (2021)
29. VDI/VDE 3695 - Engineering of industrial plants Evaluation and optimisation of the engineering Fundamentals and procedure (2020)