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Function framework for describing digital technologies in the context of lean production

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Abstract

Intensifying challenges such as volatility, individualization and consequential complexity increasingly bring lean production systems to their performance limits. Using digital technologies serves as possible solution to overcome the limits of lean production and to enhance its capability of reducing waste within production processes. Therefore, a holistic and generic approach is required that allows to characterize digital technologies with respect to their effects on reducing waste in production processes. This paper introduces a function framework that describes digital technologies based on a function-oriented and impact-driven attribution concerning their effects on reducing waste and therefore on superordinate goals of lean production.

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Keywords: Lean production system (LPS); Digital technologies; Information flow; Information functions; Information logistics

1. Introduction and motivation

Providing methods and tools that enhance efficiency and effectivity in production processes by reducing waste, the framework of lean production serves as widespread concept to enhance performance and thus to meet former demands in regard to productivity [1, 2]. As requirements for manufacturing companies increasingly intensify, i.e. through global competition, volatile markets and higher demands for individuallized products with shortening life cycles, the need for flexibly and individually adaptable production processes rises [3, 4]. With the overall increase of complexity resulting from these developments, elements of lean production more and more reach their performance limits [2]. The digital transformation of the manufacturing industry with its continuously advancing digital technologies serves as a possible expedient to overcome these constraints and to raise the performance of lean production systems (LPS) [5]. Having the potential to reduce waste in information logistical processes and thus to improve information flows [6], the appliance of digital technologies promises manufacturing companies to support resource-sparing and flexible production and thus to stay competitive by digitalizing processes [2, 7]. However, for being able to apply such digital technologies appropriately, designing production processes thoroughly and consistently through lean production constitutes a mandatory prerequisite as the desired effects of digitalization usually only unfold in close coordination with its waste orientation [2, 8]. Hence, in order to harmonize digitalization with existing lean production elements and to guarantee a successful digital transformation, manufacturing

Fig. 1. Examples for enhancing information flow with digital technologies at the Fraunhofer IGCV (© Fraunhofer IGCV / Bernd Müller)

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companies require a profound understanding of digital technologies and their manifold effects on the target goals of lean production. In addition, being able to retrace effects of their functions on the optimization and waste reduction concerning information flows enables to adapt specifically digital technologies to LPS and thus to fully exploit synergies in the sense of value-added oriented production processes.

This paper focuses on the characterization of digital technologies regarding information flows (examples see Figure 1) in order to being able to describe their probable effects on waste in production processes. By structuring and categorizing digital technologies in the context of LPS, this paper introduces a function framework that allows the allocation of individual digital technologies to the LPS goals mapped in an impact structure.

2. Fundamentals

2.1. Digital transformation with digital technologies

Increasing performance of processors, since doubling every 18 months, which is referred to as Moore´s law and the rise in value for a communication system with the square of its total users according to Metcalfe, imply increasing processing power at ever lower prices and thus technical solutions at a high value of being interconnected [3]. With the increased convergence of different technologies, the technical and economic developments according to Moore and Metcalfe are promoting interconnectedness especially within the manufacturing sector. Considering the domain of manufacturing such interconnectedness shapes the vision of a smart factory, whose practical realization in Germany is commonly addressed by Industrie 4.0. The term Industrie 4.0 stands for all applications of modern information and communication technologies associated with the digitalization of the manufacturing industry [3, 9, 10]. Hence, against the background of intending to increase added value by interconnecting all entities involved in value creation in real-time, companies support their production processes along value chains through so-called digital technologies, which by their use promote the digital transformation in manufacturing [11].

2.2. Categories of digital technologies

To digitally transform the manufacturing sector, companies receive guidance in classifying digital technologies into four production-relevant categories, namely horizontal and vertical integration, social infrastructure of labor and data analysis. Here, horizontal integration aims to support production processes in value creation by entirely integrating IT systems along consecutive steps of the value chain [11]. Vertical integration rearranges IT systems of different hierarchy levels of the traditional automation pyramid to create a consistent and integrated solution within production systems. The goal is to enhance flexibility in adapting controlled production processes to current production conditions in real-time [9]. Social infrastructure of labor highlights a human-centered view in terms of human-machine interactions (HMI) according to which machines must adapt to humans. Hence, it addresses user-friendly intelligent assistance systems whose multi-modal user interfaces are designed to support workers in production, i.e. by providing information in a way that enables workers to carry out activities productively and safely [11, 12]. Furthermore, data analysis enables to generate previously unknown insights from current and historical values and to derive estimates for future system behavior or effects. Based on these new insights, it ultimately allows to assess different action alternatives for the continuous optimization as of systems and processes [11, 13].

2.3. Fields of digital technologies

Literature mainly consistently describes information and communication technologies (ICT), identification technologies (IDT) and automation technologies (AT) as technology fields for digital technologies. Hence, as digital technologies necessarily base on ICT, IDT and AT [14], their associated technology fields are to be defined accordingly.

The technology field of ICT encompasses technical devices with the ability to digitally convert, process, store and transmit information of all kinds for data exchange and communication [8, 15]. As machines and objects of production are more and more interlinking and humans are increasingly taking over planning and monitoring activities, the communication between machine and machine (M2M) and HMI gains relevance [16]. In the smart factory such communication is guaranteed using ICT but also requires that physical and virtual objects possess an identity [14]. The existence of an identity serves likewise as a basis for a distinct assignment between real objects and their associated virtual data, thus, to interlink the physical with the virtual world. To ensure the unambiguous identification of objects, production processes require technical solutions as provided by the technology field of IDT such as identification of objects and capturing data [17]. The technology field of AT influences production processes via automation systems and automated processes. An automation system describes a technical process taking place within a technical system, in whose course a computer- and communication system collects, processes and displays information to its operator [17, 18]. In an automated process, sensors provide information about physical quantities while actuators transform a control signal to a physical quantity [18]. Sensors and actuators build the basis for the integration of autonomous and decentralized systems and thus pave the way for interconnectedness in production [19].

3. Digital technologies for managing information flow

3.1. Information and information models

As digitalization shifts communication towards M2M and HMI, the according information processes also gain relevance in production, i.e. besides cognitive information processing processes those being computer-aided become more important to be considered in context of digitalization. Accompanied with this shift, the term of information as main element of any information process requires an appropriate definition. Since based on a decision-making process with interrelated agents such as a system and its user, [20] provide a model that allows to classify information in such a context and that distinguishes it from closely related notions like data and knowledge. The model defines data as a simple syntactic unit that represents a pattern without meaning. As input of an interpretation process, data constitutes the first step of a decision-making process. Information corresponds to the output of data interpretation and thus to processed data in context. At the same time, it serves as input and is output of the knowledge-based decision-making process. Knowledge describes learned information that is available to a decision-maker as cognitive resource and for active use in a decision-making process. According to these definitions and from the user´s point of view, a system provides data that is information for the user, i.e. it can be used for a decision, provided that given a user´s knowledge it is relevant for the context and for a specific purpose. [20]

As differences in information processes may also trace back to the decision process itself, [21] describes a model that breaks down the interaction between a system and a decision-maker as its user into structural components. According to the information model, an information process consists of several process steps such as decision-making and subdivides into formalizable and non-formalizable decisions. Formalized decisions or information functions follow a defined procedure that transforms a distinct describable information input into a required information. In case needed, a process owner, a decision-maker responsible for a specific target, activates the information function, which aims to cover the demand of information and to assist the process owner in making knowledge-based decisions [21]. The communication model complements the information model as it describes processing, transmitting and storing data as steps between the information function and the data level. It characterizes the way data is organized and determines how the information function receives required data [22].

This section reveals how literature that addresses information processes highlights the handling of knowledge, information and data just as the individual components of a decision process for actionable decisions. A communality of the models presented constitutes the decision support for the ultimate purpose of a targeted action. Hence, as the described models provide a distinct scope for design thereby offering starting points and potential levers to improve information processes in the context of information logistics, they incentivize companies to use digital technologies accordingly.

3.2. Effects of digital technologies on information logistics

Information logistics are described as the planning, control and implementation of the entirety of data and information flows in order to support decisions [23]. Effects that may arise by using digital technologies manifest as improvements of information logistical processes, whose tasks within production trace back to the 6r-axiom of general logistics [24, 25]. As a widespread design principle for material flow, the axiom applies to all objects of logistics, thus to products, resources, working materials, persons and likewise to information [24, 25]. In terms of information, the 6r-axiom demands of digital technologies to provide the right information, at the right time, at the right place, in the right amount, in the right quality and at the right costs [24]. Since waste in production like waiting time does not only arise for technical reasons but also for lack of information, a fast and secure flow of information through compliance with the 6r-axiom counts as indispensable for the optimization of material flow [25, 26]. This relation between information and material flow suggests that digital technologies improve the overall production system by raising the efficiency of information logistical processes.

As the sections 2.2 and 2.3 reveal, the categories address different facets of information flow, thereby help to comply with the 6r-axiom and guide the appliance of digital technologies accordingly. Potentials for efficiency in information logistics trace back to computer-aided and cognitive information processing processes, where knowledge, information and data are handled for the purpose of decision support and autonomous decisions [11]. As for horizontal and vertical integration, the categories support interconnectedness of information technologies while avoiding media disruption [9]. As in production bad handling and media disruption causes deficits and reduced productivity, digital technologies associated with the technology fields of ICT, IDT and AT constitute enablers for efficient and effective information logistical processes [6, 14]. Waste that possibly occurs and needs to be eliminated within information logistical processes is defined by [27] as information movement, stock, activity, waiting time, processing as well as flood of information and corrections due to errors. For disclosing waste in manufacturing companies, [28] suggest an iterative analysis concerning data generation and transmission, data processing and storage as well as data usage. Key questions intend to create transparency in terms of redundant systems, storage media and media disruptions [6].

4. Necessity and requirements for a function framework for digital technologies

A generic and scientific framework for classifying and characterizing digital technologies requires to being able to describe digital technologies from different domains (categories see section 2.2 and fields see section 2.3) and needs to be time-independent. This means that such a framework has to consider different domains of digital technologies and has to be able not only to describe present digital technologies but also new digital technologies being developed in the future. Existing approaches do consider neither the domains nor the time-independency [29]. However, a framework that follows the principles of information flow and that is based upon information logistic-oriented considerations allows to meet the requirement to encompass categories and fields of current and upcoming digital technologies.

The focus on information logistical goals allows to conduct a waste-oriented assessment of information flows and enables the assumption of accompanied effects on the superordinate goals of LPS that center on reducing waste in production processes. To identify these correlations of digital technologies with information processes and thus with information logistics as well as the process-related waste reduction by lean production, the framework to classify and characterize digital technologies has to meet following requirements [compare 22]:

- Generic description of process steps
- Depiction of communication layers and their interfaces
- Handling process of data, information and knowledge
- Consideration of goals for information processes in context of information logistics (6r-axiom)
- Depiction of starting points and levers for information logistical improvements by the use of digital technologies

5. Function framework for digital technologies

To meet the requirements of chapter 4, this chapter develops a function framework considering digital technologies by their functions. First, this chapter derives information functions and defines steps of information logistical processes for their classification. Thereafter, an information logistical target system facilitates estimating potentials to enhance efficiency in information processes. Ultimately, a classification system outlines an approach for the targeted assignment of digital technologies to elements of LPS as it constitutes an intermediate that links digital technologies by their functions to the specific waste reduction. The link traces back to the relation between information and material flow, hence to the attributed potentials of digital technologies in the context of LPS.

5.1. Information functions based on digital technologies

The dynamic development of digital technologies and consequently the continuous entry of new digital solutions challenges any selection of technologies to be representative.

Table 1. Derived information functions

Function	Description
Storage function	Storage of decentralized data, which can be read out using suitable technologies and which offers connection points for further integration platforms [3, 14, 30]
Processing function	Ability to gain insights from structured, semi-structured or unstructured data to improve operational and future production processes [31, 32]
Gathering function	Ability to gather data by means of input options of technical devices, thus via multimodal channels (e.g. voice and gesture control) as well as the ability as defined as sensor capability in the context of automation systems and processes [16, 33]
Provision function	Provision of data and information via channels accessible to humans [15, 33]
Transmission function	Bidirectional transmission of data and information between software applications and transmission media, e.g. between a transponder and IT systems via middleware and by using a reading/writing device [7, 33]

Literature highlights the role of various digital technologies in terms of ICT, IDT and AT such as cloud-computing, digital twin and digital shadow, intelligent sensor networks, big data analytics, assistance systems and identification and localization systems [34, 35]. Considering various digital technologies, five information functions were derived (Table 1). For being able to classify technologies by their information functions and to describe the potentials of their according functions for improving information processes, it requires the definition of information logistical process steps.

5.2. Definition of information logistical process steps

A classification system, which allows to characterize digital technologies by their information functions, bases on information logistical process steps (Table 2). As information logistical steps enable to specify information functions using their universal definitions, they allow to differentiate digital technologies from each other and establish a mutual connection to the considered digital technologies and to their functions.

Table 2. Defined information logistical process steps

Step	Description
Gathering	Gathering new data in a process
Transmitting	Transmission of already gathered data/information to another information medium or from data level to process owner level and vice versa (transformation digital ⇄ analog)
Providing/ Deciding	Providing data/information to a process owner with/without virtual extension for a decision
Processing	Processing of data (reading and writing at data level)
Storing	Recording (writing) of data/information at data level and storing data for a longer period of time
Transition	Forwarding data/information to a consecutive information process; Transformation digital ⇄ analog possible, if forwarding is initiated by transmission

5.3. Information logistical target system

The development of a suitable target system for digital technologies follows the described relation between information and material flow (see section 3.2) using the defined categories (see section 2.2), in order to identify, analyze and specify the impact of digital technologies on information processes. Hence, it considers potential effects of more efficient information processes using digital technologies on the waste reduction of lean production elements. Consequently, the effects of digital technologies primarily have indirect influence on the goals of an LPS, a target system for digital technologies is required, which specifies their potentials for improving information logistics. Hence, the following target system is based on a methodology for the analysis and optimization of information logistics by [22, 31]. The according target system defines potential information logistical waste subject to information logistical process steps as influencing factors that affect its target figures. The use of the generic description of process steps allows to depict different communication layers according to a considered information process. Defining information logistical waste of respective process steps in turn enables to conduct an in-depth analysis that considers the handling process of data, information and knowledge as well as the level of compliance to the 6r-axiom.

The following target systems considers logistics performance and time- and quality-oriented criteria as target values. To specify these target values, the paper defines influencing factors, which in their entirety determine the information logistical target system (Table 3). Examples for influencing factors are velocity of gathering information (time-oriented) or providing right information (quality-oriented).

Table 3. Information logistical target system

Time-oriented criteria	Quality-oriented criteria
Gathering	Providing right information
Transmitting	Providing at the location of use
Storing	Providing with demanded quality
Processing	Providing on-time
Providing/Deciding	Providing in right amount
Transition	Providing with right cost

As the best possible fulfillment of criteria of the target system is subject to the use of certain digital technologies, it requires the ability to choose the right technology given a certain need for improvement, i.e. the need for flexibility in providing information. Therefore, the subsequent section describes a classification system that facilitates to create transparency in terms of waste in information logistical processes in order to enable the selection of suitable digital technologies.

5.4. Classification system

The core of the following classification system consists of key questions, which make the analysis of information processes easier to handle according to [28]. However, unlike those defined in [28], the key questions of this paper relate to the derived influencing factors of the target system (see section 5.3), i.e. they reflect the information logistical waste of the influencing factors. To establish a digitalization grid that links digital technologies with elements of LPS, it requires integrating both digital technologies by their functions and elements of LPS by their waste-orientation into the information logistical target system. The key questions constitute means to ensure such integration as they enable to consider the specific role of digital technologies and of elements of LPS concerning information logistical waste. First, the key questions assign time- and quality-oriented criteria and the associated information logistical waste to the defined information logistical process steps. The link allows to match digital technologies since being mutually connected with the information logistical process steps with the according influencing factors and thus to integrate digital technologies against the background of their influence on information logistical waste into the target system. As the key questions use an information logistical waste consideration to establish a link that connects functions of digital technologies with the waste reduction of LPS, they also determine how the digitalization grid can be used in practice. As the digitalization grid defines all possible assignments, its use in practice requires an information logistical waste analysis, which considers the needs of an examined LPS and derives recommendations for the use of digital technologies accordingly. The utilization of key questions in this analysis creates transparency within the LPS

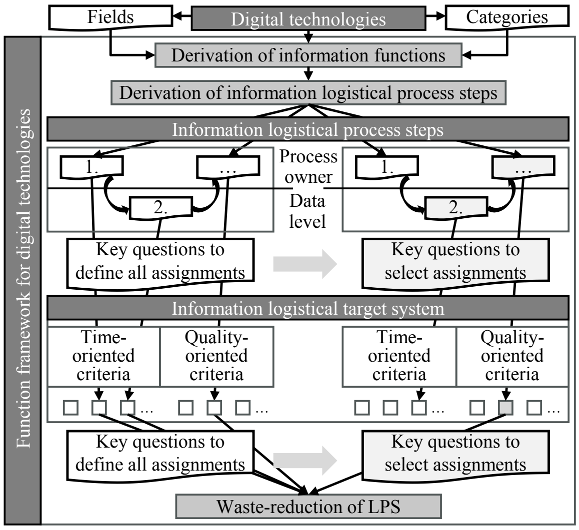

Fig. 2. Overview of function framework for digital technologies

in terms of information logistical waste and allows to select suitable digital technologies, as possible assignments between digital technologies and elements of LPS as stated in the original digitalization become ineligible (Figure 2).

6. Application example

6.1. Function-based description of a digital technology

One possible scenario for applying the digitalization grid represents its application in a small and medium-sized enterprise, which wants to digitalize its LPS systematically. Therefore, the company is planning to introduce tablets into an assembly line with installed Poka Yoke techniques. As a reasonable cost-value analysis is indispensable for a resource-sparing production aiming to be a smart factory, the company wants to estimate the efficiency gains it can expect by using tablets complementary to Poka Yoke. With the use of Poka Yoke, the company intends to minimize errors in the assembly as only fitting parts can be assembled. However, an internal value stream analysis reveals that the trial and error rate is very high at the time the assembly line changes products, i.e. paper-based assembly instructions for the new product line are not convenient to detect in the moment of product change and thus are hardly used as a reason of time.

In order to classify tablets within the digitalization grid, it first needs an analysis of its according information functions. Tablets can be assigned to a gathering function as workers can manually insert control commands or enter data. The possible information output, i.e. the supply of information adapted to the process, situation and the worker defines the ability as described as provision function. However, a tablet needs an infrastructure within the vertical integration in order to transfer its data. It can obtain information for a user by request as received through data acquisition or a manual input. Having these information functions, the digitalization grid reveals five levers for improving the waste reduction of Poka Yoke, namely through improving information logistics by the influencing factors transmitting, providing/deciding, demanded quality and on-time provision. The use of key questions in an in-depth analysis of the assembly process detects only information logistical waste in terms of on-time provision.

6.2. Results

The analysis of section 6.1 reveals that the use of tablets promises to improve the quality of information processes as it affects the information logistical target system in terms of the quality-oriented criterion of on-time provision. As the quality in information flow rises by providing assembly instructions on time, the material flow concerning the assembly line is becoming leaner as well. The more efficient information flow causes the try and error rate to decline and thus fastens the overall process of assembly. Therefore, as waste within the LPS can be reduced, the assembly process becomes more efficient by using tablets.

7. Summary and outlook

Elements of lean production are widely used in manufacturing, however, require as complement the use of digital technologies to comply with intensifying demands of flexible and individualized production and thus to secure companies' competitiveness. The digitalization grid presented allows to describe digital technologies for their appliance and provides a first step to derive the accompanied potentials for waste reduction in LPS using an information logistical consideration. For the ultimate goal of a holistic and generic approach for LPS, future research needs to extend information functions of the digitalization grid by a target-based description, which helps to concretize derived functions of digital technologies accordingly. Hence, as a target-based approach allows to specify digital technologies, it enables to analyze their potentials more accurately and to elaborate impact-related differences even in case of functional equality.

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