World Academy of Science, Engineering and Technology
International Journal of Industrial and Manufacturing Engineering
Vol:11, No:10, 2017

Digital Transformation of Lean Production: Systematic Approach for the Determination of Digitally Pervasive Value Chains

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***Abstract*—**The increasing digitalization of value chains can help companies to handle rising complexity in their processes and thereby reduce the steadily increasing planning and control effort in order to raise performance limits. Due to technological advances, companies face the challenge of smart value chains for the purpose of improvements in productivity, handling the increasing time and cost pressure and the need of individualized production. Therefore, companies need to ensure quick and flexible decisions to create self-optimizing processes and, consequently, to make their production more efficient. Lean production, as the most commonly used paradigm for complexity reduction, reaches its limits when it comes to variant flexible production and constantly changing market and environmental conditions. To lift performance limits, which are inbuilt in current value chains, new methods and tools must be applied. Digitalization provides the potential to derive these new methods and tools. However, companies lack the experience to harmonize different digital technologies. There is no practicable framework, which instructs the transformation of current value chains into digital pervasive value chains. Current research shows that a connection between lean production and digitalization exists. This link is based on factors such as people, technology and organization. In this paper, the introduced method for the determination of digitally pervasive value chains takes the factors people, technology and organization into account and extends existing approaches by a new dimension. It is the first systematic approach for the digital transformation of lean production and consists of four steps: The first step of 'target definition' describes the target situation and defines the depth of the analysis with regards to the inspection area and the level of detail. The second step of 'analysis of the value chain' verifies the lean-ability of processes and lies in a special focus on the integration capacity of digital technologies in order to raise the limits of lean production. Furthermore, the 'digital evaluation process' ensures the usefulness of digital adaptions regarding their practicability and their integrability into the existing production system. Finally, the method defines actions to be performed based on the evaluation process and in accordance with the target situation. As a result, the validation and optimization of the proposed method in a German company from the electronics industry shows that the digital transformation of current value chains based on lean production achieves a raise of their inbuilt performance limits.

***Keywords*—**Digitalization, digital transformation, lean production, Industrie 4.0, value chain.

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I. Introduction

DIGITALIZATION provides new technologies which have the ability to support companies to persist on global and volatile markets. For example, the implementation of new technologies into existing value chains can increase flexibility, transparency and collaboration. Thus, a potential to reduce the complexity cost up to 70% arises [1]. The potential for improvements enabled by digitalization are not limited to the manufacturing process. They also concern indirect departments like engineering or administration [2]. The consideration of indirect departments puts the focus on a value chain perspective instead of an isolated manufacturing perspective. However, value chains are highly diverse and characterized by high complexity and heterogeneity. This is due to the numerous tangible and intangible resources, technologies and skills that companies rely on. Consequently, the company-specific factor endowment must be considered if companies transform their value chains into digitally pervasive value chains [3].

Companies are faced with major challenges concerning the determination of digitally pervasive value chains. Especially, the selection procedure for appropriated digital solutions involves ambiguities. Only if companies know which type of solution fits into a certain type of process they can generate maximum benefit. Analyzed academic approaches offer companies guidance, but do not solve basic problems like the issue mentioned above or how to increase flexibility along existing value chain at lowest costs. In addition, it seems to be difficult for companies to estimate where the use of digital solutions is worthwhile. For this purpose, basic evaluation criteria are required that can be used to assess the sense of intended digital solutions. Further research shows that digitally pervasive value chains are emerging in some specific areas like predictive maintenance. However, many areas use digital technologies and services isolated, but only their combination opens up the full potential. In consequence, companies do not take full advantage of the potential offered by new digital solutions. Furthermore, high fundamental complexity in processes along the value chain inhibits the potential of the new digital solutions like an increased efficiency [4], [5]. In most cases, academic approaches are too general or focus only on the integration of digital solutions without providing an opportunity of optimizing processes by simple measures. Nevertheless, the initial reduction of complexity through simple measures offers a suitable starting position for the determination of digitally pervasive value chains [1]. Concerning this position, the digital transformation of lean production as an organizational and human-orientated paradigm is promising. This article presents a systematic approach in order to reduce complexity by applying lean production and, additionally, reveals a framework for the supplementary selection of suitable digital solutions and their harmonization with lean production.

II. Background

A. Lean Production

Lean Production as an organizational and human-oriented corporate philosophy pursues the main objectives of creating customer value and transparency along all processes [6]. This is achieved by focusing on value-adding activities, while eliminating and avoiding wastes. In the course of increasing cost pressure in the manufacturing sector, the focus on value-adding activities along a value chain becomes more and more important. By eliminating the eight types of waste (overproduction, waiting time, transportation, manufacturing process, inventory, motion, mistakes and unused creativity), the complexity in direct and indirect processes along the value chain can be reduced [7]. In case of mass production, the introduction of lean production generates a significant increase in productivity through the standardization of the sequence of production and the implementation of fixed cycle times. However, lean production reaches its limits, when it comes to a variant flexible mass production and constantly changing markets as well as environmental conditions [8], [9]. Exemplary limits are [4]:

1. Minimum flexibility to change product specifications after the start of production.
2. Disruptions in the production flow due to errors in inventory counting.
3. Previous knowledge needed for process adaption.
4. Human induced improvement processes.
5. Complexity through a variety of standards.

B. Digitalization

In the context of Industrie 4.0, digitalization encompasses the networking of all humans and objects along the entire value chain with the aim of improving processes and thereby creating customer values [10]. Digitalization provides solutions to overcome the performance limits of lean production and thereby to master the complexity, which is inbuilt along value chains [1], [11]. For example, digital solutions enable the optimization of production capacity, which leads to improvements in processes and thereby to a further reduction of waste in accordance with lean production [12]. More examples for the enhancement of performance limits are mentioned below [4]:

1. Intelligent systems provide changes in product specifications until unchangeable parameters are introduced into the product.
2. Digital technologies provide a real-time tracking of inventory.
3. Manufacturing of small batches become possible by plug and play, self optimization and machine learning.
4. Digital technologies provide real-time feedback by smart devices.
5. Mastery of complexity through assistance systems.

In consequence, the integration of digital solutions along the value chain like intelligent production planning and control systems allows companies, for example, to handle mass customization [4], [5].

C. Human, Technology and Organization (MTO-Model)

The holistic view of the factors human, technology and organization (MTO) leads to sustainable improvements in the competitiveness of manufacturing companies when implementing a new production system [13], [14]. Accordingly, the holistic view of the factors MTO is critical to success for lean production as a production system, for its supplement digitalization and in consequence for the determination of digitally pervasive value chains [8]. In this context, holistic view means that the interfaces between the three factors – human-technology (M-T), human-organization (M-O) and technology-organization (T-O) – need to be analysed. For a closer understanding, the three factors are explained below.

1. Human*:*

The factor "human" includes all employees within a company which are directly or indirectly involved in the manufacturing process, like production staff or plant managers [15], [16]. For the success of a digitalization project, it is necessary to examine the extent to which changes are in line with the motives and competences of the employees [17], [18].

2. Technology*:*

Technology includes all objects and systems that directly or indirectly contribute to the manufacturing process within a company, for example, assembly plants or production control tools [15]. The main reason for the failure of a digitalization project related to the factor "technology" is the use of immature, unsuitable or too complex technologies [17].

3. Organization*:*

The essential content of the organizational factor is the operational and organizational structure within a company. In addition, non-physical elements such as software solutions are considered in this factor [15], [18]. If changes, such as the introduction of new technical systems into unsuitable organizational structures (e.g. an inappropriate production planning system), are implemented, there is the risk that a digitalization project fails [17].

The link between the MTO factors is illustrated in Fig. 1 and is subsequently demonstrated on an example along their interfaces.

If, for example, smart devices are implemented for the purpose of cognitive support of employees, this relates to the interfaces M-T (qualification of employees to deal with the new technology), M-O (new form of integrating employees into the organizational structure) and T-O (integration of the smart devices into network structures). This example clearly shows that the design of digitally pervasive value chains based on the socio-technological approach can only be successful if the interdependences of the factors MTO are taken into account [17].

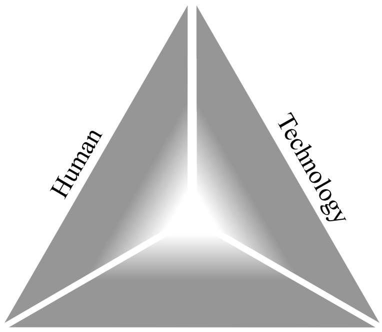


Fig. 1 Link between MTO factors [13]

D. Digitally Pervasive Value Chains

Through digitalization, the basic activities described by PORTER merge increasingly along the value chain [12]. This is due to the combination of information and communication technologies with production and automation technologies. The resulting structures and processes are named hereinafter as digitally pervasive value chains. Within a digitally pervasive value chain, for example, a system detects a defect from which the risk originates independently, is able to switch off other facilities and informs the maintenance independently [19]. A digitally pervasive value chain fulfils four central characteristics [12]: Ensuring availability of:

1. Data (What is happening?)
2. Diagnosability (Why does it happen?)
3. Predictability (What will happen?)
4. Adaptability (How can a reaction take place?)

The concept of digitally pervasive value chains covers both, architectures in which employees fulfil the capacity of adaptability (e.g. supporting an employee through smart devices) as well as autonomous cyber-physical systems. The key components for the fulfilment of the above-mentioned characteristics and thus to enable an increase in flexibility and efficiency compared to a classic value chain are:

- Physical components (e.g. sensors)
- Networking components (e.g. wireless modules)
- Intelligent components (e.g. software)

Based on the three key components, isolated processes are linked to systems and an interdisciplinary and real-time coordination becomes possible.

III. SYSTEMATIC APPROACH

A. Target Definition

The first step 'target definition' describes the target situation and defines the depth of the analysis concerning the inspection area and the level of detail. The impetus for the determination of digitally pervasive value chains can have several causes. It can take place both, market-sided and company-sided. As a rule, an improvement potential is the starting point of the project. This is exemplarily the case on the market side when a company ascertains that its customers are dissatisfied with long delivery times. On the company side, wastes such as a high reject rate or a low utilization of production capacities represent potential improvements.

First, while starting from the problem-oriented impetus, it is necessary to determine which level of analysis is appropriate for solving the problems. This is particularly relevant since the level of analysis influences the scope of consideration of the following steps. In order to ensure all problem-specific activities are included in the analysis (e.g. production planning, assembly, administration, etc.), it is recommended to start from a high level of consideration and to reduce it to lower levels until the true cause for the defined problem is identified. Accordingly, a trade-off needs to be conducted up to which level of consideration a problem is to be confined initially. On the one hand, too much differentiation increases the analysis effort (low level of consideration) and, on the other hand, a too high level of consideration carries the risk of not perceiving simple potentials for improvement.

The target definition focuses the elimination of identified problems and is based on a waste-free ideal situation. In consequence, secondly, the objectives need to be formulated. When formulating the objectives, it is important to ensure that they are in line with the corporate-objectives (for example high quality). If they are not in line with the corporate-objectives, the targets have to be adjusted.

For objectives to be formulated completely, we recommend the SMART-criteria defined by Doran. Accordingly, a target should be specific ("S"), measurable ("M"), assignable ("A"), realistic ("R") and time-related ("T") [20].

A productivity increase can already be achieved with a small investment volume by implementing digital solutions stepwise [21]. Hence, it is recommended to prioritize the previously defined objectives and to pursue those objectives first, which seems to be the most promising ones. An appropriate method for the prioritization of objectives is for example a pairwise comparison.

B. Analysis of the Value Chain

During the analysis of the value chain, the lean-ability of processes is identified and a special focus lies on the integration capacity of digital technologies. Thereby, the above-mentioned limits of lean production are raised. The approach presented in this article takes a progressive perspective and focuses on the transformation of existing value chains. The design of fundamentally new value chains is not considered. This constraint is justified by the assumption that exceedingly few companies can redesign their processes completely on the "greenfield". In addition, the complete redesign of an existing value chain entails the risk of reproducing weak points of the old process. This often happens due to a missing analysis of the actual state. Accordingly, in order to identify problem-specific potentials for improvement it is essential to perform a detailed analysis of relevant processes. The relevant processes have already been exposed in the first step "Target Definition". Beside the relevant processes along the value chain, the material and information flow as well as their interconnection need to be visualized for the mapping of the actual state [7]. For this purpose, a large number of suitable methods exist. The classic value stream mapping, established by Mike Rother and John Shook [33] as well as its modifications like "Wertstromanalyse 4.0" (engl.: Value Stream Analysis 4.0) described by Meudt et al. are considered suitable [34]. A further approach for mapping the actual state is the modelling language aixperanto, which was developed at the Laboratory for Machine Tools and Production Engineering (WZL) at RWTH Aachen University, Germany.

As a matter of principle, companies have to decide which method is most suitable for their purpose to map the actual state. While mapping the actual state, the first areas for potential for improvement can already be identified based on the recorded process structures. Experience shows that these improvements are usually based on the elimination of waste.

A potential for improvement is for example "reduce inventories" or "speed up communication between departments". In order to provide a suitable basis for the determination of digitally pervasive value chains, potential networking possibilities have to be considered while mapping the actual state. For this purpose, it is recommended to note potential networking possibilities directly into the mapped actual state. Based on this, the user of the approach is enabled to identify potential networking possibilities in regard of the targeted integration of digital solutions intuitively.

C. Determination and Digital Evaluation Process

Thereafter, the usefulness of digital adaption concerning their practicability and their integration into current production systems is analyzed. Within the 'digital evaluation process', the objective of the determination is to achieve the targets defined in the first step "Target Definition" by applying digital solutions. Firstly, it is necessary to identify suitable lean-design-principles for the process alignment towards lean production ("Process Alignment through Lean Production"). This allows companies to reduce the complexity, which is inherent in their processes. Subsequently, a methodical link between lean production and digitalization is presented ("Focusing the Design Process"). Thereby, the design process is further focused. Additionally, a 'Digitalization-Tank' allows the selection of digital solutions depending on given processes and objectives to pursue ("Selection of Solutions"). Finally, an evaluation method and essential evaluation criteria along the interfaces between the three factors human, technology and organization, which are critical for success, are presented in order to select the most appropriated digital solution ("Evaluation Method and Criteria").

Potential $= \frac{\sum_{i=1}^{m} G_i}{\sum_{i=1}^{m} i}$

Lean-Principles	Eight Types of Waste							
	Overproduction	Waiting Time	Transportation	Manufacturing Process	Inventory	Motion	Mistakes	Unused Creativity
Flow	4,50	4,50	4,33	2,33	4,50	4,17	1,17	1,67
Pull	4,33	4,17	3,00	1,00	5,00	2,33	1,00	1,33
Perfection	1,67	2,83	2,33	4,67	1,83	2,67	4,83	3,33
Standardization	3,00	3,50	3,00	4,50	3,00	2,83	4,83	2,33
Employee Orientation	2,00	1,33	1,33	2,67	1,33	1,67	3,83	5,00
Visual Management	1,83	3,17	3,67	2,33	2,83	2,83	3,17	3,00

Fig. 2 Averaged distribution of the expert validations

1. Process Alignment through Lean Production

A key prerequisite for an effective determination of a digitally pervasive value chain are efficient and transparent processes along the value chain [18]. In terms of lean production, the generation of efficient and transparent processes requires the elimination of wastes [22]. The approach described in this article uses the six lean-principles flow, pull, perfection, standardization, employee orientation and visual management to support manufacturing companies in generating processes, which contain a low amount of waste. In order to provide an intuitive selection of the lean-principles, which are most promising for the respective project, potential distributions have been developed by expert valuations. For this purpose, the method of paired comparison was used and experts from industry and research were consulted. The result is an averaged distribution of expert interview valuations and provides a first declaration about which type of waste can be eliminated by applying a specific lean-principle (Fig. 2). The scale ranges from one (no potential) up to five (high potential). For example, the flow principle has a high potential (value 4.25) for eliminating waste caused by overproduction. The visualization of the results is realized by using radar charts (Fig. 3). This approach offers the advantage of an easy following of the visualized potential distributions in order to focus on the process of generating lean processes easily and process-specifically. For example, if the analysis of the process turns out that "mistakes", as type of waste, need to be focused, the activities to be taken can be aligned using the radar chart shown in Fig. 3. It becomes apparent that the greatest potential originates by applying the principle perfection and standardization. Since multiple types of waste occur along a value chain, different potential distributions can be combined and weighted. An example with regard to the combination of two potential distributions is given in the following subsection.

2. Focusing the Design Process

Focusing, the design process is based on the methodical linkage of lean production and digitalization. For this reason, the lowest common denominator of lean production and digitalization is required. This is the common motive to increase productivity and flexibility of processes. The increase of productivity and flexibility implies the existence of waste. For this reason, the two concepts can be linked by the eight types of waste. The link between the eight types of waste and lean-principles has already been shown by the deployment of potential distributions within the step "Process Alignment through Lean Production".

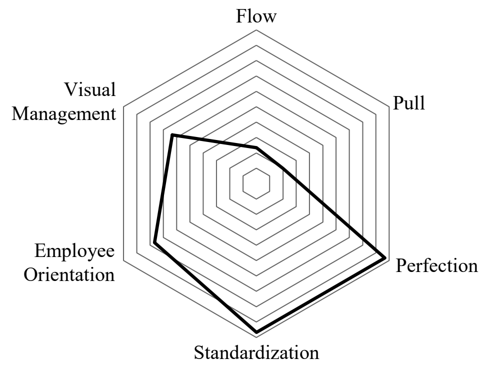
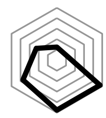


Fig. 3 Exemplary radar chart of the type of waste "mistakes"

Type of Waste (MTO-Interface)

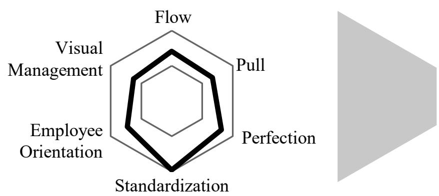
Step 1

Overproduction (Technology-Organization)		Mistakes (Human-Technology)	
Lean-Principle	**Potential**	**Lean-Principle**	**Potential**
Flow	4,50	Flow	1,17
Pull	4,33	Pull	1,00
Perfection	1,67	Perfection	4,83
Standardization	3,00	Standardization	4,83
Employee Orientation	2,00	Employee Orientation	3,83
Visual Management	1,83	Visual Management	3,17



Step 2

Common Radar Chart of Overproduction and Mistakes



Selection of the Lean-Principles Perfection and Standardization

Step 3

MTO-Interface

Technology-Organization		Human-Technology	
Potential of the Lean-Principle		**Potential of the Lean-Principle**	
Perfection	Standardization	Perfection	Standardization
1,67	3,00	4,83	4,83
Sum		**Sum**	
4,67		9,66	
Sum			
14,33			
Percentage Distribution		**Percentage Distribution**	
32,59%		67,41%	

Fig. 4 Exemplary approach for determining the percentage distribution of the relevant MTO-interfaces

Current research shows a connection between the eight types of waste and the MTO-interfaces as well as a connection between the MTO-interfaces and application scenarios of digitalization (e.g. human-machine-interaction). Application scenarios are a general description of a problem or a challenge and offer the ability to allocate application examples [23]. Application examples describe feasible digital solutions (e.g. autonomous conveyor system) and symbolize a specific implementation case [23]. In consequence, the three interfaces human-technology, human-organization and technology-organization represent the link between the types of waste and digital solutions. Fig. 4 shows the allocation of the eight types of waste to the interfaces mentioned above. For example, "waiting time" as a type of waste can be assigned to the human-organization interface since it results from interferences between a human being and the organizational structure of a company.

The following section illustrates the findings by an example and, thereby, the link between lean production and digitalization is shown (Fig. 5).

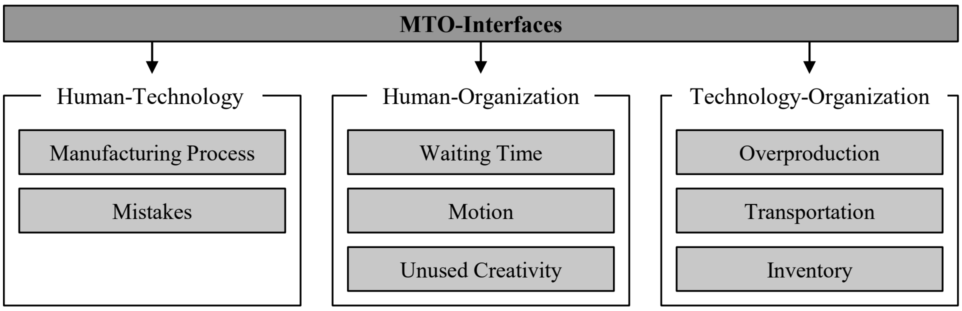
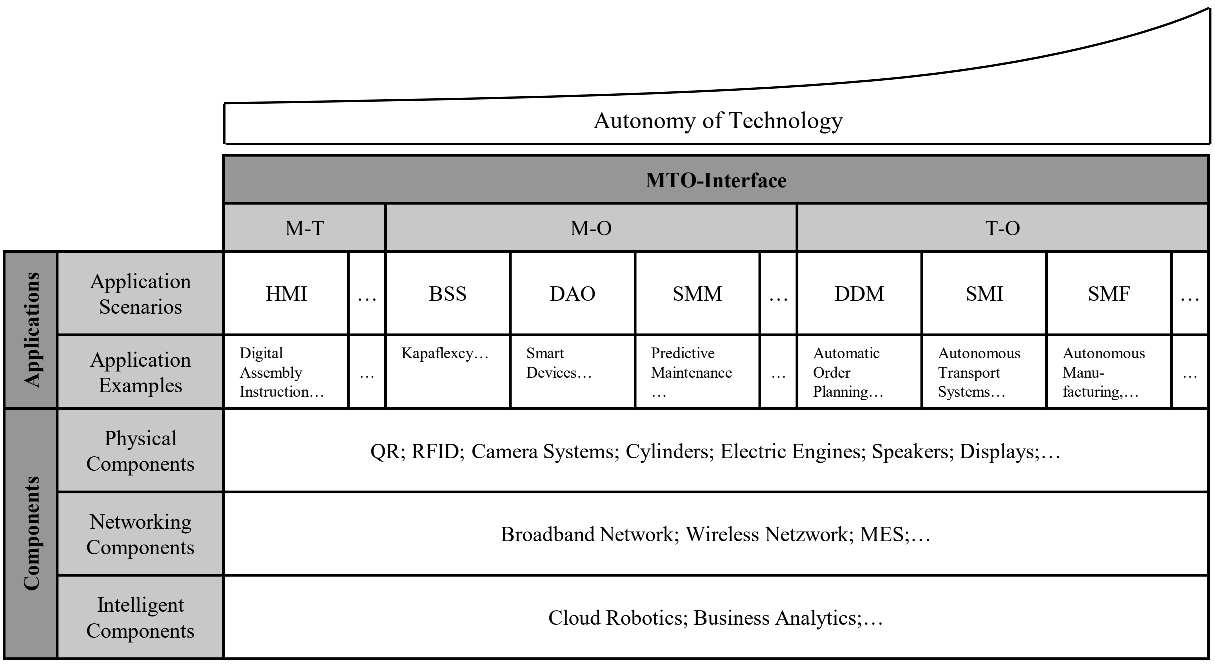


Fig. 5 Allocation of the types of waste to the MTO-interfaces



M: Human; T: Technology; O: Organization;

BSS: Business Support System
DAO: Digital-Assisted Operation
DDM: Demand-Driven Manufacturing
HMI: Human-Machine Interaction
SMF: Smart Manufacturing
SMI: Smart Intralogistic
SMM: Smart Machine

Fig. 6 Structure of the Digitalization-Tank

Firstly, the radar charts of the types of waste to be focused on are used (Step 1). In addition, the relevant MTO-interface must be noted for each type of waste. If, for example, the types of waste "overproduction" and "mistakes" are to be eliminated, the interface "technology-organization" on the side of overproduction and the interface "human-technology" on the side of mistakes must also be noted (Fig. 5). Secondly, the radar charts need to be converted into a common radar chart by summation. Subsequently, the lean-principles to be focused on are selected according to the situation of the characteristics (Step 2). After deciding which lean-principles are used to eliminate the types of waste, the potentials of the respective lean-principles are noted and summed for each type of waste (Step 3). The result is a percentage distribution, which sets the focus along the MTO-interfaces during the subsequent search for digital solutions. The recommendation for the example mentioned above is to concentrate on the human-technology interface by 32.59% and on the technology-organization interface on approximately 67.41%. Subsequently, the user can identify possible digital solutions in a so-called 'Digitalization-Tank', depending on the MTO-interface distribution.

3. Selection of Solutions

a. Digitalization-Tank

Due to the progressive technological change, new digital solutions are continuously launched. In addition, the experiential knowledge of a company is enhancing by each realized digitalization project. Therefore, the Digitalization-Tank has to be structured in such a way that it can be continuously expanded through internal and external knowledge. A morphological box is most suitable for this purpose. Accordingly, the Digitalization-Tank is clustered into the dimensions "MTO-interface", "applications" and "components" (Fig. 5). The three dimensions form the pre-structure of the Digitalization-Tank and facilitate the identification of possible digital solutions. The digital application scenarios and examples are located in the upper part of the Digitalization-Tank. These are not rigid and can be updated and adapted according to the state of the art. The key components of a digitally pervasive value chain (e.g. physical components) are integrated into the lower part of the Digitalization-Tank. Due to the situationally link of application examples and key components, the design of digitally pervasive value chains is enabled.

Relevant application scenarios are developed with recourse to the PLATFORM INDUSTRIE 4.0 [23], the Bitkom [24] and the ACATEC [25]. Along the MTO-interfaces, they are described below.

i. Human-Technology Interface

The human-technology interface focuses on human-technology interaction. Accordingly, all application scenarios in which human beings are supported to fulfil their work tasks (for example, assembly of components) are included in this interface. For example, the application scenario "Human-Machine Interaction" (HMI), which describes the interaction between humans and a physical assistance, such as a robot arm. In addition, fixed assistance systems (which support complex work processes such as digital assembly instructions and fixed maintenance) and planning aids are included in this application scenario.

ii. Human-Organization Interface

The human-organization interface encompasses all application scenarios that help to integrate human beings into the organizational structure within a company. These include the application scenario "Smart Machine" (SMM), in which machines, for example, transmit their operating requirements to an employee network, and these can register via smart devices for the upcoming work, depending on their time availability. In addition, the application scenario "Digital Assisted Operation" is assigned to the human-organization interface. In the application scenario "Digital Assisted Operation" (DAO), the employee uses location-independent and IT-based assistance systems, such as data glasses, to be enabled to control the processes more efficient. As a last application scenario, the "Business Support System" (BSS) is assigned to the human-organization interface. In this application scenario, application examples such as social media, web-based organization of working times, location-independent learning platforms and knowledge management systems as well as a smart product development are to be located.

iii. Technology-Organization Interface

An application scenario in which the internet of things is linked to the internet of services and, thus, a network between independent systems arises and characterizes the interface technology-organization. This usually includes the area of logistics systems as well as production planning and production control systems. Accordingly, the application scenario "Smart Intralogistics" (SMI) can be assigned to the technology-organization interface because a self-organizing adaptive intralogistics makes the flow structure within a company more flexible without directly affecting the human factor. As a further application scenario, "Smart Manufacturing" (SMF) is assigned to the technology-organization interface. In the application scenario of Smart Manufacturing, products and manufacturing plants communicate independently and plan their steps of manufacturing autonomously. This makes production planning and control more flexible. As a third application scenario, "Demand-Driven Manufacturing" (DDM) is classified into the technology-organization interface. In course of this application scenario, an autonomously order planning, allocation and control of all required manufacturing steps and resources is achieved [23].

The process of identifying digital solutions is an iterative solution-finding process. The starting point for the identification of suitable digital solutions is the previously compiled MTO-interface distributions. Due to the MTO-interface distributions, the interface to be focused is set in the Digitalization-Tank and thus the process of identifying digital solutions is aligned. In the iterative process, step by step all relevant application scenarios, that are located within the respective interface, are passed through and the application examples are checked for adaptability. The check for adaptability is carried out by means of a comparison with the actual state established in course of the detailed analysis.

b. Evaluation Method and Criteria

The success of a digitally pervasive value chain significantly depends on the realized organizational and technological concept of a company [26], [27]. A rigid evaluation or the definition of recommendations for action, without considering the individual corporate situation, would not be useful [28]. For this reason, the determination of a digitally pervasive value chain must be based on a company-specific evaluation and along fundamental success factors. In addition, the evaluation of the identified digital solutions must point out possible implementation risks and enable the derivation of measures. For the implementation of a digitally pervasive value chain, the MTO-interfaces must be considered. In the following, success factors are presented along the MTO interfaces (Fig. 7).

i. Success Factors of the Human-Technology Interface

The human-technology interface takes account of human acceptance in terms of a planned technical change (e.g., the introduction of an assistance system). Accordingly, it must be ensured that human beings are able to use identified digital tools. Therefore, three basic success factors have been identified:

Qualification, handling and legal aspects.

ii. Success Factors of the Human-Organization Interface

Through the human-organization interface, the employees' acceptance of organizational adaptations (e.g. decentralization of responsibility) is covered. Hence, the effort to adjust the organizational structure within a company and to generate employee acceptance concerning organizational changes is evaluated. Therefore, the two basic success factors "work organization" and "motivation" have been identified.

iii. Success Factors of the Technology-Organization Interface

The third interface technology-organization evaluates the integrability of planned technological changes into the existing organizational structure (e.g., necessary network architectures). Thus, this interface ensures the technological integrability of identified digital solutions and evaluates the related effort. Concerning this, the three success factors of "degree of technological maturity", "infrastructure" and "data" are introduced.

The evaluation is generally based on qualitative expert assessments because quantifiable information is often not available at the time of evaluation. Qualitative expert assessments often have a high degree of uncertainty. Consequently, the evaluation method must provide the possibility of considering uncertainties. Furthermore, it is important that a non-fulfilled success factor cannot be compensated by a good performance of other success factors. The previously described requirements for an evaluation method are met by the Fuzzy Axiomatic Design method. Therefore, this method is used to evaluate the identified digital solutions. The authors Vojidani et al. provide a detailed explanation of the method [29]-[31]. The result of the evaluation is the most appropriate digital solution.

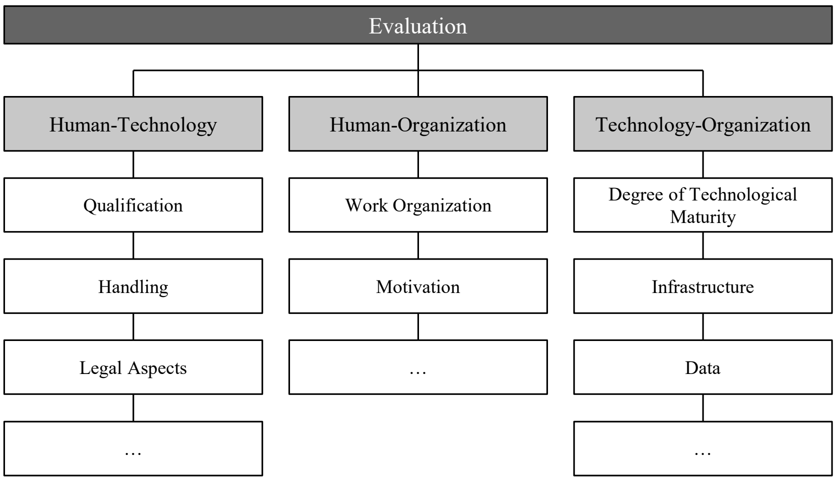


Fig. 7 Identified evaluation criteria

c. Actions to Be Performed

In the end, the basis for defining necessary actions is the evaluation process in accordance with the target situation. The two steps shown in Fig. 8 can identify measures for the implementation of a digitally pervasive value chain. The two steps are justified by the fact that digitalization can be considered as a supplement to lean production. In the first step, measures are to be formulated with regard to alignment of lean production. The second step is to develop measures for the integration of digital solutions.

First, a gap analysis between the actual state and the selected lean-principles need to be performed. Based on the results, measures can be defined and a potential actual state can be formulated. Potentially in this context, it means that no transformation of the process took place.

In the second step, a gap analysis is performed between the potential actual state and the most appropriate digital solution. Thus, it is analyzed where connecting points concerning the integration of the selected digital solution into the potential actual state lie and appropriated measures can be defined.

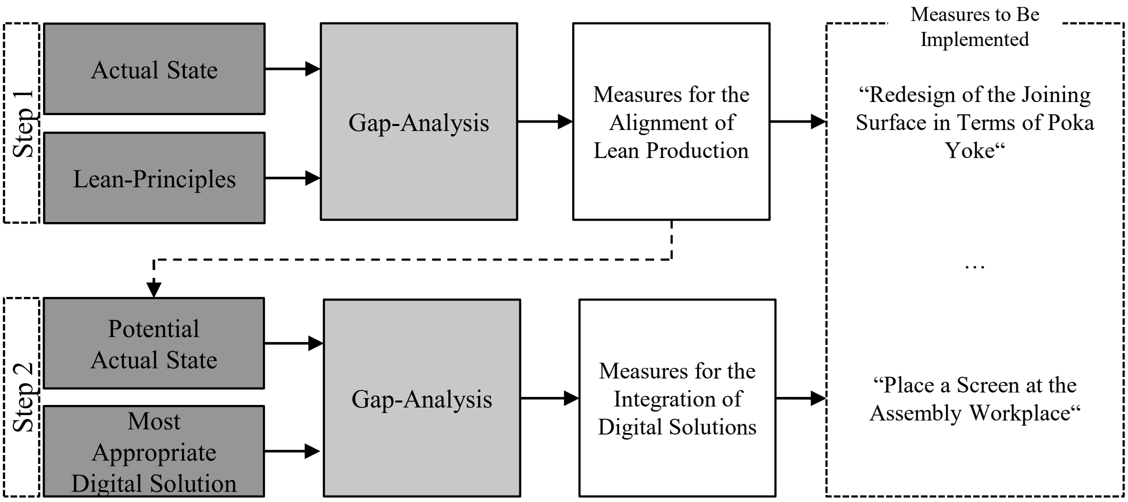


Fig. 8 Process of the identification of measures

IV. Discussion

The adaptability and efficiency of processes along the value chain have a great impact on the success of a company. In particular, through the rising demand for individualized products, the ongoing price sensitivity of customers and the increasing market volatility, companies face the challenge of making their value chains more flexible. This is achieved by the use of potential improvements in existing processes and the complementary, targeted use of digital solutions. In order to reduce the investment costs for the implementation and to maximize the benefit of a digitalization project, a structured approach is required. In this article, we presented an approach that guides companies to transform their value chains into digitally pervasive value chains systematically.

During the validation of the developed approach at the Weidmueller Group, the methodical link between lean production and digitalization proved to be particularly useful. The methodical link enabled, for example, to focus on the relevant MTO-interfaces within the Digitalization-Tank, thus facilitated the identification of digital solutions. By means of the developed four steps, the user of the approach is enabled to organize the determination process and to focus the significant potential improvements. In addition, the systematic approach helps companies to get transparency about the prevailing problem areas and to identify the most appropriate digital solutions. The company-specific content within the Digitalization-Tank also reduces the complexity of the identification process of digital solutions. The results of the validation and optimization of the presented method in a German company from the electronics industry demonstrate a clear trend. Inbuilt performance limits of current value chains can be raised due to their digital transformation based on lean production.

The evaluation criteria presented in this article focus on the feasibility of a digital solution. In order to create a comprehensive decision-making approach, a detailed cost-benefit analysis is needed, which was deliberately omitted in this article. Regarding the benefits of digital solutions, there is agreement in industry [32]. However, it is difficult to quantify the profit of a digital solution, especially with regard to the comparison of several digital solutions.

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