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A Concept For The Development Of A Maturity Model For The Holistic Assessment Of Lean, Digital, And Sustainable Production Systems

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Abstract

Manufacturing companies today face a volatile environment with a variety of challenges. Particularly, external factors such as the climate change, the digitalization, the material scarcity, or the shortage of skilled workers can be noted. At the same time, these factors are forcing companies to take measures to remain competitive and ensure their production system's future viability. In this context, established paradigms such as Lean Production and Industry 4.0 promise optimization potentials in terms of efficiency, quality, and costs. A new paradigm has gained importance with the emergence of the topic of sustainability, which aims to improve companies' use of resources and the recyclability of their products. However, there is no transparent model that enables companies to assess the status quo of their production system regarding these three paradigms, considering the interdependencies between the paradigms, and at the same time showing the implementation potential of methods or technologies within these paradigms. To support companies in rationalizing, digitalizing, and making their production processes more sustainable, this scientific paper presents a three-stage concept for a holistic maturity model. By providing transparency about the status quo of production systems in terms of Lean Production, digitalization, and sustainability, the model contributes to ensuring the future viability of such production systems in this highly competitive environment and under the political, social, and regulatory challenges.

Keywords

Maturity Model; Lean Production; Industry 4.0; Sustainability

1. Introduction

Manufacturing companies today face a turbulent environment. Increasing cost pressure, changing consumer behaviors, the shortage of skilled workers, or the scarcity of resources are production-specific challenges that have an impact on almost the entire value chain [1]. At the same time, climate change is raising public and political expectations regarding the sustainability of manufacturing companies [2]. As a result, in addition to the existing economic challenges, there is an increasing focus and need for action concerning the responsibility of companies towards the environment, the society, and their employees.

The two developments Lean Production and Industry 4.0 have led many companies to transform their production in recent decades [3,4]. While Lean Production (LP) focuses on the waste reduction and the customer orientation [5], Industry 4.0 (I4.0) aims to increase the effectiveness and the efficiency to reduce costs by digitizing and networking corporate and production processes [6]. This requires companies to implement digital technologies in production [7]. However, there is still a lack of comprehensive and widespread implementation of LP and I4.0 in companies [8,9].

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In the context of the additional challenge of sustainability, industry and research are increasingly recognizing the opportunity to also improve the production's sustainability through the targeted use of digital technologies. One example is the use of additive manufacturing, which can help to decarbonize existing manufacturing processes and to make them more environmentally friendly, i.e., by reducing waste or material consumption [10]. The role of the people in production, and therefore the inclusion of soft factors in the assessment of a company and its production, is also becoming increasingly important. These requirements can be met both by considering all sustainability dimensions equally and by considering digital technologies from the perspective of supporting employees [11,12].

In recent years, an integrative view of the three paradigms LP, I4.0, and sustainability in production has received increasing attention in the academic environment [13–15], cf. **Figure 1**. The increasing speed, scope, and complexity of the challenges require companies to maintain their competitiveness through transparency of both the degree of implementation and the targeted identification of improvement potential in the lean, digital, and sustainable transformation [16]. In this context, maturity models can serve as supportive tools to assess the status quo of the company regarding the paradigms and also to allow for the identification of potentials for action [17,18]. Therefore, this paper presents a concept for a holistic maturity model for the assessment of lean, digital, and sustainable production systems that considers the interactions of the paradigms.

To this end, the first section provides an overview of the fundamentals of LP, I4.0, and sustainability (2.1), as well as maturity models (2.2), before presenting the state of the art and deriving the research gap (section 3). At the beginning of section 4, the concept is briefly introduced before the individual steps are presented in detail (4.1 – 4.4). The paper concludes with a summary and an outlook (section 5).

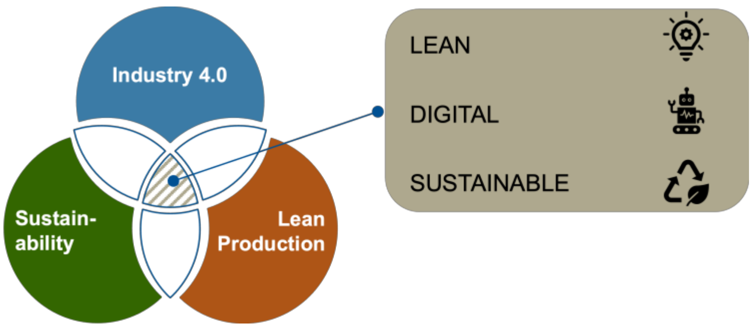

Figure 1: Lean Production, Industry 4.0, and sustainability as a holistic approach for future-proof production systems

2. Fundamentals

2.1 Lean Production, Industry 4.0, and Sustainability

"All we are doing is looking at the time line, from the moment the customer gives us an order to the point when we collect the cash [19]." This quote from Taichii Ono describes the principles of the Toyota Production System, which was introduced in the 1980s and forms the basis of the lean philosophy. At the heart of LP is the pursuit of the highest quality, the shortest lead times, and the lowest costs through systematic, employee-supported principles and methods such as waste elimination, stable and efficient processes, or a continuous improvement process. [5,20] In industry today, LP is often implemented and realized in the form of a Lean Production System (LPS), where LPS primarily describes the interaction of people, technology, and organization. VDI 2870-1 [21] describes an LPS as an "enterprise-specific, methodical system of rules for the continuous orientation of all enterprise processes to the customer". This clearly states that every company needs an individual adaptation of the production system as well as an overarching structuring of the methods like 5S or JIDOKA. Moreover, it is essential that the processes are aligned with the company's objectives using appropriate methods. [22]

The Fourth Industrial Revolution (Industry 4.0) is the latest revolution in the industrial environment and aims to optimize industrial value creation [23,24]. In this context, the term I4.0, which was introduced in 2011, describes the entire scope of the reorientation, redesign, and further development of existing production systems [23]. With the aim of creating new, intelligent factories, reducing production costs, and optimizing material and information flows along the value chain, I4.0 particularly characterizes the networking and digitalization of people, processes, plants, and products [24,25]. To achieve this goal, the data collected and analyzed play an increasingly central role [26]. In addition, various technologies such as the automatic identification of objects or people via data exchange or the additive manufacturing of products or tools have become established as part of the digital transformation, and their implementation is a building block on the way to the digital factory [27,28].

Driven by political and societal expectations and rules, e.g., penalties for failing to meet climate targets, the importance of sustainability in the industrial sector has increased significantly in recent years. The key challenge for future sustainable production is to achieve economic development without harming the environment [29]. The system of sustainability involves the use of a regenerative system in such a way that the essential characteristics of the system are preserved and natural regeneration of its stock is possible [30]. According to Elkington [31], the three dimensions of economic, environmental, and social sustainability are brought together under the term sustainability, and their equal consideration is becoming increasingly important. While the former focuses on a company's economic success, environmental sustainability focuses on reducing a company's negative environmental impact, such as CO_2 emissions, in order to protect natural resources [32,33]. Social sustainability places people and society at the center of consideration, focusing on the well-being of the company's employees [34,35]. Within these dimensions, different sustainability aspects like the educational support or the consumption of resources exist [32,36].

2.2 Maturity Models

Maturity models have gained importance in various industries and domains as they serve as basic frameworks to capture the current status quo of an organization and to define clear goals for further development or to reveal possible company-specific evolution paths [17,37]. By applying maturity models and thus revealing the current and desired state of a company in an area, companies are given a tool to improve the performance of a specific area within an organization [38,39].

According to Becker et al. [17], a maturity model comprises a sequence of maturity levels for a class of objects and thus describes an "anticipated, desired or typical evolution path of these objects shaped as discrete stages", starting from an initial stage to full maturity. Three maturity models can be distinguished depending on the purpose of the application or use: descriptive, prescriptive, and comparative maturity models [40]. Descriptive maturity models are particularly suitable for assessing the current state (of an organization, process, or domain), as they allow the current capabilities of an entity to be captured [17]. Prescriptive maturity models already identify concrete improvement or action options that can be used to achieve a target maturity level [17,18]. A comparative maturity model can be used for internal or external benchmarking to provide a comparative assessment across, for example, regions or industries [41,42,40].

The components of maturity models can be divided into four essential core components [41,43,37]. At the first level, there are the maturity levels, which form a kind of overarching framework in the maturity model through the targeted selection of labels, e.g., in the form of keywords (e.g., initial, repeatable, defined, managed, optimizing) [41]. The maturity levels clearly define the requirements for achieving each level [44]. They are in turn associated with key process areas at the second level, which are used to evaluate the measurement of the maturity level and within which certain targets must be achieved to reach a higher maturity level. The selection of suitable key process areas is therefore a difficult and an essential part of the development of the maturity framework, as they must comprehensively reflect the state of maturity and thus have a direct impact on the effectiveness of the model [42]. Common features at level 3 structure the key process areas into understandable sub-goals. Common features are in turn described by key practices, which are concrete activities that need to be carried out and build the fourth level. [41,43,37]

3. State of the Art

The literature review (LR) is a central starting point and a foundation for conducting a research project, as it captures the literature relevant to the topic under investigation, strengthening both the rigor and the relevance of the research [45]. An LR thus avoids re-examining knowledge that has already been developed and ensures that the existing knowledge base is fully utilized [46]. To obtain an overview of the state of the art in maturity models for the holistic assessment of production systems in the context of LP, digitalization, and sustainability, a systematic LR in SCOPUS was conducted following Webster & Watson [47] and Brocke et al [48]. The LR has shown that there are a variety of approaches to assessing maturity within the individual paradigms of LP, I4.0, and sustainability. Due to the holistic view of the paradigms aimed at in this concept, approaches that either combine LP and I4.0 or also consider sustainability are presented below.

3.1 Approaches in the Area of Lean Production and Industry 4.0

With the Production Assessment 4.0, Pokorni et al. [49] provide an approach to assess the maturity of a medium-sized manufacturing company concerning Lean Management (LM) and I4.0. The approach distinguishes between the three levels of the domain, the sub-domain, and the point of consideration (PoC). In this way, it covers an assessment of manufacturing and assembly processes or the organization through sub-domains such as the I4.0 target planning or the production leveling to points of consideration such as the digital factory layout. The two-stage assessment starts with an assessment of the capability levels (CL) of the PoCs belonging to a sub-domain. The average of the CLs of the PoCs finally results in the assessment at the sub-domain level and thus in the first identification of improvement potential. Subsequently, the sub-domains are systematized based on their allocation to the domains LM, I4.0 fundamentals, and I4.0 excellence. Rößler & Haschemi [50] also provide a methodology for assessing the Lean I4.0 maturity of production and logistics with their Smart Factory Assessment (SFA), which includes twelve categories such as the product and the material flow or the shop floor management and whose application aims to derive improvement paths towards Lean and I4.0 excellence. The seven Lean categories and five I4.0 categories have subcategories that are discussed during the factory visit in the expert-based SFA and rated on a five-point scale. These ratings are then consolidated and ultimately used to calculate the Lean and I4.0 criteria scores, representing the status quo. Finally, recommendations for action can be derived by comparing the target and the actual status. Even though the two approaches integrate both paradigms, LP and I4.0, none of them provides a comprehensive inclusion. The model of Pokorni et al. [49] focuses on small and medium-sized enterprises (SMEs) and uses different granularities in the evaluation of the paradigms of the same observation level. The maturity model proposed by Rößler & Haschemi [50] does not provide a uniform allocation of the LP and I4.0 paradigms.

3.2 Approaches in the Area of Lean Production, Industry 4.0, and Sustainability

The maturity model by Zoubek et al. [51], published in 2021, provides an approach for assessing CO_2 reduction taking into account I4.0 technologies in the dimensions of production, logistics, maintenance, and IT. Based on the core processes with environmental potential identified through value stream analysis, it shows how manufacturing processes can be shifted towards environmentally friendly production. The level of the dimensions depends on the assessment of specific indicators within these dimensions. Each dimension has been assigned three indicators describing environmental aspects, such as the degree of automation in production, energy sources and means of production, and environmental aspects of the production system. For the indicators considered, the authors propose an assessment of the carbon footprint (CF) in six levels, starting from level 0, where the company has a 0% CF reduction of the indicator considered, to level 5, which describes a carbon-neutral company. In their approach published in 2022, Wessing & Müller [15] consider Lean, Automated, Sustainable, and Digital (LAND) as the core characteristics of future production and develop a five-stage maturity model based on this. Nine areas form the pillars and foundation of their production of the future and assign the function of a pillar to sustainability, digitalization, and lean management, among others. The result of this approach is a five-level network diagram based on the I4.0 Readiness Study to assess the maturity of each pillar. The approach of Zoubek et al. [51] does not provide a general and comprehensive integration of individual LP methods, I4.0 technologies, and sustainability aspects within the dimensions for assessing the maturity of companies in the individual paradigms, as it only considers individual indicators under the aspect of CF. In the approach of Wessing & Müller [15], both a clear description of the individual maturity levels and a more specific consideration of the three paradigms LM, I4.0, and sustainability are missing. Furthermore, although interactions between the pillars are shown, a more detailed consideration at the level of methods, technologies, or aspects would be helpful.

It becomes apparent that research has so far lacked a comprehensive, general, and company-specific model for the assessment of future-proof production systems, which allows a holistic, multidimensional view of the maturity of LP, I4.0, and sustainability from the production system level to the level of methods, technologies, and aspects, considering the interdependencies of the three paradigms. By including interdependencies, it can made transparent how achieving a higher level of maturity in one paradigm depends on improving maturity in another paradigm. To fill this gap, the following section presents a concept for a holistic maturity model to create transparency and derive actions for future-proof production systems.

4. Concept

This paper aims to present a concept for a holistic, multidimensional maturity model for the assessment of lean, digital, and sustainable production systems. The maturity model to be developed should provide a transparent visualization of the status quo of a manufacturing company in terms of methods, technologies, and aspects within the three paradigms, considering the interactions between them. **Figure 2** illustrates the four-step approach to achieve this overarching goal. The four steps can be assigned to the two phases of the preparation and the development of the maturity model.

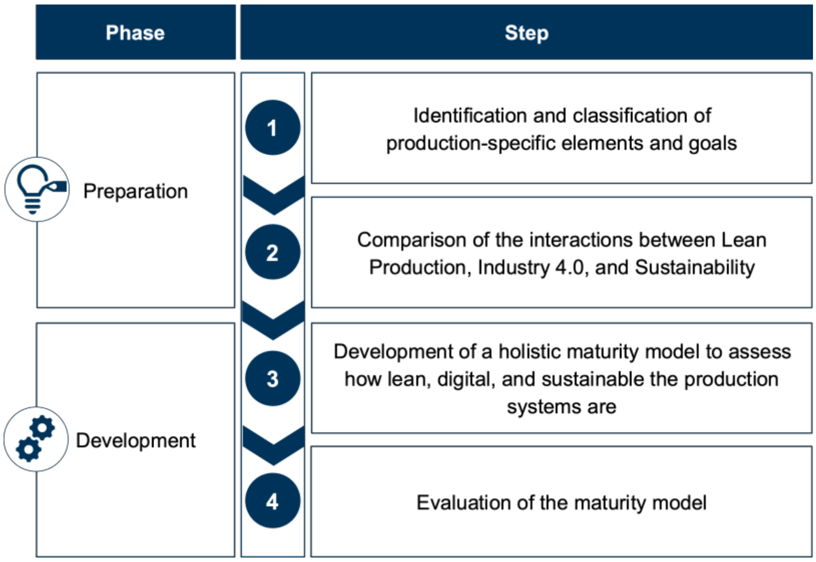

Figure 2: Concept for a holistic maturity model

Due to the presence of the sustainability paradigm, the first two steps of the concept are shown below for sustainability. The procedure is analogous for the two paradigms of lean production and digitalization in the sense of a holistic view and will be presented with the corresponding work results in further publications.

This builds on the previous preliminary work by Aull [52] and Dillinger et al. [27,53], which specifies the LP methods and the I4.0 technologies and analyze interdependencies.

To develop the holistic maturity model, the relevant elements (LP methods, I4.0 technologies, and sustainability aspects) within the paradigms must first be identified and classified. Here, elements are factors that help to improve LP, I4.0, or sustainability in the company by integrating new measures or developing existing ones. The first step is therefore a systematic analysis of the production-specific sustainability aspects, including all sustainability dimensions that are relevant to production. The next step is to examine the interactions within and between paradigms, with the focus of this concept is on the interactions within and with sustainability in production. Before a cross-paradigm comparison of the elements takes place, the interactions within the sustainability paradigm are examined at the beginning of the second step. The actual development of the maturity model starts with the elaboration of the third step. To achieve the third step, requirements for the maturity model to be developed are first derived, e.g., through design guidelines and company specifications. Furthermore, in the third step, a maturity model is developed based on the scientific approach of Design Science Research according to Hevner & Chatterjee [54]. The concept concludes with an evaluation of the maturity model, which, in addition to the scientific evaluation, includes a first industrial evaluation as a prototype. In the next section, the individual steps and the associated scientific procedure are described in more detail.

4.1 Step 1: Identification and classification of production-specific elements and goals

Due to the widespread importance of the sustainability paradigm in society, politics, and legislation, it is becoming increasingly important to select and to specify from the available sustainability aspects those whose implementation or further development in production directly affects the company's objectives. The first step for developing the maturity model is therefore to identify and then to classify the sustainability aspects relevant to production. With the help of a comprehensive LR, the extent to which the established dimensions of sustainability (economic, environmental, social) can be transferred to production systems and which aspects within these dimensions can be used to advance sustainability at the production level are examined (see **Figure 3**, left). Subsequently, the developed sustainability aspects are transferred into a multi-level, meaningful model with the help of a clustering procedure and finally evaluated for completeness and relevance from an industrial perspective. Following the development of the sustainability aspects (SA), existing production-relevant goals are analyzed from a sustainability perspective with the help of an extensive literature research and expert interviews. In this way, general sustainability goals are specified based on the three dimensions of economic, environmental, and social sustainability in the production context. The analyzed production-specific sustainability goals (SG) are then examined for existing correlations with the previously identified sustainability aspects, as shown in **Figure 3** on the right. This connection allows for a goal-oriented and therefore company-specific visualization of the relevant measures.

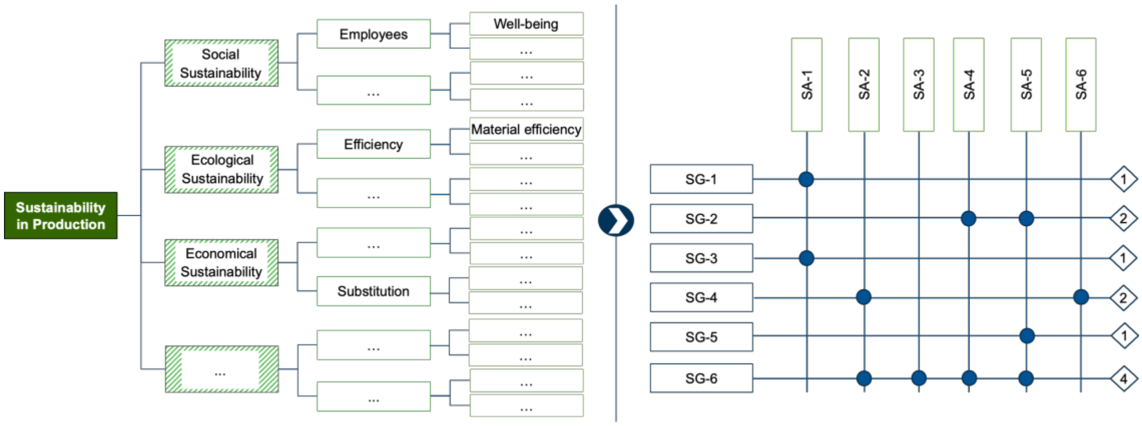

Figure 3: Production relevant sustainability aspects and goals

4.2 Step 2: Comparison of the interactions between Lean Production, Industry 4.0, and Sustainability

In the second step of the preparation phase, the extent to which the three paradigms LP, I4.0, and sustainability (SB) influence each other is examined (cf. **Figure 4**). The analysis of the interdependencies is initially carried out through a comprehensive literature review and is supplemented by an empirical study (e.g., a Delphi study). To elaborate and visualize the interdependencies, either a Domain Structure Matrix (DSM) or a Domain Mapping Matrix (DMM) is used, depending on the linkage, as they are intuitively readable and very compact [55].

At the beginning of the second step, an analysis of the interaction at the paradigm level (LP, I4.0, SB) is carried out. This means that it is analyzed to what extent there is a positive, negative, or no correlation between the paradigms. A positive correlation means that one paradigm supports the other, while a negative interaction means that one paradigm hinders the implementation or development of the other. In the case of no interaction, the paradigms can be considered or implemented independently. After the analysis of the interactions at the paradigm level, the second step is the interdependency analysis at the element level: lean methods (LP-1 to LP-y), I4.0 technologies (I4.0-1 to I4.0-z), and sustainability aspects (SA-1 to SA-x). Based on the SA identified in the first step, a paradigm-specific analysis of the SA is carried out to conclude whether the advancement of one SA (e.g., from the area of social SB) also influences another SA (e.g., from the area of environmental SB). For the elaboration and visualization of the paradigm-specific interdependencies, a DSM is used as described above. The paradigm-specific interdependency analysis is followed by the cross-paradigm analysis. Here it is examined to what extent LP methods or I4.0 technologies influence the implementation of SA or vice versa. The interdependencies are then compared in a DMM.

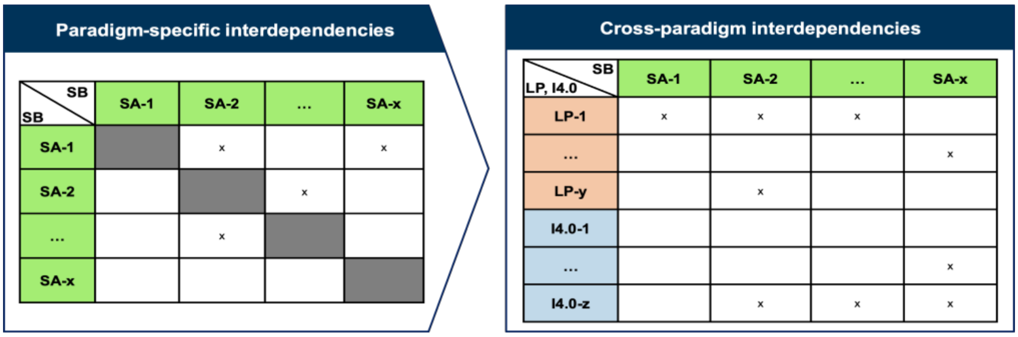

Figure 4: Comparison of interdependencies within and between the paradigms

4.3 Step 3: Development of a holistic maturity model to assess how lean, digital, and sustainable the production systems are

The third step aims to develop a holistic model for assessing the maturity of production systems in terms of their lean production, digitalization, and sustainability. At the beginning of the third step, requirements for the maturity model to be developed are defined, which include basic scientific quality criteria [56], and also design or functional principles [40] of the model. Furthermore, the identification of content-related requirements, such as paradigm-specific or cross-paradigm requirements, for a holistic maturity model is planned. For this purpose, the data obtained through expert interviews will be subjected to qualitative content analysis with inductive category formation [57]. The identification and definition of the requirements for the maturity model should ensure the later applicability and also the usefulness of the model, which is why the inclusion of the industrial perspective is planned in addition to the scientific preparation. In this way, it will also be possible to examine the extent to which the requirements of SMEs coincide with those of large companies. Subsequently, scientific approaches for the development of maturity models, such as those by Mettler [58], Becker et al. [17], or Maier et al. [42], will be compared and examined for their suitability for the use case considered in the research project. After the selection of a suitable procedure model for the development of the maturity model for the holistic assessment of lean, digital, and sustainable production systems, the individual phases will be executed step by step. This includes the definition of the level of abstraction, the selection of an assessment method, and the definition of maturity levels and maturity factors.

4.4 Step 4: Evaluation of the maturity model

In step 4, the final evaluation of the developed model regarding criteria such as validity, completeness, or unambiguity ensures that the result is independent of the user when the developed model is applied [41]. First, the maturity model should be subjected to a scientific evaluation. For this purpose, the previously developed model is evaluated in its entirety by research experts regarding the maturity architecture and maturity factors. To ensure a heterogeneous evaluation, an industrial evaluation of the suitability of the maturity model is also planned. Again, a sufficient number of experts are selected who have expertise in the three paradigms LP, I4.0, and sustainability in a production context and who are familiar with the handling of maturity models. The results of the evaluation will be used to validate the requirements previously defined in step 3 and to identify the potential for improvement. In addition, the results of the evaluation serve as a basis to initiate an iterative process to adapt and improve the maturity model if needed.

5. Conclusion and Outlook

For their future competitiveness, manufacturing companies should include the implementation status of the LP, I4.0, and sustainability paradigms in their target definition and control. The use of a holistic maturity model, which identifies the production-relevant elements of LP, I4.0, and sustainability, helps companies to assess their current implementation status in relation to their objectives, to identify gaps and weaknesses, and to derive measures for improvement. In addition to identifying areas for implementation and improvement, the inclusion of interactions can make transparent the extent to which achieving a higher level of maturity in one paradigm depends on improving the level of maturity in another paradigm. Moreover, the holistic maturity model can be used for benchmarking, e.g., by a plant manager to compare the maturity of his production system with the maturity of other production systems in his company, but also of competitors. In this way, experience in the companies' production network can be used to improve production systems if those with a higher maturity serve as inspiration or scale. Overall, by generating transparency, this model promotes the future viability of production systems and is becoming increasingly important, especially due to the growing demands for resilient and flexible production as well as the support of employees through digital technologies, such as through Industry 5.0 [59].

The validated maturity model resulting from this scientific project can be easily integrated into an organization's existing process environment. Furthermore, it can be directly linked to the company's strategic objectives, and selected values can be used as key performance indicators and, for example, as part of the company's balanced scorecard. In addition, through programming and software-based preparation, the model can be integrated into the company's tool landscape. In this way, the developed maturity model can become an integral part of management's daily leadership tasks. At the same time, the clear and in-depth approach with parameters helps employees and their lower management levels to easily understand and apply the model and its results, and at the same time to provide feedback to optimize the model for the specific needs of their company's production.

The four-step concept presented provides a general approach for multidimensional maturity assessments and thus for creating transparency of production systems in terms of their lean production, digitalization, and sustainability. The two main phases of preparation and development ensure that the required production-specific parameters are first comprehensively determined and that the basis for a holistic assessment is ensured by including cross-paradigm interactions before the systematic development and evaluation of the maturity model begins. The next step will be the detailed and systematic elaboration of these steps. Following the presented four-step concept, the topics will be elaborated in further publications.

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