Logistics Research (2023) 16:5
DOI_10.23773/2023_5

Towards a Maturity Model for Digital Supply Chains

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Received: 7 April 2022 / Accepted: 9 March 2023 / Published online: 19 April 2023

ABSTRACT

Emerging technologies like artificial intelligence, cloud computing, or big data play an important role in the digitalization of today´s society, also impacting companies and their supply chains. However, the associated challenges are not only restricted to the technical dimension but include organizational or managerial issues as well. For companies, it is difficult to "get a grasp" of the complex digitalization processes regarding their supply chains. A maturity model provides a beneficial starting point to assess the current state and subsequently guide the further digitalization. Therefore, the paper aims to conduct the first steps necessary to develop a maturity model in the area of digital supply chains. As a result, a first draft of the "Digital Supply Chain Maturity Model" (DSCM²) is presented. The model development is accurately documented and follows a rigorous scientific methodology, grounded in in-depth literature reviews and expert interviews. First, the topic area is structured into four dimensions, namely business, organizational, process & method, and technological digitalization. Second, subdimensions, as well as maturity levels and their related maturity characteristics, are identified and described. Third, the model is evaluated from a practitioner's perspective in several iterations. The feedback from the experts is positive and minor changes are implemented. However, the model and the provided online self-assessment tool still have to be evaluated on a larger scale. Despite its limitations, this preliminary research can motivate future research and serve as a solid foundation for continued development of the model.

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KEYWORDS: Digitalization · Supply Chain Management · Maturity Model Development · Literature Review · Semi-Structured Interviews

1 INTRODUCTION

Artificial intelligence (AI), blockchain, big data, cloud computing, and the internet of things (IoT) – the list of emerging technologies that have an increasing impact on society and the way of conducting business and, thus, change entire industries can be continued at will [1, 2]. This complex social-technical phenomenon, known as digitalization, goes beyond applying novel technologies but further requires changing organizational structures, processes, capabilities, and cultures [3].

The related change process for digitalizing organizations is termed digitalization [4]. Apart from transforming single isolated companies, practice and academia currently investigate the transformation in networks of companies, leading to "digital supply chains". In this paper, the term does not refer to the type of goods handled in the supply chain but that the process of value creation in the supply chain and its management are supported with innovative technologies in a digital manner [3], promising high benefits [1]. A consultancy analyzed that implementing a digital supply chain enables an increase in efficiency of 4.1 % and in revenue of 2.9 % [5]. A further incentive to support the transformation surfaced during the COVID-19 crisis, when the need for digital supply chains became alarmingly obvious [6]. Researchers call supply chain digitalization "the prerequisite to success within the pandemics and afterwards" [7]. This highlights the actuality and importance of the topic area of digital supply chains. It is not a question of whether to transform the supply chain but how: "Companies cannot opt-out digital transformation and expect to survive" [3]. Therefore, it is unsurprising that most companies plan to initiate or accelerate the digitalization of their supply chains.

However, only a few leading supply chain companies consider having reached a “digital first” point in their transformation journey [8]. Furthermore, various studies show that currently around 70 % of all digitalization projects do not meet their targets and fail [9]. Different causes can be identified. First, the digitalization represents a far-reaching endeavor with complex challenges and hindrances [10, 11]. Furthermore, critical challenges are how to make use of digitalization and how to conduct the digitalization in a target-oriented, efficient, and effective manner [2, 12, 13]. Isolated small-scale projects without a clear goal do not unfold the full potential and can even impede the digitalization. To counteract this, organizations demand a starting point from which digital transformation initiatives can be designed, planned, implemented, and controlled in a coordinated fashion [14–16]. Instead of unstructured ad-hoc attempts, the digitalization should be based on “a thorough analysis of the current status” [17]. In one of our interviews carried out for the research, the expert explicitly stresses that identifying the current state of digitalization from which targeted transformation roadmaps can be derived is a major challenge for many organizations.

In this context, maturity models come into play. The general idea of these models is to comprehensively depict typical capabilities, processes, concepts, or characteristics of an organization at a fixed number of sequenced maturity levels for different aspects of the domain of investigation. Maturity models enable the assessment of the current situation and transformation into a desired, improved state [18–20]. Maturity models are popular tools in both practice and academia [21]. Despite the ever-increasing popularity and their adoption in numerous areas, digital supply chain maturity models are not addressed sufficiently yet. The existing models only consider single or industry-specific aspects of supply chain digitalization, e.g., focusing on the manufacturing process or single technologies like artificial intelligence [22, 23].

This paper aims to close this gap by providing an initial draft of a generally applicable maturity model for digital supply chains (in the following: DSCM²). To this end, the major research question is posed: *How can the current state of a company´s supply chain regarding its digitalization be assessed and depicted by a maturity model?* The respective research goal is to develop an initial design of a descriptive maturity model for digital supply chains. The major research goal is addressed by the following three research questions:

- What are the digital supply chain key dimensions and levels?
- How can the identified dimensions and levels be structured into a representation of the current state of a digital supply chain?
- How should an assessment model be designed to support the maturity evaluation of digital supply chains?

To achieve the research goal, the paper is structured as follows: In Chapter 2, the conceptual background of digital supply chains and maturity models are provided. Chapter 3 describes the applied research methodologies. Next, Chapter 4 follows the development process steps: After the problem definition, existing models in the literature are identified and compared. Based on that, the iterative maturity model development is presented, detailing maturity levels, (sub)-dimensions, corresponding characteristics for each combination and the assessment. The developed maturity model is evaluated and critically discussed in Chapter 5. Finally, the paper concludes with a general discussion and avenues for further research.

2 CONCEPTUAL BACKGROUND

2.1 The State of Research on Digital Supply Chains

Digitalization is perceived as one of the most important trends nowadays that impacts organizations significantly [24]. To create a uniform basis for this paper, we follow the definition provided by Legner et al. where digitalization is described as “the manifold sociotechnical phenomena and processes of adopting and using these technologies in broader individual, organizational, and societal contexts” [25]. They take into account the business as well as information system perspective, expanding the view of technologically focused definitions.

Moving from digitalization in general to the digitalization of supply chains, it is astonishing how many different terms are proposed by academia and practitioners, e.g., digitalized supply chains, supply chain 4.0, intelligent or smart supply chain, as well as digital supply network [3, 26–28]. The concepts are still evolving, and associated terms are often used inconsistently, leading to misunderstandings [29]. In this paper, the frequently used term “digital supply chains” is applied and defined in the following. However, if sources use alternative terms like smart supply chains but are generally in line with our definition, we also consider the sources in our research. We apply the definition by Büyüközkan and Göçer: “A Digital Supply Chain (DSC) is a smart, value-driven, efficient process to generate new forms of revenue and business value for organizations and to leverage new approaches with novel technological and analytical methods. [A] DSC is not about whether goods and services are digital or physical; it is about the way how supply chain processes are managed with a wide variety of innovative technologies” [3]. In the definition, the value-creating character becomes apparent, and that only applying novel technologies is insufficient to successfully master the transformation. The alignment of digital initiatives with general strategic management and supply chain management to create digital business models is required to realize the potential for optimizing performance [30].

Already in 2005, Bowersox et al. published an article in the supply chain management review predicting that “[t]rue supply chain excellence will only come from making a digital business transformation” [31]. They discuss different dimensions of the transformation and name positive examples from industry, highlighting the continuously ongoing and encompassing character of the transformation [31]. However, it took some time until more literature regarding the digitalization of supply chains followed. For example, Capgemini Consulting published a conceptual report about the digitalization of supply chains in 2011 [30]. Other grey literature explored technological trends in supply chain management [32, 33]. The content is often vague, and the character of the reports is exploratory. In 2018, Büyüközkan and Göçer were among the first researchers to offer a thorough state-of-the-art overview of publications in the context of digital supply chains, extracting definitions as well as components and applied technologies in this research stream [3]. Other, less extensive literature reviews followed [34–36]. As the maturity of the research field grows, we observe different research streams emerging, e.g., one stream focuses on the application and use cases of specific technologies [37, 38], another stream targets the strategy formulation and adaptation [39, 40], and yet another stream relates to identifying capabilities and measuring the maturity degree [29, 41, 42].

The latter is the field and scope of this research. We aim to depict and measure the current state of a company regarding its digitalization initiatives along the supply chain. All supply chain functions are taken into account. Furthermore, the connection to suppliers, customers, and other key partners along the supply chain is also relevant to enable a network-wide view.

2.2 Characteristics and Requirements for Maturity Models

In general, maturity is defined as someone or something having reached the most advanced or complete state of some kind of development process [43]. Regarding enterprise-related maturity, the general purpose of maturity models is to assess the state of maturity of a particular maturity factor regarding a specific domain of interest based on a set of criteria in a comprehensive manner [44]. Therefore, the models facilitate the consecutive improvement of aspects in the domain of interest. The ultimate goal is to realize and maintain competitive advantages, e.g., by reducing costs or increasing the quality of processes [18, 19, 21].

There is no uniform structure for maturity models, yet, the majority of developed models follow the characteristics introduced by Fraser et al., including several maturity levels with descriptors and characteristics for each level, several maturity dimensions (and/or subdimensions) with characteristics and their specification on each level [19]. The maturity levels represent an organization’s anticipated, desired, or typical evolutionary path in the associated domain. This path starts at an initial level (e.g., the organization having no or only minimal capabilities in the domain) to an advanced level (e.g., the organization having all or optimized capabilities), passing several intermediate levels. A specific maturity level is passed when all criteria or characteristics of the level are fulfilled [18, 19, 44]. The first prominent maturity model dates back to 1979 when Crosby presented a maturity model in the organizational quality management context [45]. Later, the popularity and relevance of maturity models increased significantly with the Capability Maturity Model for Software developed by Paulk et al. [46]. Nowadays, many different models with various assessment foci in all kinds of application areas with different levels of detail exist [21, 44]. For example, a prominent model with a supply chain management focus stems from Lockamy and McCormack [47]. In recent years, maturity models, including digital aspects of supply chains, have evolved [16, 22]. The existing maturity models are compared and critically reviewed in Chapter 4.1, where their shortcomings are also addressed.

For the analysis of the existing maturity models, nine characteristics and requirements are presented (see Fig. 1). The requirements are derived from literature, ensuring that the necessary characteristics are addressed, and a suitable maturity model is developed [16, 48]. Key literature for general maturity model development methods [e.g., 18, 44] is taken as a basis. It is supplemented with elements from design science research, a paradigm that solves problems by building and applying artifact (in this case: maturity models) [49]. Domain-specific literature is added for context-specific requirements [e.g., 16, 17]. Furthermore, current maturity model literature following a similar approach is also considered [16, 17, 48, 50, 51].

The first two requirements ensure that the examined maturity model meets the topic and scope suitable for this paper, namely, addressing supply chains (#1) and addressing digitalization (#2). Most maturity models share a basic structure, depicting activities, best practices, processes, or other comparable characteristics of an organization at a fixed number of sequenced maturity levels [19]. The characteristics that represent the domain of interest are assigned to maturity dimensions and levels, and their description detail varies between different model types. Generally, maturity grids are more specific and provide a more differentiated and sophisticated analysis for targeted improvement activities [18, 19, 52]. In contrast, linear maturity models compute one overall average maturity score, providing a more straightforward assessment, while their applicability and benefit in the context of complex domains are subpar [18, 19, 52]. It is essential to provide a suitable level of detail in the descriptions to be precise but not artificially restrict the scope of interpretation, which results in the third requirement, granularity (#3) [50, 53]. The characteristics are assigned to each combination of maturity levels. The clarity of the model's dimensions, levels, and structure is necessary to enable a transparent assessment procedure, resulting in the fourth requirement, clarity of structure (#4) [16, 53].

Maturity models are popular tools in academia and practice; however, a common flaw is the insufficient quality of the documentation, missing a detailed explanation of the development and evaluation process [44, 53]. This is also mirrored in the design science principle of research rigor: methods should be rigorously executed and the process documented [49]. Thus, the fifth requirement is thoroughly applying and describing a model development methodology (#5). In addition, many maturity models lack a fundamental empirical evaluation based on, for example, extensive expert interviews or case studies. The sixth requirement demands a sufficient empirical evaluation of the model (#6), also considered important by the call for "well-executed evaluation methods" in design science research [16, 49].

To be applicable in different companies and supply chains, the maturity models need to provide a certain degree of flexibility in the assessment. One solution is to give different weights to the (sub-)dimensions before the assessment according to the company´s prioritization (requirement #7, adaptability) [17, 48]. Furthermore, the procedure of assessment varies. Common is the five-point Likert scale method that assigns a value from zero to five to each domain, or (sub-)dimension, while other assessments are based on more complex, qualitative questionnaires or on-site visits. The form of assessment, data collection, and communication also differs, ranging from self-assessment via document-based checklists or software solutions to interviews or audits by third parties [18, 20, 44]. For the application of a maturity model, an assessment method and (if further advanced) an assessment tool is required (#8, assessment) [50]. This tool represents the delivered artifact, following the design science research guidelines [49].

Three application purposes of maturity models are identified in the literature. A descriptive model focuses on describing the as-is state in the domain of interest without any support or recommendations regarding improvements for achieving a higher maturity level. Next, a prescriptive model additionally provides the relationship of the maturity levels to the business performance and activities, best practices, or other characteristics for reaching the next maturity level. Thus, these models facilitate and support the design of desirable improvement strategies, resulting in the last requirement, guidelines for improvement (#9) [16, 17]. Finally, a comparative model enables benchmarking other organizations in the same industry or geographical region regarding the domain [18]. Notwithstanding, many maturity models are hybrids or evolve, changing or extending their focus [18]. In this paper, an initial design of a descriptive maturity model for digital supply chains is developed, also serving as an improvement suggestion guideline to reach higher maturity levels.

	Characteristics and requirements
1	Addressing supply chains
2	Addressing digitalization
3	Providing sufficient granularity
4	Ensuring clarity
5	Presenting model development methodology
6	Depicting evaluations and test runs
7	Ensuring adaptability
8	Providing an assessment method
9	Offering guidance for improvement

Fig. 1: Overview of characteristics and requirements for digital supply chain maturity models

3 RESEARCH METHODOLOGY FOR THE MATURITY MODEL DEVELOPMENT

The literature distinguishes two design approaches for maturity models: Top-down and bottom-up [18]. In a top-down approach, the definitions of levels and dimensions are created before developing characteristics and measures fitting these definitions [18, 44]. In a bottom-up approach, these characteristics, measures, and further requirements are created initially, followed by definitions of levels and dimensions reflecting them [51]. Whereas a top-down approach is best suitable for relatively new domains without a clear definition of the respective maturity existing, bottom-up approaches are more advantageous in the context of an already developed domain for which aspects of its maturity are known and already determined [18]. However, a comparison shows that all approaches contain similar steps, only in different execution orders [21]. For this paper, the procedure model (top-down approach) proposed by Becker et al. is chosen for three main reasons [44]. First, the field of digital supply chains is rather young and therefore lacks uniform and consistent definitions of its maturity. Second, the procedure proposed by Becker et al. is conducted iteratively [44]. Hence, it features a continuous evaluation of the resulting design and provides a more flexible plus responsive development process that is valuable in evolving and dynamically transforming areas like digital supply chains. Lastly, the procedure by Becker et al. incorporates essential elements of design science research, e.g., the iterative build and evaluate cycle [49]. The design science research paradigm is suitable for a maturity model development as the designed maturity

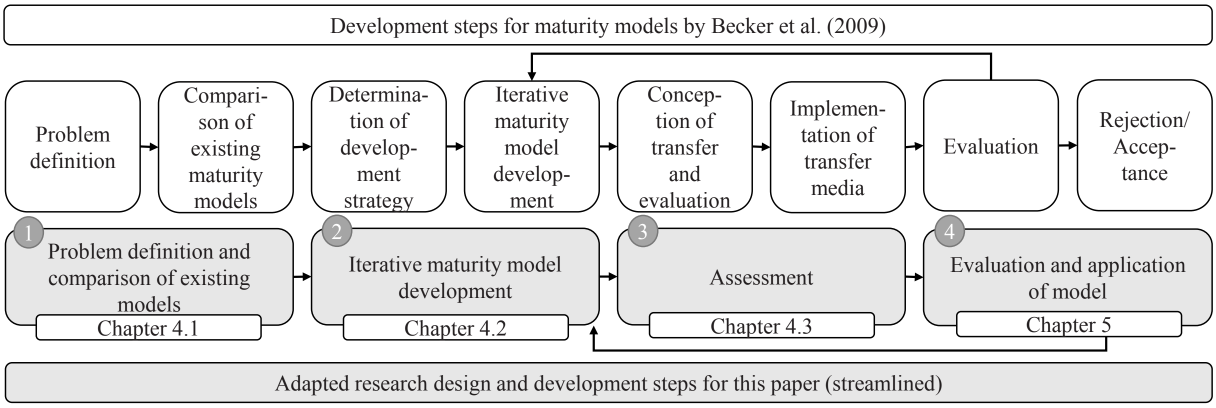

Fig. 2: Adapted procedure model for maturity model development in this paper

model represents an IT artifact. Building and evaluating IT artifacts is the rationale of design science research [49]. The streamlined procedure model applied in this paper is depicted in Fig. 2 and explained in the following. Similar streamlined approaches exist in the literature [18, 54].

First, the problem area needs to be defined in terms of the relevancy of the target domain, the target group, and the problem relevance [44]. Not only the relevance of the topic domain itself but the relevance of a maturity model in this topic domain has to be presented. To generate a state-of-the-art overview and to identify existing maturity models in the topic domain, a literature review following the steps by Thomé et al. is conducted [55]. Academic publications such as journal articles or conference papers are extracted from the databases and reviewed. Since the digitalization of supply chains is interdisciplinary, the review is not confined to a specific discipline such as supply chain management or information systems. Moreover, as it is a rather novel field, the review does not require any timewise restriction on the resulting set of publications but considers all papers published until July 2022. The publications are extracted from the complementary scientific databases Scopus and Web of Science. Using other additional sources resulted in significant redundancies during preliminary searches conducted for testing. The search string (see Fig. 3) consists of three different parts: The area of digitalization and related domains ("digit*" OR "smart*" OR "intellig*" OR "*4.0*"), the area of supply chain management ("supply chain*" OR "value chain*" OR "logistic*"), and the identification of maturity models ("maturity"). The wildcard notion with the asterisk ensures that the search focuses on the word stem. Terms having the same word stem (e.g., "digitalization" or "digital") are covered. After the identification of relevant maturity models in the field, they are compared based on requirements and characteristics to build a knowledge base of the current state of the art. After duplicate removal and keyword, abstract, title screening, the amount reduces to 92. At least two researchers conduct the inclusion and exclusion process. To check in how far the two researchers align, Krippendorff´s Alpha is calculated [56]. It represents a "reliability coefficient developed to measure the agreement among observers, coders […]" [57]. The result (0.879) confirms an acceptable agreement level (> 0.8) and that both researchers apply

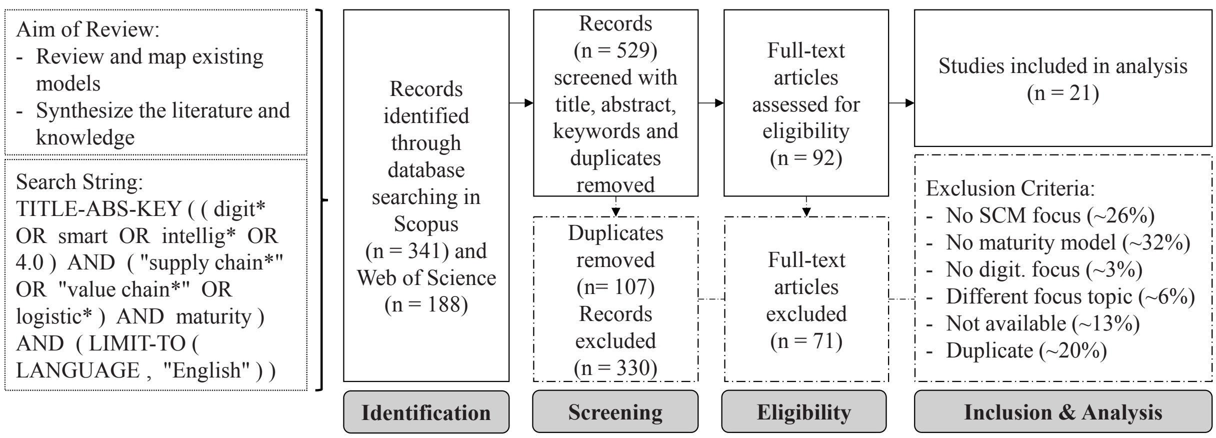

Fig. 3: Process of literature review on maturity models (adapted from Moher et al. [63])

the inclusion and exclusion criteria similarly. Next, the full-text read limits the included papers to 21. Papers are excluded if at least one exclusion criterion applies, e.g., when the supply chain focus is missing or no maturity model is developed and presented. During the review, the authors identify multiple maturity models from related research areas, e.g., Industry 4.0. Prominent maturity models, e.g., the IMPULS Industrie 4.0 Readiness model by Lichtblau et al [58] or the Industrie 4.0 Maturity Index by Schuh et al. [59], stem from practitioners. But also in scientific literature, multiple maturity models focus on manufacturing and digitalization (e.g., [60–62]). However, these sources are excluded in the present study as their main focus does not lie on supply chains but rather on production and/or mechanical engineering aspects. Including supply chain aspects as a side note is not sufficient for inclusion in this study. Yet, if the goal of future research is to diversify and enlarge the number of analyzed maturity models, this might be a promising approach. Performing a forward and backward search for complementation did not lead to further articles. The process of the literature review is illustrated in Fig. 3. After identifying the 21 maturity models relevant to this research, they are compared.

In the second step (see Fig. 2), the development strategy of the DSCM² needs to be determined [44]. In this paper, the approach of transferring some existing models´ components to a new topic area is applied because the literature review reveals several maturity models that present valuable building blocks that can be transferred to the domain of interest. The iterative development of the model is initiated by creating the model´s fundamental architectural structure and basic frame. The dimensions are designed deductively. Gradually, more details are added, and subdimensions and characteristics are drawn and added from the literature knowledge base inductively. The methodological approach of combining deductive and inductive stems from the literature [64]. Deductive development means that the dimensions stem from a theory or other already existing literature and are applied to the context at hand [64, 65]. For our maturity model, the dimensions are created by adapting already established dimensions from general digital (supply chain) transformation literature. One of the most prominent frameworks in information systems is the people, process, and technology framework with its three dimensions. As this thesis focuses on the digital supply chain, the framework by Büyüközkan and Göçer gives valuable additional input regarding the supply chain-relation. They present the three dimensions supply chain management, digitalization, and technology implementation with associated subdimensions [3]. Four dimensions of the digital supply chain emerge by merging the two existing frameworks. The challenge is to balance the number and content of dimensions. On the one hand, creating too many dimensions leads to overlaps and redundancies in the model. On the other hand, creating too few dimensions results in a too high level of aggregation, leading to an inconsistent depiction of maturity. In contrast to this, inductive development means that the subdimensions are iteratively created and emerge from the literature [64, 65]. The subdimensions are inductively developed and mainly sourced from other maturity models. The more granular subdimensions are allocated to the four deductively developed dimensions. Not only the labels of the subdimensions but the actual content is compared. To shed more light on the methodological process of deriving the subdimensions, this is exemplarily described for one subdimension, namely the digital strategy subdimension. Table 4 in the appendix lists all influential maturity models and highlights elements important for the respective subdimension. In the example, investments, roadmaps, business models, and leadership aspects frequently appear as important elements in the examined maturity models. They are allocated to different dimensions and subdimensions in the models, so the authors´ task is to extract and structure them under the digital strategy subdimension, as they all relate and contribute to it. Even though the terms or specific expressions may vary (e.g., investment plan, financial viability, etc.), they are merged into one subdimension in our maturity model. Following this approach, we create as few overlaps as possible and as many subdimensions as necessary. Methodologically, this approach is repeated for all other subdimensions. However, due to scoping reasons, this is not detailed in this paper.

The third step (see Fig. 2), namely the assessment step, merges two steps from the original process by Becker et al.: the conception and implementation of transfer media because both go hand in hand. Here, the developed model is presented to the respective community, and a transfer media is chosen [44]. Many possibilities exist, from paper-based checklists to more sophisticated software solutions, which need to be selected and made accessible. In this paper, an online self-assessment tool is applied.

The evaluation of the model is the final step of the procedure model (see Fig. 2). Yet, the whole process has an iterative character, and feedback can lead to changes in the model. Several iterations are common until a satisfactory result is presented [44]. We continuously evaluate the model in several iterations and with different methods (see Fig. 4). No intermediate steps are presented in this paper to ensure a consistent presentation of the (final) model and ease the readability and understandability. More details on the evaluation methods and participants are depicted in Table 5 in the appendix.

The first evaluation iteration consists of semi-structured interviews to evaluate the model´s structure and content. The choice of semi-structured interviews as a qualitative evaluation approach is based on different reasons. First, flexibility is achieved due to open-ended and follow-up questions. This closer

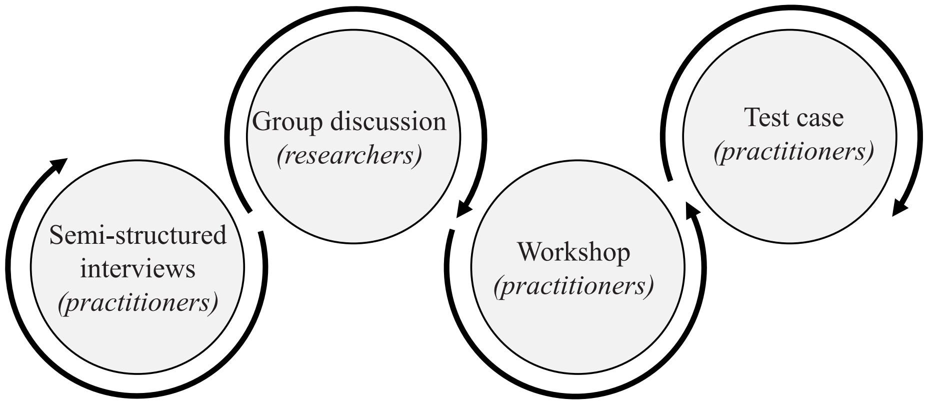

Fig. 4: Evaluation Cycles and Methods

interaction with the interview partners gives beneficial insights, e.g., when disagreeing with the current setup [66]. Second, suggestions for improvement can be added and discussed immediately [16]. The process of designing and conducting the semi-structured interviews is based on the approach by Rabionet [67]. Experts from practices in the field of (supply chain) digitalization are chosen as interview partners to include practitioner views on the maturity model. The interviews last between 60 and 90 minutes (see Table 5 in the appendix).

As a second evaluation iteration, we present the DSCM² at an international conference where we gather valuable feedback from academics from similar research areas. After a 30 minutes presentation of the model, we discuss the development method and content. Collecting feedback from fellow researchers interested in similar research topics helps to deepen the understanding of partial aspects of the model, e.g., the methodological approach. Researchers specialized and interested in the area of maturity models attend the presentation. They contribute with aspects generally not perceived as highly relevant by practitioners, focusing more on the process (how is the model developed?) rather than the results (what is the outcome?). This is helpful complementary input for the maturity model development.

In the third evaluation iteration, the focus is on gathering practitioner feedback. But, instead of targeting the development method of the maturity model, this iteration focuses on the developed online self-assessment tool. It is applied in a workshop on digital supply chains with seven participants from different companies and industries. At the beginning of the workshop, maturity models in general and their goals are introduced. Afterward, the participants are asked to fill out the online self-assessment tool on behalf of their companies. This workshop tests the applicability of the self-assessment tool, the understandability of measures and questions, and generalizability in a real-world environment [18].

Lastly, we apply the model to a company as a test case and evaluate its applicability in practice [16, 48]. The company has not been involved in any of the maturity model development or evaluation steps. Researchers support to use of “independent” sources for validation, as they can provide a “fresh” perspective which increases the reliability [16]. For the test case, we use several sources for data triangulation, namely, interviews, on-site visits, and documents. The assessment questions are completed in the assessment tool by two company employees. Two researchers are also present and observe and discuss the assessment. Feedback is gathered to test the model´s applicability, reliability, and validity. The final maturity scores are based on the consensus of the participants.

4 TOWARDS THE DESIGN OF A MATURITY MODEL FOR DIGITAL SUPPLY CHAINS

4.1 Problem Definition and Comparison of Existing Maturity Models

Following the methodology described above, first, the target domain of the maturity model has to be specified. The target domain consists of supply chains of companies handling physical products (including retail). The focus here is the degree of digitalization of the given supply chains (not the product). The target domain is kept broad on purpose in order to apply the model to many companies in different industries and sectors and compare their degree of digitalization. The authors of this paper are aware that the high degree of generalization comes with the drawback of not giving specific advice and missing to consider the particularities of different industries. This research does not target the examination of certain company sizes as an object of investigation, in contrast to other authors who focus on small and medium-sized companies [17, 68]. The relevance and necessity for designing a model are highlighted (c.f Chapter 1 and Chapter 2), accentuating the failure of existing maturity models to fulfill the stated needs. This, in turn, stresses the necessity for designing a new maturity model. In the interviews conducted for this research, the experts further confirm the high relevance of a model in this domain. Besides, the high interest in the digitalization of supply chains is expressed in the growing number of articles and supported by claims for further research [16, 41, 69].

Furthermore, comparing existing maturity models includes searching for already existing and related maturity models based on the problem definition. Identifying relevant, transferable aspects of these models and existing gaps are substantial tasks [44]. For this phase, the authors conduct a literature review (see Chapter 3), and the synthesized knowledge is utilized in the following. Table 6 in the appendix depicts all identified maturity models and selected details, e.g., number of levels, name of dimensions, etc. Overall, 21 maturity models were identified. They are published between 2017 and 2022 (with one exception from 2010). Table 1 presents the identified maturity models and the requirements´ fulfillment degree. While the digitalization focus (requirement #2) is frequently addressed, most models do not incorporate the supply chain requirement (#1) sufficiently, e.g., focusing on manufacturing and logistics [70] or intra-logistics [17]. The granularity (requirement #3) of the described models varies a lot, but the authors provide a sound

Table 1: Requirement analysis of maturity models identified in the literature

#	Authors	Publication Year	Addressing SC (#1)	Addressing Digitalization (#2)	Granularity (#3)	Clarity (#4)	Methodology (#5)	Evaluated/Tested (#6)	Adaptability (#7)	Assessment Method (#8)	Guidance for Improvement (#9)
1	Asdecker & Felch	2018	◔	◑	◕	◕	◑	●	◑	◑	◑
2	Bibby & Dehe	2018	◑	◑	◑	◑	◔	◑	◔	◑	○
3	Buntak et al.	2021	◕	◑	◔	○	○	○	○	○	○
4	Caiado et al.	2021	◑	◑	◕	◕	●	◕	○	◑	◕
5	Chaopaisarn & Woschank	2021	◕	◕	◔	◔	◔	○	○	◔	○
6	Çınar et al.	2021	◑	◕	◕	◑	◕	◕	◑	◑	◑
7	De Carolis et al.	2017	◔	◑	◑	◔	◔	◔	◑	◔	◔
8	Ehrenspenger et al.	2021	◑	◕	◔	◔	◑	◑	○	◔	○
9	Facchini et al.	2020	◑	◑	◔	◑	◔	◕	◑	◑	○
10	Frederico et al.	2020	●	◕	◑	◑	◕	○	○	◔	○
11	García-Reyes et al.	2022	◕	◑	◔	◔	◔	○	○	○	○
12	Klötzer & Pflaum	2017	◕	●	◑	◕	◕	◔	◔	○	○
13	Krowas & Riedel	2019	◔	◑	◑	◑	◔	◔	◕	◔	◔
14	Methavitakul & Santiteerakul	2018	◑	◑	◔	◔	○	○	◔	○	○
15	Plomp & Batenburg	2010	◕	◔	◔	◔	◑	◑	◔	◔	○
16	Vasconcellos et al.	2021	◕	◕	◑	◑	◕	◕	◔	◕	◔
17	Wagire et al.	2021	◑	◕	◕	●	◑	◑	●	◕	◔
18	Ward et al.	2018	◕	◑	◑	◔	○	◑	◔	○	◑
19	Weerabahu et al.	2021	◕	◕	◔	◔	◔	○	○	○	○
20	Werner-Lewandowska & Kosacka-O.	2019	◑	◔	◔	○	◔	○	○	○	◔
21	Zoubek & Simon	2021	◔	◔	◑	◔	◑	◔	○	◔	○

Degree of fulfillment: ● = very high ◕ = high ◑ = medium ◔ = low ○ = n.a.

description of the levels and dimensions in most cases. Yet, the clarity (requirement #4) is addressed less carefully in the literature and sometimes even wholly neglected [71].

We agree with other authors on the finding that most maturity model developments do not follow and describe a suitable methodology (requirement #5), weakening the scientific rigor and traceability [44]. The evaluation of the models (requirement #6) ranges from sophisticated in some cases [53] to no evaluation in many cases [41, 68, 71–73]. Furthermore, the adaptability requirement (#7) is often omitted, and the same holds true for the assessment method requirement (#8). Even if an assessment method is presented, no tool or further material to facilitate the assessment is provided (e.g., [74, 75]). Only one paper presents guidance for improvement (requirement #9) on a more detailed level [16]. Other papers are aware of this task, yet, they do not substantially contribute to tackling it [48].

All in all, the analysis reveals deficits in the current literature and the potential to develop a maturity model for digital supply chains as no identified maturity model meets the requirements. Yet, the identified models are not generally discarded, but useful information is extracted and used to create the new model.

4.2 Iterative Maturity Model Development

4.2.1 Level Design

Following the approach by Becker et al., the architecture and structure of the DSCM² are designed first, starting with the levels [44]. Fraser et al. suggest using three to six levels [19]. To include the research that has been conducted before, the structural components of the maturity models identified in the literature are compared. Here, the number of levels ranges from four to six (if indicated). The most frequent (~50 %) number of levels is five (see Table 6 in the appendix). Thus, the DSCM² is structured into five maturity levels.

The level descriptors are adapted from the ones proposed by Becker et al. [44] and Maier et al. [52], adding a digitalization focus. The level description provides transparency and comparability (i.e., none, initial, repeatable, defined, managed, and optimized). The definition of the respective levels is based on the levels of the maturity models identified during the literature review. The typical evolution and attributes of the levels are extracted and applied to the domain of supply chain digitalization.

The five levels of the DSCM² represent the maturity stages of digital supply chains. The key characteristics of the levels are described in the following. They are partly based on already existing research, as indicated in the text, merged in a consistent way, and if necessary, adapted to the topic domain. An overview of the maturity levels and their essence is presented in Table 2.

The first level characterized by the lowest digitalization maturity is no supply chain digitalization. On this level, no digitalization initiatives of any kind are conducted neither within the supply chain nor within the company [16, 48]. Nevertheless, the awareness of the importance of (supply chain) digitalization and related

Table 2: Maturity levels of the DSCM²

Level	Description
Level 1: No Supply Chain Digitalization	- No digitalization initiatives - Starting digitalization awareness within the company
Level 2: Initial Supply Chain Digitalization	- First, unsystematic and reactive digitalization initiatives - Digital pilot projects for gaining experience with digitalization - Initiatives and projects conducted within the company
Level 3: Defined Supply Chain Digitalization	- Defined digitalization agenda at the company comprising widespread digitalization initiatives along the supply chain - Integrative digitalization initiatives and projects within the majority of supply chain functions and selected key partners - First benefits in terms of effectiveness and efficiency improvement as a result of digitalization initiatives and projects
Level 4: Managed Supply Chain Digitalization	- Defined digital supply chain strategy and governance at the company - Systematic, supply chain-wide digitalization management coordinating digitalization initiatives targeting all functions and partners - Digital supply chain leading to advantages over competitors of the company
Level 5: Optimized Supply Chain Digitalization	- Digitalization best practices implemented result in all maturity dimensions covering each supply chain function and partner - Digital supply chain fully automated and autonomous in decision making - Best practices implemented result in outstanding competitive advantage in each maturity dimension

opportunities, challenges, and changes (at least partly) emerge [22, 41]. On the second level, initial supply chain digitalization, primary unsystematic, reactive, and local digitalization initiatives are instigated and performed [41, 70]. For instance, initiatives comprise the processes, investments, or resources involved in digitalizing single areas of the supply chain [53]. Moreover, digital pilot projects are conducted to gain experiences with selected aspects of digitalization, e.g., related to smart production machines [17, 76]. The majority of these initiatives and projects target the company and are not conducted supply chain-wide. The third level is defined as supply chain digitalization. As part of this level, a digitalization agenda is defined by combining widespread digitalization initiatives [17, 70]. These initiatives are realized in an integrative manner covering most of the functions while concentrating on both the company and key supply chain partners [16, 41]. These partners include suppliers, service or technology providers, and customers of importance that are determined based on the specific nature of the investigated supply chain. Moreover, the implemented digitalization initiatives result in first benefits in terms of efficiency and effectiveness [16, 41]. Based on the specific subdimension, these benefits range from process performance improvements to more consistent and enhanced customer experiences [22]. On the fourth level, managed supply chain digitalization, an integrative digital supply chain strategy and governance are defined and realized within the entire supply chain [70]. It comprises the systematic management and coordination of the supply chain digitalization in a holistic manner. Thus, associated initiatives and implementations cover all supply chain functions and all partners [41, 53]. Therefore, the digitalization of the entire supply chain is considered successfully realized at this level [22]. As a result of the digitalized supply chain, first competitive advantages can be accomplished, such as optimized processes or automated decision support based on anticipation of future scenarios or demands [68]. The fifth level representing the most mature state of a digital supply chain is optimized supply chain digitalization. The highest maturity level is generally considered to be difficult to achieve but serves as inspiration on where the digital transformation might lead. On this level, best practices regarding digitalization are implemented for all maturity dimensions as well as areas, functions, and partners within the supply chain [16, 76]. These implemented best practices lead to outstanding competitive advantages over competitors in each maturity dimension. Most importantly, the digital supply chain is fully automated and autonomous in decision-making due to a realized supply chain intelligence [17, 53]. Other advantages include, for instance, cutting-edge skills within the entire supply chain and a highly innovative, disruptive, and continually developing business model [68]. The term best practices is open and rather vague, making it challenging to operationalize in the maturity model. Therefore, more details regarding each subdimension on each level are included in the matrices and the assessment questions. Suggestions and additional measures might evolve over time when testing and implementing the maturity model extensively in practice.

4.2.2 Dimension and Subdimension Design

As described in Chapter 3 of this paper, the DSCM² consists of four deductively developed dimensions: business digitalization, organizational digitalization, process & method digitalization, and technological digitalization. To examine in how far the four dimensions are covered in the literature, Table 3 depicts an overview. The result shows the necessity to combine the identified models in order to create an encompassing maturity model for digital supply chains. No model covers all dimensions sufficiently. Some models only consider one or two of the four dimensions to a small degree.

The inductively developed 18 subdimensions are allocated to the four maturity dimensions of the DSCM². An aggregated graphical overview of the developed maturity model is given in Fig. 5. However, a more detailed presentation of every (sub-)dimension and the characteristics on the different levels is additionally presented in the appendix of this paper in form of matrices (see appendix Table 7 for the business digitalization dimension, Table 8 for the organizational digitalization dimension, Table 9 for the process & method digitalization dimension, and Table 10 for the technological digitalization dimension). The content of the dimensions and subdimensions is briefly described in the following.

The business dimension (see Table 7 in the appendix) covers the digitalization of the business steering and management (i.e., strategy and governance) as well as external-facing areas (e.g., product and service offering) of the supply chain reflected in nearly all maturity models [e.g., 16, 22, 48, 50, 68, 72, 76]. Digital strategy deals with the realization of digitalization roadmaps and management practices for the entire supply chain [3, 41, 48, 76, 77], while digital governance focuses on the establishment of related digitalization governance mechanisms and structures [50, 78]. Moreover, a digital portfolio digitalizes the product and/or service offering [72, 79], whereas customer experience creates enhanced and individualized interaction with customers based on digital touchpoints and channels [16, 22, 48, 72]. Lastly, business model innovation realizes the continuous enhancement and digitalization of the entire business model [50, 68], while the realization of a systematic achievement of innovations in all areas, such as products, services, processes, or technologies, is achieved by innovation management [22, 76].

The organizational dimension (see Table 8 in the appendix) targets internal-facing aspects reflected in some of the maturity models examined [17, 22, 41, 48,

Table 3: Maturity models and coverage of dimensions

#	Authors	Publication Year	Business	Organizational	Process & Method	Technological
1	Asdecker & Felch	2018	○	◔	◕	◑
2	Bibby & Dehe	2018	◑	◔	◑	◔
3	Buntak et al.	2021	◔	◔	◕	◔
4	Caiado et al.	2021	◔	○	●	◕
5	Chaopaisarn & Woschank	2021	◑	◔	◔	◑
6	Çınar et al.	2021	◕	◕	◑	◕
7	De Carolis et al.	2017	○	○	◑	◑
8	Ehrenspenger et al.	2021	◔	◔	○	◑
9	Facchini et al.	2020	◔	◔	○	◑
10	Frederico et al.	2020	◕	◕	◕	●
11	García-Reyes et al.	2022	◔	◔	◑	○
12	Klötzer & Pflaum	2017	◕	◔	◕	◕
13	Krowas & Riedel	2019	○	◑	◑	◑
14	Methavitakul & Santiteerakul	2018	◑	◕	◑	◑
15	Plomp & Batenburg	2010	○	○	◔	◔
16	Vasconcellos et al.	2021	◔	◑	◑	◔
17	Wagire et al.	2021	◕	◕	◕	◕
18	Ward et al.	2018	◑	◔	◔	◑
19	Weerabahu et al.	2021	◑	◑	◑	◑
20	Werner-Lewandowska & Kosacka-O.	2019	○	○	○	◑
21	Zoubek & Simon	2021	○	○	◑	◑

Degree of fulfillment: ● = very high ◕ = high ◑ = medium ◔ = low ○ = n.a.

50, 68, 70, 72, 76]. Culture development describes the extent of an open, dynamic, and supportive cultural identity within the supply chain, allowing its successful digitalization [3, 22, 48]. Next, organizational design deals with the realization of dynamic structures within the supply chain as well as roles, responsibilities, units, etc., related to digitalization [3, 70]. Digital employee assistance addresses the support of staff by technological means such as augmented reality or machine-to-human communication [3, 50, 75]. Finally, the acquisition of skills for digital supply chains and the systematic employee development based on education processes or platforms is realized by the subdimension knowledge management [22, 68, 72, 76, 80].

We propose the process & method dimension (see Table 9 in the appendix) in our maturity model, following other models in the literature even though the denotations differ [16, 17, 22, 48, 53, 70, 72, 79]. Digital process automation comprises the standardization, digitalization, and automation of all business or supply chain-related processes [3, 16, 17, 53, 75]. Supply chain intelligence addresses integrating and applying advanced analytics technologies for decision-making and implementing self-learning capabilities into the supply chain [16, 80]. Supply chain collaboration focuses on the partner network, especially implementing advanced supply chain collaboration practices and initiatives for creating a highly flexible and dynamic network of partners [16, 22, 53, 74]. Lastly, performance management includes the systematic measurement of process performance and the optimization of the process execution based on this data [14, 48, 70].

We adopt the technology dimension (see Table 10 in the appendix) prominent in many maturity models [17, 41, 48, 53, 68, 72, 73, 79]. It encompasses smart objects realizing autonomous service systems by designing and deploying all types of smart objects in supply chain processes or functions [22, 69, 71, 73]. Furthermore, the standardization and integration of data from all types of

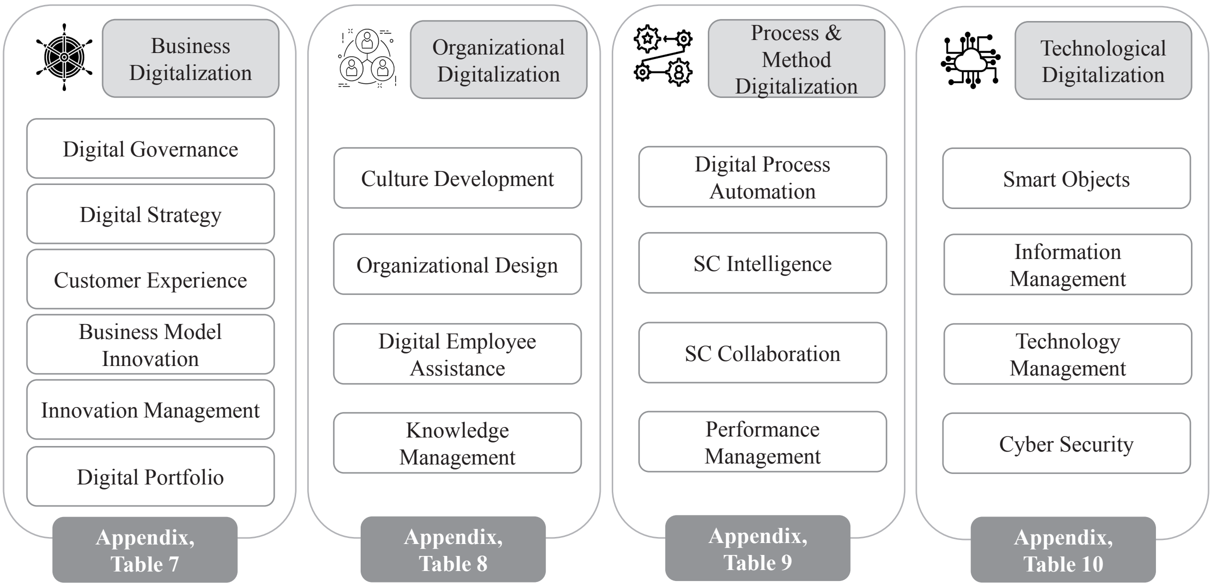

Fig. 5: Dimensions and subdimensions of the DSCM²

available sources into a single information management platform is targeted and subsumed under information management [17, 68]. The technological dimension also includes all information-related processes to enable a target-oriented information supply in real-time [48, 53, 68]. Technology management consists of developing and procuring the technological foundation for a digital supply chain and realizing an appropriate technical architecture [14, 22, 41, 53]. Cyber security additionally establishes a systematic management process and integrative strategy for ensuring data protection and general IT security [48, 50, 72, 78].

4.3 Assessment of the Maturity Model

Different maturity assessment methods exist, varying in the level of detail, reliability, and required effort [81]. The maturity assessment of the DSCM² is based on a qualitative questionnaire. It determines the distinct maturity level for each subdimension enabling the maturity model to represent various supply chains with different states of digitalization. Questionnaires are a common approach to collect the necessary data for assessing maturity [e.g., 48, 68, 69] and range from self-assessment to supervised or third-party assessments [51]. Furthermore, the questionnaires can be paper-based or online. In our research, we develop and test an online self-assessment tool for the DSCM². We argue our choice as follows. First, the online tool provides the functionality to access the model from different locations and at any time. Furthermore, the calculations are automated, and human error can be reduced. According to Mettler et al., online tools are one of the most helpful auxiliaries to ease the applicability [51]. Third, as no third party has to be involved, the required effort of the company using the model is moderate. Therefore, it can be integrated into the operational routine, and thus, the inhibition to apply the maturity model is lower than in a more time-consuming assessment with external parties.

All questions and possible answer-paths of the assessment are presented in the appendix (see Table 11 in the appendix). The assessment is structured as follows: Four to eight questions are allocated per subdimension. They can be answered with either yes or no, which simplifies the assessment for the user. Furthermore, compared to a scale, it can lead to less biased results. On a scale, the user needs to express the degree of agreement, often automatically transferring this to the corresponding level number in the model [81]. Depending on the answer, either the next question regarding the subdimension is provided, or there is no follow-up question. The maturity score is then set at this point for this subdimension. The sequence of the questions is specified by the model's developers, thematically organized to move through the different dimensions and from immature to mature. The questions reflect the maturity characteristics of different levels in the subdimensions. To the user, the underlying structure of the questions and their sequence (answer-path) is unknown because the online self-assessment tool only shows one question at a time. That way, a less biased answering of the assessment questions is achieved. Furthermore, what question is presented next depends on the answer to the previous questions. Therefore, the assessment is customized, preventing companies with low maturity levels from answering questions only relevant to high-mature companies.

The user can view the results immediately when all the relevant assessment questions have been answered. The user can choose the level of detail of the maturity result. The result can be visualized per subdimension (not aggregated), per dimension (moderately aggregated), or as one overall maturity score (highly aggregated). The determination of maturity levels per subdimension enables a detailed representation of the current state of maturity. Regarding the calculation and aggregation of maturity scores, different methods exist in the literature [82]. We suggest applying the weighted mean method to depict the aggregated levels as detailed as possible and simultaneously giving the opportunity to adapt the weights of the dimensions according to the user´s requests. However, the assessment tool implementation and evaluation are only on an initial basis. Further research in this direction and on a larger scale will follow as a next step and is not part of this paper.

5 MATURITY MODEL EVALUATION

For evaluating the DSCM², the results of the in Chapter 3 presented four evaluation iterations (see Fig. 3) are presented and discussed in the following. The results are also summed up in Table 5 in the appendix. In the first evaluation iteration, two semi-structured interviews are conducted. During the interviews, the levels, dimensions, and subdimensions are presented to the experts and discussed. Overall, the experts appreciate the idea of a maturity model in this topic domain and see its utility. Regarding the maturity levels, the depicted climax is considered easy to understand and consistent while representing the practice correctly. Furthermore, the increasing integration of supply chain partners on higher maturity levels is appreciated. Only minor changes are incorporated, e.g., the unification of terms. Additionally, the first version of the level descriptions does not include the benefits of digitalization initiatives. Thus, some high-level benefits in the model’s level descriptions and subdimension characteristics are added. With this, users applying the assessment can match the achieved benefits in their company cases to the level descriptors and assess their state of maturity more precisely. Regarding the maturity subdimensions, one expert proposed merging two subdimensions in the technological dimension to reduce overlaps. Also, minor adjustments in renaming subdimensions are conducted to clarify the content. Furthermore, the request by one expert for providing a little more detail, especially regarding supply chain intelligence, is addressed by integrating advanced analytics and AI as more specific classes. Overall, the two experts support the maturity model’s structure and consider it a beneficial tool for their organizations.

The second evaluation iteration takes place at a conference where the maturity model is presented and followingly discussed with the group of attending academics. In general, the set-up of the dimensions and subdimensions is well received. Furthermore, they acknowledge that the maturity model represents the digitalization of supply chains completely, consistently, and adequately. The discussion participants notice and approve that the maturity model features some subdimensions that have a general digitalization perspective (e.g., digital governance, digital portfolio, culture development) and, thus, do not differ significantly from the ones of digitalization-related maturity models, while other subdimensions focus on supply chain digitalization (e.g., smart objects, supply chain collaboration). Some attending researchers also work on developing a maturity model, yet in other areas. They can relate to the more general digitalization subdimensions and agree on them. Furthermore, feedback concerning the methodology, especially testing and evaluation of maturity models, is very helpful. The group discussion leads to interesting results and future research ideas.

The third evaluation iteration consists of a workshop that practitioners from different companies attended to educate themselves about digital supply chains. In this context, the online self-assessment tool of the maturity model is presented, and the participants are asked to fill it out on behalf of their company. Overall, the participants successfully complete the online self-assessment. They are confident that the model adds value to better understanding and guiding transformation initiatives in their companies. The positive feedback from the users underlines the applicability of the online tool. Minor suggestions for improvement are given. For example, it is suggested that specifications (e.g., position or knowledge area) for the person filling out the assessment questions in the online tool should be defined prior to the assessment. The maturity model covers many areas, e.g., strategic as well as technical aspects of the supply chain. Therefore, supporting the identification of the most suitable employee(s) to answer the assessment might be beneficial. However, during the workshop, the participants do not report any issues using the assessment tool.

The fourth evaluation iteration consists of an exemplary application of the DSCM² in a company as a test case to evaluate the model´s content, structure, applicability, and generalizability. The manufacturing company “Aero company” (pseudonym due to confidentiality reasons), with headquarters in Germany, has around 350 employees and manufactures aircraft parts. During the test case, the researchers use several sources to gather data about the supply chain´s maturity and triangulate it. Two employees complete the assessment questions in the online assessment tool, and the researchers supervise and observe. Overall, the participants agree on the maturity scores and confirm the model´s applicability. Yet, minor issues are revealed. For example, during the assessment, the employees sometimes struggle to decide for either yes or no in the answers. The results of the maturity model application are shown in Fig. 6 and discussed in the following. Overall, most subdimensions of the Aero company´s supply chain maturity are assessed between the second and third maturity level (initial and defined supply chain digitalization). However, when analyzing the assessment results, we observe some peculiarities. First, the most mature subdimension is cybersecurity (level 5). Not only are rules and policies for data access strictly defined, but there are also advanced security mechanisms in place, mostly established network-wide. The need for high-security standards stems from the industry in which the Aero company operates: It requires applying existing cyber security best practices. This also became clear in observations and talks with employees, who all point out the strict security specifications issued by the Aviation Federal Office and other important players. Interestingly, similar findings are presented by Caiado et al. in their research paper [16]. The second most mature subdimension of the Aero company is culture development (level 4). The employees emphasize the open culture of communication, especially inside the company. Large internal projects, for example, require co-determination by the works council so that employees are involved in decisions. But also business partners are included, and, e.g., risks that arise with the digitalization are openly addressed. Third, lagging on Level 1 are subdimensions like digital portfolio, customer experience, and smart objects. Regarding the digital portfolio, the Aero company´s product range is business-to-business, strongly project-based, and characterized by small series or prototypes. The company regularly examines the market but currently has no plans to move into services such as, e.g., advanced predictive maintenance. This is surprising as the strong customer focus and meeting customer requirements are especially important in "build to order" industries. This gap was also identified by the researchers on-site. A similar picture emerges when examining the customer experience subdimension. According to the interviewed employees, the product range and the company´s position in the supply chain make it less interesting to implement digital touchpoints or additional channels, such as a mobile app. However, exploring how to partly integrate the customer in some process steps of the production seems promising to them. Lastly, the assessment revealed that the subdimension of smart objects is also on the first level as smart objects are neither in use at the moment nor are pilot projects carried out. This was also confirmed when visiting the production facilities.

The evaluation iterations so far corroborate the model´s general applicability. Several minor improvements were already incorporated into the model during the four evaluation iterations. However, some limitations of the model remain. The results of the evaluation are discussed in the following. First, the test case shows that it would be beneficial to include adaptation options, e.g., leaving out subdimensions that are irrelevant to the assessed company and its supply chain. In the Aero company's test case, the customer experience subdimension was not considered relevant. With the current model setup, it is possible to leave out certain subdimensions. However, this was not tested. Instead of excluding the subdimension altogether, another approach could be to reduce the weighting of a subdimension. By still considering the subdimension, it might deliver useful ideas for improvement without distorting the overall maturity result. Following the line

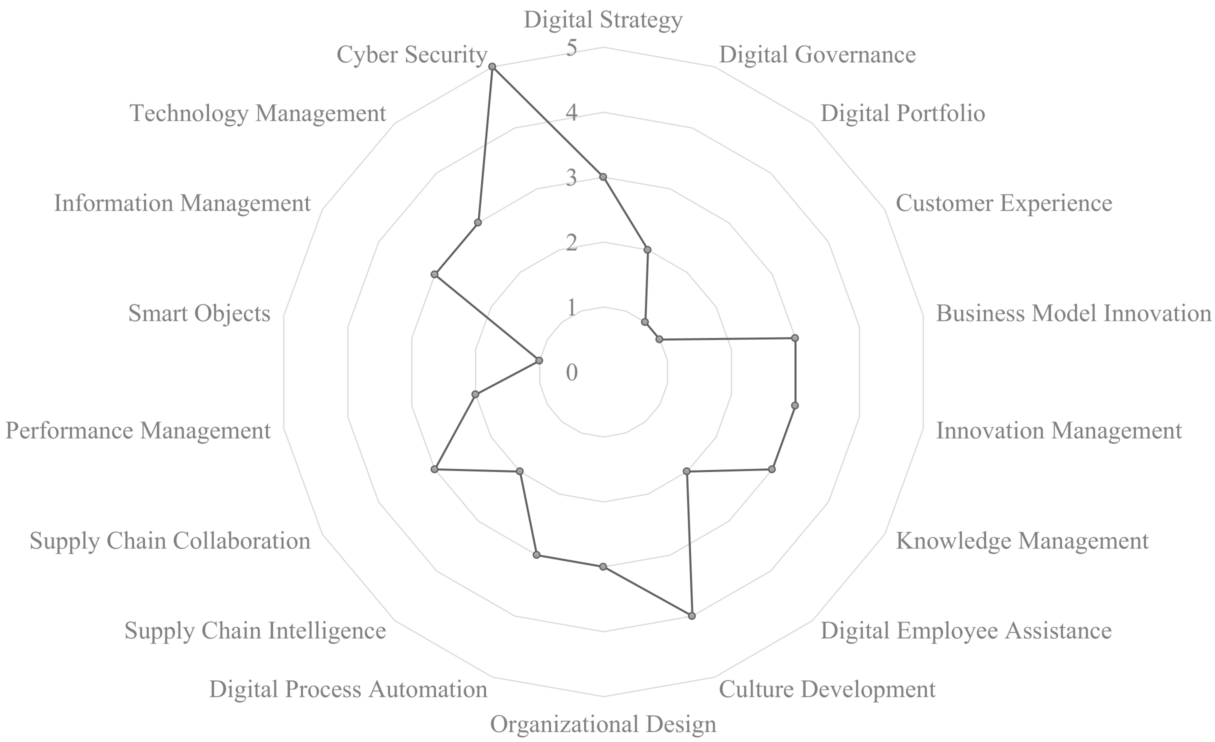

Fig. 6: Assessment results at the company Aero

of thought for testing and exploring the applicability of the model, another reasonable next step for researchers could be to extend the model into a comparative model. The Aero company was interested in the results achieved by other assessments. Therefore, applying the DSCM² to more companies and measuring their current degree of digitalization in their supply chains could lead to interesting insights. A large-scale application would be a challenging but promising endeavor. During the test case, it became apparent that the assessment method comes with certain limitations. We are aware that the design of the online self-assessment tool with binary answer options (yes or no questions) poses a risk of oversimplifying the assessment. In the test case, two participants filled out the assessment questions together. On the one hand, they sometimes struggled to decide on one answer option. On the other hand, they appreciated the ease of use of the tool, and they pointed out that the discussion to reach an agreement on either yes or no was very helpful. They had to deliver arguments and reflect on the current maturity instead of just compromising and "meeting in the middle" on a scale. Furthermore, the evaluations revealed that identifying one employee knowledgeable enough to answer the whole questionnaire with the different topics in detail is challenging. In the workshop, this did not pose a problem. Yet, this could be because employees do not want to openly admit their shortage of knowledge, as this might be regarded as unprofessional. Uninformed, biased, or estimated answers to the questions might further distort the results [83]. The workshop participants propose to develop guidelines answering questions like "Who should fill out the self-assessment (e.g., position in the company)?". They also recommend forming small teams to complement each other´s knowledge. Tackling this challenge from a more encompassing point of view is the idea of implementation guidelines for the maturity model. Most practitioners realized the value of the maturity assessment and appreciated the self-assessment method. Yet, some practitioners expressed the need for further guidance, e.g., what to do with the results. This is promising future research and recently expressed by researchers who "recommend formulating implementation guidelines that describe how exactly to apply the model, how to structure the learning, and what resources are needed to do this effectively so that a [maturity model] unfolds practical value" [84].

Finally, we openly want to address the challenge of a thorough and in-depth evaluation of a complete and encompassing maturity model like the DSCM². The level of detail with five levels, 18 subdimensions, and corresponding maturity characteristics for each combination make it very complex. We counteract the frequently voiced criticism that maturity models are often weakly evaluated by applying a multimethod evaluation approach to gather feedback and iteratively improve the model. However, the timeframes for the interviews, group discussions, workshops, and test case are restricted (ranging from 45 to 90 minutes). Discussing and evaluating every detail of the DSCM² was not possible. Even though the resulting discussions were fruitful, the evaluation remains limited in scope, and we strongly recommend further evaluation rounds. More ideas regarding this are discussed in the following chapter.

6 DISCUSSION AND CONCLUSION

6.1 General Discussion and Implications for Future Research

This paper contributes in several ways to researchers and practitioners. It is briefly discussed how far the requirements presented in Figure 1 (Chapter 2.2) are fulfilled. First, the DSCM² focuses on the intersection of supply chain management and digitalization (requirements #1 and #2), covering all aspects presented in Table 3. Also, the level of detail is high (see Table 7 to Table 10 in the appendix) because characteristics are presented for each subdimension and level (requirement #3). Furthermore, the clarity of the model´s structure is underlined with overviews regarding the model´s content, assessment method, and assessment path (requirement #4). The clear structure also has the advantage that the subdimensions can be weighted individually or left out if the user requests. Thus, the DSCM² meets the adaptability requirement (#7). Furthermore, the paper delivers a methodologically rigorously developed maturity model for digital supply chains, including an assessment model, by following Becker et al.´s development steps (see Figure 2) and thus fulfilling requirement #5. The DSCM² is evaluated and refined in several iterations with experts from industry and academia, addressing and fulfilling requirement #6. Generally, the provided feedback is positive: the model is considered complete, comprehensive, and well-described. In addition, the application of the DSCM² shows its applicability in practice. Also, the assessment is structured comprehensively and easy to understand, achieving requirement #8 satisfactorily. Regarding completing the final requirement, to offer guidance for improvement (#9), the authors remain skeptical. One can argue that a descriptive maturity model already supports companies by pointing out their weak spots and presenting higher levels for increasing maturity. However, higher maturity levels are only depicted without action plans or guidelines how to increase the maturity. Summarizing, requirements #1-#8 are achieved by the DSCM², while the final requirement (#9) is only partly fulfilled.

This research is not without limitations, and some shortcomings and ideas for further research are discussed in the following. Until now, four evaluation iterations have been conducted. Following the iterative procedure, further adaptations that should be incorporated into the model might arise in upcoming evaluations. Some subdimensions might benefit from further clarification and a more detailed explanation of the content and operationalizations. For example, regarding the knowledge management subdimension, the focus is on how the skillset development and education system along the supply chain is organized, remaining rather vague on what exactly the skillset entails. More information can be added with more (in-depth) research. Therefore, the maturity model is a work-in-process. Adding to this point, most maturity models constantly need to be (re-) evaluated and, if necessary, updated. New technologies, changing conditions, or new research insights might compromise its long-term applicability [44]. Therefore, a valuable contribution in the future can be to design and implement a process to supervise and conduct regular updates to the model.

Regarding future research to evaluate the model, plenty of options and different formats are envisioned. One option is to conduct more in-depth expert interviews. In our research, the interviews proved to be a helpful and target-oriented method and should be continued in a greater number. Also, specific experts for certain dimensions could be contacted and interviewed only in their area of expertise. Furthermore, interviewees from different industries (e.g., consultancies, manufacturing industry) should be included to provide viewpoints from different perspectives. This would especially target the question of the general applicability of the model in different industries, company sizes, etc. Other options for further evaluations are focus group discussions. Depending on the evaluation goal, they could take place with or without the application of the self-assessment tool. Another option suggested in the literature is to make the assessment model available as a free web-based self-assessment. Thus, a larger number of participants can be achieved, and the results can be compared [44]. However, more test cases or even longitudinal studies are promising to get a more detailed understanding of the maturity of specific company supply chains.

Currently, the DSCM² is a descriptive model that depicts the as-is state of supply chain digitalization. While the feedback from practitioners shows that determining the as-is state for these 18 subdimensions is an important starting point for the transformation, it is also mentioned that the model's value for companies and supply chains would increase significantly if the model also guided transforming the supply chain onto the next maturity level. For example, it could recommend potential digitalization initiatives to be conducted or technologies and procedures to be implemented for reaching the next maturity level in each subdimension following the assessment. This targets the final requirement (guidance for improvement #9) completion. Therefore, further research could extend the DSCM² into a prescriptive maturity model, primarily assessing the as-is state and recommending targeted transformation initiatives for reaching the consecutive maturity level. Another suggestion for future research is to depict which quantitative benefits are realized on each level and for each subdimension, for instance, the percentual increase in customer satisfaction.

The discussion of providing guidance for increasing the current maturity level of a company raises the question of what maturity level should be the target. Literature warns against blindly targeting the highest maturity levels in all dimensions: Companies should rather critically reflect and consider their specific supply chain setup, their strategy, objects, as well as costs and benefits [48, 53, 85]. A procedure for the descriptive and prescriptive model application and the following road map formulation seems to be a promising avenue for future research [85].

A limitation is the structure of the model, centered on one company. Supply chains are complex constructs, including all levels of suppliers and customers, and their digitalization degrees would result in an extremely extensive assessment. Therefore, we limited our research and decided to focus on the company and move upstream or downstream according to their point of view. However, to gain a complete overview of the supply chain, the companies´ suppliers and customers (at least the first tiers) should be included in the assessment. In the test case, the experts preferred a more differentiated view between external and internal integration in the assessment and the whole model. They also explained that they could see a difference between upstream and downstream collaboration in their supply chain, which is currently not pictured in detail by the maturity model. This raises the question if one assessment questionnaire would be sufficient for the different supply chain parties or if different questionnaires need to be developed, targeting to measure the same constructs from different angles. In this regard, correlations between the maturity levels within one supply chain would provide interesting research opportunities.

6.2 Conclusion

This paper aims to answer the presented research question of how to assess and depict the current state of a company´s supply chain regarding its digitalization by using a maturity model. The analysis of the literature shows that there is a lack of maturity models addressing this. Deficiencies in existing models are (among others) the weak methodological descriptions of the development, the insufficient consideration of all digitalization dimensions, and an insufficient level of detail. This finding stresses the need for developing a new maturity model capable of assessing all aspects of digital supply chains. Also, from the practitioners´ side, a maturity model is perceived as a valuable tool to provide a starting point to structure the challenging and complex process of digitalization. High failure rates of digitalization projects underline the necessity to provide support and guidance.

Targeting the first research question, we use the identified models to filter out the key dimensions and levels of digital supply chains with inductive and deductive qualitative research approaches. Building on this, we develop the DSCM² with four dimensions, further detailed into 18 subdimensions and respective maturity characteristics for each level, thereby answering the second research question. Followingly, we implement an assessment model with respective assessment questions for an online self-assessment tool in research question three. Several evaluation iterations, e.g., expert interviews and group discussions, lead to interesting insights and modifications of the model. The experts generally confirm the correct, consistent, and complete representation of the topic area. Furthermore, the applicability of the model is underlined with a test case.

To conclude, the designed DSCM² can currently support a company in assessing the maturity degree (as-is) of digitalization in its supply chain. In addition, it provides a beneficial starting point for guiding its further digitalization. Yet, more evaluation cycles are necessary to shape the model further and include updated information to improve the model. From a managerial perspective, the model represents a valuable tool that determines the current state of a supply chain so that digitalization initiatives, roadmaps, or entire strategies being targeted to the specific supply chain can be derived. Moreover, the model presents insights into development opportunities towards achieving higher maturity degrees. For researchers, it offers an important foundation for further research. For instance, the DSCM² can be utilized as a foundation for developing a more specific industry-focused maturity model of digital supply chains. In addition, the theoretical background and the subdimensions of the model depict essential building blocks of digital supply chains. Thus, this paper accomplishes a better understanding of digitalizing supply chains and digitalization in general for further academic discussion and practical application.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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APPENDIX A.

Table 4: Subdimension digital strategy and elements incorporated from literature

Authors	Digital Strategy
Bibby & Dehe	Strategy: Importance of **robust and clear strategy** development; Creating an ambitious and well thought out **technology investment plan;** Have an **agility vision**
Buntak et al.	Creation of new business paradigms: Each organization has created **new paradigms of business**, and started creating synergy within the organization
Chaopaisarn & Woschank	Strategy: **Strategy creation and development** to strategically implement I4.0 and **increase data usage;** I4.0 strategy development and **investments**
Çınar et al.	Management 4.0: Structural characteristics and the **internal/external dynamics** of the organization; Identification phase of the objectives to be achieved to **determine a roadmap** to integrate innovative strategies (incl. company's potential for **competitiveness** in the market); **Investment plan** and strategy 4.0
Ehrensperger et al.	Every involved enterprise has transparency on[...] **business models**, and the **strategy of partner-enterprises**
Facchini et al.	Management: **Strategy and Leadership; Investment** decisions; Strategy formulation in regard to **integration of value chain parts**
Frederico et al.	Managerial capability supporters: **Leadership support** regarding transformation initiatives; **Awareness** of the transformation; Creation of a **strategic vision**, **communication** of it and compliance to it Strategic outcomes: Customer focus; **Derive strategic impacts** to be expected from SC4.0 and how to realize them
Klötzer & Pflaum	Strategy Development: Development of **roadmaps** for digitalization; Focus on **integrative strategy; Data-driven strategy** development and management Structural Organization: **Management promotion** regarding digitalization strategy
Krowas & Riedel	Intellectual capital: Holistic, **socio-technical perspective** as a strategic
Methavitakul & Santiteerakul	Strategy: Creation and implementation of I4.0 **roadmap;** Available **resources** for realization; **Investment** (plans) Leadership: **Willingness of leaders;** Management of competencies and method; Existence of a **central coordination** for I4.0; Utilization of **customer data**
Wagire et al.	Industry 4.0 awareness: **Familiarity** with the topic; **Sensitivity** towards the impact of digital transformations; **Usefulness** of I4.0 to company; **Preparedness** for I4.0 adoption Organizational strategy: **Digital vision and roadmap;** Financial **investment**
Ward et al.	Product: Development of **market intelligence** and deduction of product **concept and strategy, Financial** viability
Weerabahu et al.	Strategic DMSC planning and **road mapping**

APPENDIX B.

Table 5: Details on evaluation participants

Type of Evaluation	Participants	Position	Years of experience	Duration [min]	Generated results of evaluation and improvement
Interview 1	Expert interviewee 1	Head of SCM, technology, and innovation	13	60	*Mitigation of overlaps in dimensions and measures of the model *Addition of benefits to general level descriptions and subdimensions´ characteristics *Reformulation of misleading terms and unification
Interview 2	Expert interviewee 2	SCM consultant with a focus on digitalization and artificial intelligence	15	90	*Mitigation of overlaps in dimensions and measures of the model (e.g., merging two subdimensions into technology management) *Renaming of subdimensions to clarify content (e.g., digital portfolio instead of digital products) *Addition of details and prescriptive characteristics helpful
Group discussion on conference	Discussion participants (8)	International professors and researchers with information systems, supply chain management or engineering background	mixed	45	*Improvement of research methodology description and development steps of levels and subdimensions (e.g., what references are used to create what subdimensions) *More testing and evaluation plan necessary to ensure replicability and robustness also across different industries/company-sized etc. (future research ideas)
Workshop with assessment application	Workshop participants (7)	Practitioners from different companies with supply chain management and engineering background	mixed	45	*Provision and specification of requirements for person filling out the assessment questions necessary *Addition of examples and identification of industrial practices (e.g., regarding supply chain intelligence subdimension) *Refinement of assessment method
Test case with interviews	Practitioner 1	Project manager	18	90	*Strengthening the supply chain reference and including more refined measures for upstream and downstream partners along the chain *Description of implementation plan necessary and how to analyze and use the results of the assessment model *Limitations of binary answers
	Practitioner 2	Head of IT and IS	19		

APPENDIX C.

Table 6: Analysis excerpt of maturity models related to supply chain digitalization

Authors	# of Levels	# of Dimensions	Dimensions	# of Subdimensions
Asdecker & Felch	5	5	1. Order processing 2. Warehousing 3. Shipping	n.a.
Bibby & Dehe	4	3	1. Factory of the future 2. People and culture 3. Strategy	13
Buntak et al.	6	5	1. Conduction of digital transformation 2. Communication in organization and in supply chain 3. Creation of new business paradigms 4. Synergy in organization and in SC 5. New technologies	n.a.
Caiado et al.	5	3	1. Supply chain management 2. Supply chain management and POM (common) 3. POM	7
Chaopaisarn & Woschank	5	6	1. Strategy 2. Customer 3. Product 4. Operation 5. People 6. Technology	18
Çınar et al.	5	4	1. Factory 4.0 2. Logistics 4.0 3. Operator 4.0 4. Management 4.0	32
De Carolis et al.	5	5	1. Process 2. Monitoring & Control 3. Technology 4. Organization	n.a.
Ehrensperger et al.	5	7	1. Transparency 2. Governance 3. Expandability 4. Cybersecurity 5. Knowledge base 6. Reusability 7. Standardization	n.a.
Facchini et al.	5	3	1. Management 2. Flow of material 3. Flow of information	7
Frederico et al.	4	4	1. Managerial and capability supporters 2. Technology levers 3. Process performance requirements 4. Strategic outcomes	21
García-Reyes et al.	6	n.a.	n.a.	n.a.

Table 6 (continued): Analysis excerpt of maturity models related to supply chain digitalization

Klötzer & Pflaum	5	9	1. Strategy development 2. Offering to the customer 3. Smart product / smart factory 4. Complementary IT system 5. Cooperation 6. Structural organization 7. Process organization 8. Competencies 9. Innovation culture	9
Krowas & Riedel	5	4	1. Data 2. Communication 3. Processes 4. Intellectual capital	12
Methavitakul & Santiteerakul	n.a.	7	1. Strategy 2. Technology 3. Manufacturing and Operation 4. Supply Chain 5. Employee 6. Product 7. Customer	31
Plomp & Batenburg	4	2	1. Technological dimension 2. Organizational dimension	n.a.
Vasconcellos et al.	6	6	1. Strategy, organizational sturcture and culture 2. Workforce 3. Smart factories 4. Smart processes 5. Smart products and services 6. Technology	19
Wagire et al.	4	7	1. People and culture 2. Industry 4.0 awareness 3. Organizational strategy 4. Value chain and processes 5. Smart manufacturing and technology 6. Product and services oriented technology 7. Industry 4.0 base technology	38
Ward et al.	5	3	1. Technology 2. Supply Chain 3. Product	17
Weerabahu et al.	3	5	1. Industry 4.0 enabled integrated processes 2. Technological innovations 3. Stakeholder and legal conditions 4. Sustainable practices 5. Human capital	n.a.
Werner-Lewandowska & Kosacka-O.	6	n.a.	n.a.	n.a.
Zoubek & Simon	6	5	1. Manipulation 2. Storage 3. Supply 4. Packaging 5. Material identification	14

APPENDIX D.

Table 7: Subdimensions and levels of business digitalization

Level	Digital Strategy	Digital Governance	Digital Portfolio
1	• No digitalization or digital SC agenda • Awareness of digitalization importance on top management level	• No digitalization governance • Awareness of governance importance on top management level	• Portfolio comprises only physical products or services • Awareness for enhancing products digitally or offering digital services
2	• First isolated and reactive allocation of processes, resources, and investments regarding digitalization strategy within company • Emerging but limited managerial support and sponsorship	• First isolated and reactive processes, resources, and mechanisms regarding digitalization governance within company • Basic, unsystematic governance principles and policies applied in isolated manner	• Basic digital enhancement of portfolio, for instance: • Simple digital services and/or • Combinations of physical products with digital services and/or • Prototypes of smart products collecting and reporting data
3	• Digital transformation roadmap designed and realized for focus company and key partners • Unsystematic evaluation of digitalization performance based on defined indicators	• Basic digitalization governance defined and established comprising simple processes, steering structures, policies, and principles • Digitalization governance mechanisms and structures established within company and key partners	• Definition and realization of digitalized portfolio, comprising for instance: • Smart products capable of processing data and offering simple digital services and/or • Sophisticated digital services • Utilization of generated and analyzed service and/or product data for design process
4	• Integrative digital SC strategy and management practices for entire SC designed and implemented • Systematic measurement of digitalization indicators for transformation performance • Strategy development, implementation, and evaluation is analytics-driven	• Systematic governance function for entire digital SC • Digital SC governance addresses digitalization as well as all business areas • Analytics-driven execution and evaluation of governance	• Systematic digital portfolio management based on collected and analyzed information • Portfolio largely digitalized • Portfolio comprising sophisticated smart products and/or services capable of real-time data analysis and adjustment • Shift of focus towards offering solutions-as-a-Service
5	• Best practices implemented regarding digital SC strategy and management achieving highest effectiveness • Digital SC strategy regarded as prime business driver • Digital SC strategy automatically evaluated and optimized by SC intelligence	• Best practices ensuring most effective and efficient digital SC governance • Governance function automatically executed and evaluated based on SC intelligence	• Best practices regarding digital portfolio implemented • Offering of highly sophisticated smart products or services being able to adjust to specific customer autonomously and dynamically based on context-awareness

Table 7 (continued): Subdimensions and levels of business digitalization

Level	Customer Experience	Innovation Management	Business Model Innovation
1	• No consideration of customer experience • Customer-related data not collected deliberately and stored in silos	• No deliberate achievement of innovations • Innovation activities if existing only related to products or services	• Traditional business model without any digital facets
2	• First basic initiatives for offering consistent customer experiences based on data and technology • Simple digital touchpoints established • Limited informing of customer	• Unsystematic and non-standardized processes for achieving innovation • Instead: Isolated, spontaneous pilot projects by local departments in innovation-related areas	• Unsystematic and non-standardized processes for digitalizing business model of company • Integration of basic, isolated digital solutions into selected areas of business model
3	• Consistent, digitally enhanced customer experiences designed and established based on simple digital touchpoints and channels • Digital touchpoints and channels integrated to some extent • Increased informing of customer and basic integration of key customers	• Basic innovation processes and units defined and established within company and key partners • Major focus on product/service and technology innovation	• Basic business model digitalization processes defined and established for company and key partners • Selected areas of the business model digitalized • Digital solutions tested for each area of business model
4	• Systematic, analytics-driven management of digital customer experiences for SC • Customer experience individualized based on detailed customer profiles or micro-segments • Real-time information sharing and collaboration with customers • Customer centricity established as major driver of SC	• Systematic, analytics-driven innovation management implemented within entire SC • Systematic measurement of innovation performance • Innovation covering all business areas	• Systematic, analytics-driven business model innovation function implemented within SC • Business model completely digitalized • Business model is data- and service-oriented
5	• Customer-centric best practices implemented within entire SC • Customer experiences exceptional and highly individualized based on customer profiles of highest granularity	• Best practices for innovation management implemented throughout the SC • SC acknowledged as innovation leader • Proactive innovation management based on SC intelligence	• Best practices implemented regarding business model innovation • Business model highly disruptive and adaptive • Proactive business model innovation enabled by SC intelligence

Table 8: Subdimensions and levels of organizational digitalization

Level	Knowledge Management	Digital Employee Assistance	Culture Development	Organizational Design
1	• No relevance of skills and competencies regarding the digitalization	• No consideration of technological support of employees	• Culture not open to digitalization or innovation • No fast-failure culture • No intra-organizational trust but silo- thinking	• No specific roles, responsibilities, or units regarding digital SCs
2	• Starting awareness for skillsets required regarding digitalization and technologies • Acquisition of first methodological, technology-related skills by company • Basic, unsystematic education of selected employees regarding digitalization knowledge	• Non-systematic, ad hoc usage of technology for supporting employees in executing tasks • Testing of mobile technologies by individual employees	• Digitally open mindset partially brought into company by hired employees, but culture largely innovation-opposing • Intra-organizational trust only in cooperating departments • No transparency of digitalization impact and risks by company	• Adjustment of IT and R&D department of company for digitalization • Allocation of basic digitalization or innovation tasks to established roles and units of company
3	• Required methodolog. and transformational skills regarding digitalization, SCM, analytics, and innovation defined • Skill acquisition and development process defined and implemented within company and key partners • Development of managerial digitalization skills for company and key partners	• Use cases defined for technological employee assistance • Application of mobile technologies for selected areas and processes of company and key partners • Pilot initiatives regarding the assistance through advanced technological solutions with focus on AR, smart objects, and systems	• Design, communication, and partial establishment of cultural identity for company and key partners • Cultural identity comprises fast-failure thinking, openness towards innovation, and inter-organizational trust • Partial communication of impact and risks of digitalization and related support for employees	• New roles and responsibilities defined regarding digital transformation, analytics, and innovation within departments of company and key partners • First initiatives for increasing the flexibility of work practices and structures within selected areas of company and key partners
4	• Analytics-driven systematic knowledge management and employee development function within entire SC • Interdisciplinary mindsets established within entire SC • Methodological and transformational skills and mindsets regarding digital supply chains established within entire SC	• Systematic deployment of digital technologies and AR within entire SC • Employee support by technology-enabled smart services integrated into entire SC • Automated assistance by smart objects and systems comprising target-oriented information provision	• Systematic management of cultural identity within entire SC • Dynamic, digital, and innovative cultural identity featuring high inter-organizational trust established within entire SC • Total transparency about impact and risks of digitalization within SC including extensive associated support of employees	• Functional units dedicated to digital SCs and related areas defined and established for entire SC • Management roles dedicated to digital SCs and related areas defined and adjusted for entire SC • Realization and systematic management of agile SC structure and organization capable of dynamic adjustment and innovation support
5	• Best practices for knowledge management and employee development implemented in SC • Cutting-edge skills regarding all aspects of digital SC on each level	• Best practices implemented for digital assistance of employees • Assistance entirely automated and performed autonomously by smart objects and the SC intelligence	• Best practices realized regarding cultural development • SC identity established and serving as a prerequisite for new partners or employees	• Organizational best practices implemented within SC • Highly adaptive SC structures and organization • Management roles and units tailored for constant innovation

Table 9: Subdimensions and levels of process & method digitalization

Level	Digital Process Automation	Supply Chain Intelligence	Supply Chain Collaboration	Performance Management
1	• No process documentation or standardization • Electronic process support if available only rudimentary, undocumented, and ad hoc	• No systematic or data-driven decision making • Analytics of minor importance	• Collaboration and information sharing with external partners perceived as risk • Sporadic internal collaboration and information sharing	• No efforts regarding performance measurement
2	• Local pilot projects initiated regarding digital support of processes within company • Documentation of processes	• Decision making largely based on gut- feeling and simple reports • First data analysis implementations tested for decision support within company	• Increased internal collaboration and information sharing • Ad hoc collaboration and information sharing with key partners on a basic level • Outsourcing of simple unimportant resources, services, and processes	• Basic, unsystematic, and undocumented measurement of process data within company • No utilization of performance information for process improvement
3	• Business and SC processes defined and standardized within company and key partners • Digitalization of basic, isolated processes within company and key partners • Pilot projects for utilizing emerging technologies for process improvement within company and key partners	• Defined analysis processes and techniques for application within company and key partners • Data-driven decision making established in selected areas of company and key partners • Pilot implementations of advanced analytics and AI solutions for decision support for management level of company and key partners	• High level of internal collaboration and information sharing • Increased provision of information to key partners and integration of service or technology providers • Collaboration practices plus plans defined and integrated • Prototype implementations of advanced collaboration practices with selected key partners	• Defined performance measurement processes, indicators, and goals for company and key partners • Increased measurement and adjustment of processes based on indicators for company and key partners • Initial integration of digital technologies for supporting performance measurement
4	• Systematic, analytics-driven management regarding process digitalization and optimization for entire SC • Majority of processes digitalized and automated within SC • End-to-end automation of SC not achieved and human decision making required for important processes	• Pervasive analytics-driven decision making support close to real-time within entire SC • Application of advanced analytics and AI in majority of SC functions focusing on the predicting of future scenarios for improving the decision quality • Self-learning functionality increasingly implemented into systems, smart objects, and technologies for decision support	• Systematic, analytics-driven management of dynamic partner network allowing quick integration of new providers or partners • Automatic real-time information sharing within entire SC • Systematic deployment of advanced collaboration practices on all levels	• Automated systematic performance measurement based on digital technologies within entire SC • Real-time visibility and synchronization of physical plus information flow throughout entire SC realized • Proactive management of processes based on performance analyses and predictions
5	• Best practices implemented regarding SC process management • SC processes end-to-end digitalized, automated, and optimized • SC intelligence enables autonomous process execution and continuous adjustment	• Analytical best practices implemented within entire SC • SC characterized as intelligent being capable of autonomous decision making and self-learning in real-time	• Best practices realized regarding SC collaboration • SC highly flexible allowing dynamic partner integration close to real- time • SC intelligence automatically optimizes network close to real-time	• Best practices regarding performance management implemented within entire SC • Fully digitalized and automated performance measurement of SC • SC intelligence enables proactive real-time process optimization

Table 10: Subdimensions and levels of technological digitalization

Level	Smart Objects	Information Management	Technology Management	Cyber Security
1	• No application of smart objects • Emerging awareness of smart object use cases	• No data management or related activities • If data collected, only basic information being stored in silos • Data collection and provision performed manually	• No deliberate technology management • Technological infrastructure consists of inflexible legacy systems • Technology and architecture not suitable for digitalization	• No awareness of cyber security or related risks
2	• Local pilot initiatives and prototypical application within focus company • Smart objects equipped with functionalities for data gathering and reporting • Identification of additional use cases	• Collection of increased amount of data, but performed manually • Still large data silos • Unsystematic, manual sharing of data within company	• Technology-related processes based on local, isolated initiatives of company • Adjustment of interfaces for pilot projects regarding smart objects within the company • Enterprise systems not connected, only supporting single areas	• Awareness of cyber security risks within company • Reactive, isolated, and sporadic implementations of simple security means within company
3	• Smart object application within various SC processes and levels • Smart objects connected within respective functional areas • Focus on adding functionality for data processing and execution of simple tasks	• Basic data standards and processes defined for company and key partners • Increased automation of data collection and sharing based on connected enterprise systems and technologies for company and key partners	• Technological prerequisites of digital SC identified, defined, and implemented • Technological architecture for digital SC designed and realized for company and key partners • Redesign of systems regarding connectivity and interoperation • Procurement of cloud-based business IT	• Policies and rules for data access and information defined for company and key partners • Advanced security mechanisms and technologies defined and implemented within company and key partners • High level of cyber security within company and key partners ensured to large extent
4	• Systematic management and pervasive integration of smart objects within entire SC • Smart objects combined to flexible service systems for automating entire processes • Smart objects embedded with analytical functionalities for decision making and performing complex tasks	• Systematic information management established within entire SC • Holistic data integration into single information management platform from various internal and external sources • Automation of data-related processes • Systematic data lifecycle and information quality governance defined and established	• Systematic, analytics-driven technology and architecture management within entire SC • Technological architecture allows dynamic and rapid integration of new partners, systems, and technologies • Service-oriented architecture realized within entire SC • Deployment of most advanced technologies and cloud-based operational platform for entire SC	• Integrative cyber security strategy and systematic security management throughout SC defined and implemented • Advanced cyber security technologies, mechanisms, and processes implemented within entire SC • High level of cyber security within entire SC ensured to large extent
5	• Best practices implemented regarding smart objects • Smart objects pervasively connected across entire SC automating end-to-end processes	• Best practices regarding information management and governance established within SC • Optimized and autonomous data provision by systems, technologies, and objects throughout SC	• Technological and architectural best practices implemented • SC characterized as technology leader having proactive innovation-focused technology management • Highly standardized, flexible, and open architecture within SC allows instant integration of all systems, technologies, and partners	• Cyber security best practices implemented within entire SC • Cyber security and risks management proactively for entire SC based on SC intelligence • Achievement of highest security standards SC-wide

APPENDIX E.

Table 11: Assessment questions of DSCM² (ML= Maturity Level)

	#	Question	Yes	No
Digital strategy	1.1	Is a roadmap for the digital transformation implemented both, for the company and for key partners including some mechanisms for evaluating its performance?	1.2	1.6
	1.2	Do you have a digital supply chain strategy and management practices in place that integrate all partners?	1.3	ML=3
	1.3	Do you evaluate the strategy performance systematically and is the strategy development, implementation, and evaluation driven by analytics?	1.4	ML=3
	1.4	Are digital supply chain strategy and management best practices implemented allowing automatic evaluation and optimization of both aspects based on the supply chain intelligence?	1.5	ML=4
	1.5	Is the digital supply chain strategy your most important business driver?	ML=5	ML=4
	1.6	Are first isolated or reactive processes, resources, or investments allocated in the context of a digitalization strategy, which result from an initial sponsorship by the management?	ML=2	ML=1
Digital governance	2.1	Are basic digitalization governance mechanisms, processes, structures, or similar established for the company and key partners?	2.2	2.4
	2.2	Is a systematic, analytics-driven, and holistic governance function implemented for the entire supply chain?	2.3	ML=3
	2.3	Are governance best practices implemented and is it executed and evaluated automatically based on the supply chain intelligence?	ML=5	ML=4
	2.4	Are first basic initiatives in the context of digitalization governance conducted, including e.g. processes, mechanisms, policies, or rules?	ML=2	ML=1
Digital portfolio	3.1	Is a digitalized portfolio deliberately defined and realized comprising, for instance, smart products, digital services, or combinations?	3.2	3.6
	3.2	Are your (digital) products and/or services designed based on data collected about their utilization?	3.3	3.6
	3.3	Is there an analytics-driven function within your supply chain that manages the digital portfolio?	3.4	ML=3
	3.4	Is your portfolio majorly digitalized comprising sophisticated and digitalized products and/or services, which are offered as-a-Service?	3.5	ML=3
	3.5	Are best practices regarding the digital portfolio implemented and are your products and/or services able to adapt autonomously to their usage and specific customer?	ML=5	ML=4
	3.6	Are some aspects of the existing portfolio digital (-ized)?	ML=2	ML=1
Customer experience	4.1	Did you deliberately design and realize enhanced customer experiences based on digital touchpoints and channels, which are integrated to some extent?	4.2	4.6
	4.2	Are key customers integrated in some related processes and do you share relevant information with them?	4.3	4.6
	4.3	Are digital customer experiences systematically managed and individualized based on detailed analyses of the respective customer?	4.4	ML=3
	4.4	Is customer-centricity one of your important drivers and do you collaborate and share information with customers in real-time?	4.5	ML=3
	4.5	Are customer-centric best practices implemented within the entire supply chain enabling highly individualized and exceptional customer experiences?	ML=5	ML=4
	4.6	Do you conduct first initiatives for consistent customer experiences, implement digital touchpoints, and inform customers at least in some regards?	ML=2	ML=1

Innovation management	5.1	Did you and your key partners establish innovation-related processes and organizational units, which target product, service, and/or technology innovation?	5.2	5.4
	5.2	Is a systematic and analytics-driven innovation management function implemented and continuously measured for the supply chain covering widespread innovations in all business areas?	5.3	ML=3
	5.3	Is the supply chain considered as an innovation leader based on implemented best practices and proactive innovation management based on the supply chain intelligence?	ML=5	ML=4
	5.4	Do you conduct innovation-related processes, initiatives, or pilot projects at all?	ML=2	ML=1
Business model innovation	6.1	Did you and your key partners implement processes that focus on the digitalization of the business model allowing that some aspects of the model are already digitalized, while other aspects are tested for this purpose?	6.2	6.4
	6.2	Is a systematic, analytics-driven business model innovation function implemented for the supply chain resulting in a fully digitalized, data- and service-oriented business model?	6.3	ML=3
	6.3	Is your business model highly adaptive and disruptive based on implemented best practices as well as proactive business model innovation by the supply chain intelligence?	ML=5	ML=4
	6.4	Do you have processes in place that cover the digitalization of your business model, so that certain aspects of it are partially digitalized?	ML=2	ML=1
Knowledge management	7.1	Did you and your key partners define and implement a skill acquisition and development processes leading to employees as well as the management with required methodological and transformational skillsets?	7.2	7.5
	7.2	Is a systematic, analytics-driven function implemented covering the knowledge management and employee development for the entire supply chain?	7.3	ML=3
	7.3	Are the required methodological and transformational skillsets as well as interdisciplinary mindsets pervasively established within the entire supply chain?	7.4	ML=3
	7.4	Are best practices for knowledge management and employee development implemented ensuring the availability of cutting-edge skills throughout the entire supply chain?	ML=5	ML=4
	7.5	Did you acquire some employees with a skillset required for the digitalization and did you establish initial associated education initiatives?	ML=2	ML=1
Digital employee assistance	8.1	Did you and your key partners define use cases for the digital assistance of employees and do you apply mobile or advanced technologies in this regard?	8.2	8.5
	8.2	Are digital technologies and augmented reality solutions systematically applied for the assistance of employees?	8.3	ML=3
	8.3	Are your resources applied within the supply chain capable of providing information to your employees in a target-oriented manner and are smart services offered internally?	8.4	ML=
	8.4	Are best practices implemented throughout the supply chain resulting in employees being automatically supported by autonomous smart objects and the supply chain intelligence?	ML=5	ML=4
	8.5	Do you deploy any technological solution for assisting your employees and do your employees use mobile technologies?	ML=2	ML=1

Culture development	9.1	Did you and your key partners design and realize a cultural identity that is open to digital innovations as well as accepts failures as learning experiences while having inter-organizational trust?	9.2	9.6
	9.2	Do you and your key partners communicate risks and changes due to the digitalization at least partially and do you offer support to affected employees?	9.3	9.6
	9.3	Is a systematic management of the cultural identity for the entire supply chain established leading to a dynamic, digitally open, and failure accepting culture with high inter-organizational trust?	9.4	ML=3
	9.4	Is your supply chain completely transparent with risks and changes caused by the digitalization and do you support your affected employees comprehensively?	9.5	ML=3
	9.5	Are best practices implemented for cultural development and does your supply chain identity serves as a prerequisite for new partners or employees?	ML=5	ML=4
	9.6	Are some employees open to digitalization or innovation and are your departments trusting each other, for example, regarding sharing information or collaborating?	ML=2	ML=1
Organizational design	10.1	Did you and your key partners establish new roles and responsibilities dedicated to the subdomains of digitalization?	10.2	10.6
	10.2	Do you and your key partners conduct initiatives targeting an increased flexibility for selected work practices and structures?	10.3	10.6
	10.3	Are dedicated functional units and management roles established, which are concerned with the supply chain digitalization within each level and partner?	10.4	ML=3
	10.4	Is the supply chain structure and organization systematically managed leading to a high level of agility and ability to adjust dynamically?	10.5	ML=3
	10.5	Are organizational best practices implemented resulting in highly adaptive supply chain structure as well as organization and comprising units plus management roles dedicated towards digitalization and innovation?	ML=5	ML=4
	10.6	Are established roles and responsibilities of the IT and R&D departments adjusted with a focus on the (supply chain) digitalization?	ML=2	ML=1
Digital process automation	11.1	Did you and your key partners define and standardize existing processes, so that basic ones are digitalized while for other ones technological support is being tested?	11.2	11.5
	11.2	Is there a systematic, analytics-driven process management established within the entire supply chain leading to the digitalization and automation of the majority of processes?	11.3	ML=3
	11.3	Are all end-to-end processes of the supply chain digitalized, automated, and optimized?	11.4	ML=4
	11.4	Are process management best practices implemented, while processes are autonomously executed and adjusted by the supply chain intelligence?	ML=5	ML=4
	11.5	Do you document your processes and conduct pilot projects for supporting their execution digitally?	ML=2	ML=1
Supply chain intelligence	12.1	Do you and your key partners make decisions based on data and analytics as well as defined analysis processes and techniques?	12.2	12.6
	12.2	Do you and your key partners conduct pilot implementations of using advanced analytics and AI for supporting management decision making?	12.3	12.6
	12.3	Is analytics-driven decision making support implemented within your supply chain that is close to real-time and based on advanced predictive analytics as well as AI pervasively?	12.4	ML=3
	12.4	Are self-learning functionalities increasingly implemented into all systems, objects, and technologies within your supply chain for decision support?	12.5	ML=3

	12.5	Are analytics best practices implemented characterizing the supply chain as being intelligent and thus, capable of self-learning as well as making decisions autonomously in real-time?	ML=5	ML=4
	12.6	Do you support decision making with reports and do you test analytical solutions in that regard?	ML=2	ML=1
Supply chain collaboration	13.1	Is there a high level of internal information sharing and collaboration within your company?	13.2	13.7
	13.2	Is there a raising level of sharing information with key partners and do you increasingly integrate technology and/or service providers?	13.3	13.7
	13.3	Are collaboration practices and plans defined and established, while advanced collaboration practices are tested with key partners?	13.4	13.7
	13.4	Is a dynamic network of partners realized and systematically managed based on analytical insights that allows to integrate partners and/or providers quickly?	13.5	ML=3
	13.5	Is your supply chain characterized by automated information sharing in real-time and systematic deployment of advanced collaboration practices throughout the entire supply chain?	13.6	ML=3
	13.6	Are supply chain collaboration best practices implemented realizing a highly flexible integration of partners as well as an automated adjustment based on the supply chain intelligence close to real-time?	ML=5	ML=4
	13.7	Does your company feature a moderate level of internal collaboration and information sharing?	13.8	ML=1
	13.8	Does your company provide information to as well as collaborate with key partners sporadically and do you make use of outsourcing?	ML=2	ML=1
Performance management	14.1	Do you and your key partners measure the performance of processes based on defined associated procedures, indicators, and goals?	14.2	14.6
	14.2	Do you and your key partners increasingly apply digital technologies for measuring the performance and adjust processes based on these results?	14.3	14.6
	14.3	Is there an automated measurement of performance throughout the entire supply chain based on digital technologies, while advanced analytical solutions enable its proactive management?	14.4	ML=3
	14.4	Does this pervasive measurement realize real-time visibility of the entire supply chain?	14.5	ML=3
	14.5	Are best practices implemented leading to fully digitalized and automated performance management of the entire supply chain, while its intelligence enables the proactive optimization in real-time?	ML=5	ML=4
	14.6	Do you measure process data within your company even when it is not in a documented or standardized manner?	ML=2	ML=1
Smart objects	15.1	Do you apply connected smart objects within various processes and levels of the supply chain that are capable of collecting, processing, and providing data as well as executing simple tasks?	15.2	15.5
	15.2	Is there a systematic management and pervasive integration of smart objects within the entire supply chain that posses analytical functionalities for making decisions?	15.3	ML=3
	15.3	Are these smart objects combined to flexible service systems that can automate entire processes?	15.4	ML=3
	15.4	Are best practices implemented regarding pervasively applied and connected smart objects enabling automated end-to-end processes?	ML=5	ML=4
	15.5	Do you conduct pilot projects for deploying smart objects that can collect and report data while identifying more and more use cases?	ML=2	ML=1

Information management	16.1	Do you and your key partners define basic data standards and processes while automating the data collection and provision based on connected enterprise systems?	16.2	16.5
	16.2	Is there an information management function implemented into the supply chain including a systematic data lifecycle management and quality governance?	16.3	ML=3
	16.3	Does your supply chain feature automated data-related processes as well as an information management platform into which data is holistically integrated from all types of sources?	16.4	ML=3
	16.4	Are information management and governance best practices established within the supply chain resulting in an automated and optimized provision by all systems, technologies, and objects?	ML=5	ML=4
	16.5	Does your company collect data at least manually and unsystematically, while it is stored in silos?	ML=2	ML=1
Technology management	17.1	Did you and your key partners define and realize the technological architecture and infrastructure required for digital supply chains?	17.2	17.7
	17.2	Are systems redesigned for increasing the connectivity and interoperability and do you procure the business IT as-a-Service?	17.3	17.7
	17.3	Is there systematic, analytics-driven technology and architecture management implemented within the supply chain leading to the deployment of highly advanced technologies and cloud-based operations platforms?	17.4	ML=3
	17.4	Is a service-oriented architecture realized within the supply chain that allows to integrate new partners, systems, and technologies dynamically and rapidly?	17.5	ML=3
	17.5	Are technological and architectural best practices implemented, so that the supply chain is considered as a technology leader having a proactive and innovation-focused technology management?	17.6	ML=4
	17.6	Is the architecture implemented throughout the supply chain highly standardized, flexible, and open allowing an instant integration of new systems, technologies, and partners?	ML=5	ML=4
	17.7	Does your company conduct technology-related processes as well as pilot projects for adjusting enterprise systems to integrate applied smart objects?	ML=2	ML=1
Cyber security	18.1	Did you and your key partners establish policies and rules for data access as well as implement advanced security mechanisms and technologies ensuring a high level of cyber security?	18.2	18.5
	18.2	Is there an integrative cyber security strategy as well as cyber security management defined and implemented for the entire supply chain?	18.3	ML=3
	18.3	Are advanced cyber security mechanisms, technologies, and processes integrated into the entire supply chain ensuring a high level of cyber security for all partners and levels?	18.4	ML=3
	18.4	Are cyber security best practices implemented, so that this security as well as related risks are managed proactively based on the supply chain intelligence to ensure highest security standards for the entire supply chain?	ML=5	ML=4
	18.5	Is your company aware of cyber risks and are basic cyber security means implemented?	ML=2	ML=1