Framework for Quantitative Digitalization Measurement in Supply Chain Planning

Tim Lauer

Infineon Technologies AG

Technical University of Dortmund
Am Campeon 1-15
85579 Munich
E-Mail: tim.lauer@infineon.com

Maximilian Wolf

Infineon Technologies AG

Munich University of Applied Sciences
Lothstraße 64
80335 Munich
E-Mail: maxi.wolf5@t-online.de

Jörg Puchan

Munich School of Engineering and Management
Munich University of Applied Sciences
Lothstraße 64
80335 Munich
E-Mail: puchan@hm.edu

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ABSTRACT

Measurement is a central element for any effective management. The megatrend of digitalization enables new possibilities, but also requires research on its appropriate monitoring considering digital transformation. In supply chain planning, today's methods are mostly qualitative. Thus, this study analyzes how the impact of digitalization can be quantified scoped to this field of application.
Based on the literature streams supply chain planning performance measurement, digitalization assessment and digital technologies the authors develop a holistic framework for quantitative digitalization measurement (QDMF). The framework comprises three dimensions: 'Man', 'Technology', and 'Organization'. These itemize to 22 measurands specific to the context. The logic allows the comprehensive assessment of the effectiveness of digitalization projects and provides reliable, informative value for decision-making by the quantitative scaling. The framework is applied by conducting expert interviews for customization and data collection, whereon analytics calculates the measurands. In the end, experts interpret the results.
For verification and validation, the framework is deployed to the empirical use case of Infineon Technologies AG, Europe's largest semiconductor manufacturer. The study concludes that quantitative digitalization monitoring is promising and can deliver new insights for effective managerial decision-making. Obstacles as limited data availability and constrained explanatory power are investigated and provide options for further studies.

INTRODUCTION

Digitalization is an extensive megatrend that no longer affects only traditional IT companies, but rather transforms all industries and business segments (BMWi, 2019; Yoo *et al.*, 2010). Moreover for supply chain management, digitalization is an ongoing driver (Klötzer and Pflaum, 2017). Digitalization enables great potentials to increase efficiency, to improve productivity, to create new revenue streams, and to find new value adding opportunities (Kotarba, 2017). It is important to state, that digitalization goes beyond the conversion from analog to digital, it rather signifies the transformation of entire socio-technical structures (Yoo *et al.*, 2010). Nevertheless, proceeding digitalization poses major challenges to companies (Furmans and Wimmer, 2018). Thus, new management approaches are needed, to implement digitalization effectively. According to classical management literature, e.g. PDCA-cycle (Deming, 2000), and more specific management 4.0 literature, e.g. Dortmund Management Model (Furmans and Wimmer, 2018), the monitoring of digitalization projects, besides planning and implementation, constitute a key element. To measure the progress in these processes, digitalization has to be assessed. Recent literature discusses several assessment tools mainly introduced by research agencies, consulting companies, government organizations, and other interest groups. A metalevel of production surroundings often comprises the focus of these approaches (Klötzer and Pflaum, 2017). The models are limited in their scope, their qualitative assessment methods, and their scientific resilience and foundation. Supply chain management poses a suitable research area due to rare but raising attention in actual publications in this context. Moreover, the number of digital technologies and innovations is steadily and rapidly growing. For instance, artificial intelligence, machine learning or data mining are technologies promising to cope with the challenges of planning in volatile and competitive market environments (Panetta, 2018).
As deduction, further investigations into digitalization assessment in the direction of quantification might be promising for supply chain planning. As a result, the authors aimed at narrowing the research gap by dealing with the following research questions:

Reserarch Question 1: How can digitalization be quantified for supply chain planning processes?

Reserarch Question 2: How does the implementation of digital technologies affect digitalization measurement?

Therefore, in Chapter 2 the literature foundation is provided. Chapter 3 outlines the development of the framework and ends by summarizing the final approach. Chapter 4 discusses the use case validation. Finally, in Chapter 5 the authors draw conclusions and describe future enhancement options.

LITERATURE REVIEW

Embedding this research in its scientific context, the relevant literature streams are reviewed. This study is located in the field of application of supply chain planning with focus on measuring and monitoring. Hence, the first subchapter deals with classical metrics and measures in terms of planning. This extensive summary gives the foundation of the developed framework. Due to the purpose of quantifying digitalization, existing the assessments of digitalization are discussed. As this stream is one core element, the second subchapter is the most extensive and detailed one verifying the announced research gap as well. To consider a use cases oriented point of view the authors furthermore reviewed current digital technologies trends. Subsequently the framework conditions for the construction of a theoretical model can be set.

Performance Measurement in Supply Chain Planning

The recent literature regarding performance measurement in supply chain planning targets on the collection and development of indicators as well as the evaluation of indicator sets. Consequently, a huge number of performance measurement indicators and systems have been developed in the recent years.

Well-known review papers providing those performance measurement frameworks are Gunasekaran *et al.* (2001), Gunasekaran, Patel and McGaughey (2004) and Chae (2009). In-depth literature reviews like Gunasekaran and Kobu (2007), Shepherd and Günter (2011)) show that indicators are related to different contexts. Thus, the researchers differentiate indicators by their decision-making horizon (Gunasekaran *et al.*, 2001; Gunasekaran *et al.*, 2004), their financial base (Gunasekaran *et al.*, 2001), their measurement base (Shepherd and Günter, 2011), their measured supply chain goal (Shepherd and Günter, 2011) or their level of consideration (Chae, 2009).

Concisely, a huge number of performance measurands associated to the area of supply chain planning is identified. However, there is no connection between performance measurement and digitalization of supply chain planning yet. Consequently, the insights into the effects of digitalization in this functional area is limited.

Digitalization Assessment

Since the terms digitalization and industry 4.0 are strongly related especially in German-speaking countries (Furmans and Wimmer, 2018), both terms are taken into account in the literature research.

Regarding digitalization or industry 4.0 assessment, the analysis of literature shows that current research concentrates on maturity or readiness models. Whereas some others differentiate between both terms in practice these are used synonymously (Schumacher *et al.*, 2016). Within the recent years a vast number of these models have been developed by research institutes, consulting companies and other interest groups. The authors identified a list of models which is presented in Table 1.

Table 1: Digitalization Assessment Models

Model Name	Author, Date
Industry 4.0 Maturity Model	Schumacher *et al.*, 2019
Reifegradmodell Industrie 4.0	Schagerl *et al.*, 2016
360 Digital Maturity Assessment	Colli *et al.*, 2018
Acatech Industrie 4.0 Maturity Index	Schuh *et al.*, 2017
SIMMI 4.0	Leyh *et al.*, 2016
Impuls Industrie 4.0 Readiness Model	Lichtblau *et al.*, 2015
Industry 4.0 Reifegradmodell	Lanza *et al.*, 2016
Digital Index	Gruda *et al.*, 2016
The Connected Enterprise Maturity Model	Beadley, 2014
Industry 4.0 Maturity Model	Geissbauer *et al.*, 2016
APM Maturity Model (Asset Performance Management Maturity Model)	Dennis *et al.*, 2017
Digitalization Degree of Manufacturing Industry	Bogner *et al.*, 2016
Three stage maturity model	Ganzarain and Errasti, 2016
Industry 4.0 Maturity Model	Gökalp *et al.*, 2017
M2DDM (Maturity Model for Data Driven Manufacturing)	Weber *et al.*, 2017
Pathfinder i4.0	Innovationszentrum für Industrie 4.0, 2019
DREAMY (Digital REadiness Assessment MaturitY model)	Carolis *et al.*, 2017
The Digital Maturity Model 4.0	Gill and VanBoskirk, 2016
VTT Model for Digimaturity	Leino *et al.*, 2017
Digital Maturity Model	Berghaus and Back, 2016
Digitalization Maturity Model for the manufacturing sector	Canetta *et al.*, 2018

Five of these models are recognized as particular basis for this research work, selected by the evaluation of their scientific background and their level of delivered details. In the following sections a brief overview of these models is presented:

The 'Acatech Industrie 4.0 Maturity Index' (Schuh *et al.*, 2017; Zeller *et al.*, 2018) was introduced in 2017 by the National Academy of Science and Engineering (Acatech). It is a practice-oriented but scientifically grounded industry 4.0 assessment model dedicated to manufacturing industries. The emphasis of the model is on the evaluation of maturity on a business process level.

An application to sub-processes such as the supply chain planning is not proven. A questionnaire of around 600 questions evaluates indicators representing the digitalization assessment methodology. These indicators are based on the judgment of interviewees and therefore bears the risk of subjectivity. Hence, the eligibility of the model for the desired purpose, the digitalization monitoring of single processes and projects, is limited especially through its extensive scope, the unverified industry transferability and the lack of objectivity.

The 'Industry 4.0 Maturity Model' (Schumacher *et al.*, 2016; Schumacher *et al.*, 2019). publicized in 2016 and updated in 2019 was developed by the Fraunhofer Austria Research GmbH in cooperation with the Institute of Management Science at Vienna University of Technology. It constitutes a scientifically grounded maturity model with a validated applicability for manufacturing industries. The model focuses mainly on organizational aspects of digitalization. Assessment, therefore, is performed on a general company level. The scope of the model is limited to 65 questions for the maturity evaluation. Subjectively valued indicators in the form of a moderated self-assessment provide the evaluation basis. Consequently, the limited industry validation, the level of consideration, as well as the potential subjectivity in the assessment are an issue for the use as a monitoring tool for digitalization.

The 'Impuls Industrie 4.0 Readiness Model' (Lichtblau *et al.*, 2015), developed on behalf of VDMA's IMPULS foundation, was published in 2015. The authors review revealed that it is a scientifically well-grounded, widely used, valid readiness model in the mechanical and plant-engineering sector. Thereby, the model is designed to assess companies as a whole. The assessment is based on an online self-assessment relying on the subjective valuations of the assessors. However, there is no proof of applicability in other industries, the level of consideration is limited and there is a risk of subjectivity in the assessment. Subsequently it is not directly suitable for the desired purpose.

The 'Readiness Model for Industry 4.0' (Jodlbauer and Schagerl, 2016; Schagerl *et al.*, 2016). was developed in 2016 by Business Upper Austria – OÖ Wirtschaftsagentur in cooperation with the Institute for Intelligent Production at University of Applied Sciences Upper Austria. The approach targets on the assessment of industry 4.0 readiness and is not limited to a specific industry sector or application scope. Although the indicators are derived from literature, no detailed insight in the development methodology is given. The number or industry sectors of companies that have applied this model are unknown. The assessment is performed by structured interviews. Accordingly, even if the level of consideration and the wide application scope is eligible for the monitoring application, the model lacks on objectivity and on insights verifying the validity.

An examination of the previously presented models shows, none of the existing digitalization assessment models is particularly designed as monitoring tool for an operational sub-process level. Most approaches lack information on the value of improvement through their measurements based on an interval scale, for instance 'Acatech Industrie 4.0 Maturity Index', 'Industry 4.0 Maturity Model' and 'Impuls Industrie 4.0 Readiness Model'. The method of questioning, mainly judgmental based questions, of all reviewed models also bears the risk of subjectivity due to the personal views of the assessors. The scope of some models is too extensive for the use as a monitoring tool, e.g. 'Acatech Industrie 4.0 Maturity Index'. Regarding the results, most assessment models are not applicable for the evaluation of operational sub-processes such as the supply chain planning, as they target on a generalized meta-level of digitalization. In particular, just whole companies or overall business processes can be assessed. Solely the 'Readiness Model for Industry 4.0' is not limited to a specific assessment level. But as it lacks information about validity and applicability, none of the existing models is appropriate for the desired application.

Nevertheless, there is huge scientific foundation in the delimitation of digitalization characteristics within these models. Thus, they form an important basis for the suggested solution of this research paper.

Digital Technologies

This section summarizes the current state of research on digital technologies to set the framework conditions and derive structuring criteria for its development.

Digital Technologies can be defined as the entirety of technologies to generate, process, transmit, and use digital assets (Loebbecke, 2006). For instance, these include technologies such as artificial intelligence, machine learning or datamining technologies. Analyzing current technology trend overviews, for instance Gartner's hype cycle for emerging technologies 2018 (Panetta, 2018; Payne, 2016) or the Munich Re trend radar (Bonaty, 2018), indicates that digital technologies are in focus of recent research, fast and unpredictable emerging and unstructured in deployed methods and application fields. Looking into detail, a rough categorization of their targets can be drawn: improving the human-machine interaction (e.g. conversational interfaces), enhancing the acquisition of data (e.g. smart factory), connecting and integrating data and systems (IOT platform), advancing the analytics to support or automate decisions (advanced machine learning) and refining the production, the processes, the products and the services (e.g. location based services). Many of the in brackets mentioned technologies are associated with artificial intelligence (AI) and are expected to change current business models (McAfee and Daugherty, 2017). Concluding from the reviews and the categorization, there is a huge number of emerging digital technologies with potential impact on processes and business models.

In the field of supply chain planning the main challenges are to deal with uncertainty, ambiguity and the complexity (Böhnke *et al.*, 2017). Experience has shown, digital technologies such as advanced analytics enable to counteract these challenges and increase the planning performance. However, the literature review demonstrated that digital technologies are often discussed in more general. Detailed and comparable information on the precise impact of dedicated digital technologies especially on the supply chain planning are not in the focus of digital technology research yet. Therefore, the measurement of digitalization effect through a standardized framework adapted to the specific field of application opens up new opportunities. Furthermore, the literature review revealed that digital technologies can be structured by their purpose. To measure the effect of these technologies this structure can be applied to the technological structuring of the framework.

Findings

Summing up the literature review, a missing link between the performance measurement in supply chain planning and evaluating digitalization is identified. Furthermore, the existing digitalization assessments are not applicable as monitoring tools due to reasons of scope, risk of subjectivity, assessment level and of validity. There is a lack of research regarding the impact of technology implementation as representation of digitalization and performance. Thus, the authors develop a framework narrowing the identified research gap by combining the research fields of supply chain planning and digitalization assessment, fulfilling the requirements of monitoring and enabling impact monitoring of technology implementations.

QUANTITATIVE DIGITALIZATION MEASUREMENT FRAMEWORK (QDMF)

To fill the analyzed research gaps the authors developed a new framework called Quantitative Digitalization Measurement Framework (QDMF), which delivers an alternative approach for measuring digitalization based on quantitative measurands. Therefore, the authors set up a development procedure allowing for the development of a scientifically substantiated framework. This procedure, as well as the final framework and the subsequent case validation of the framework are presented in the following subchapters.

Development Procedure

Screening scientific standard methodologies, the authors decided to go for a literature-based meta-development procedure. The main reasons are the large amount of suitable publications, as stated in the literature review, and the vast scope of fundamental theories, which need to substantiate the indicators.
From the comparison of different approaches, i.e. Bourne *et al.*, 2000; Lohman *et al.*, 2004; Neely *et al.*, 1997; Neely *et al.*, 1995; Franceschini *et al.*, 2019a, the authors extracted a five step development procedure and enhanced by two steps at the beginning to bridge to the targeted sub-process level:

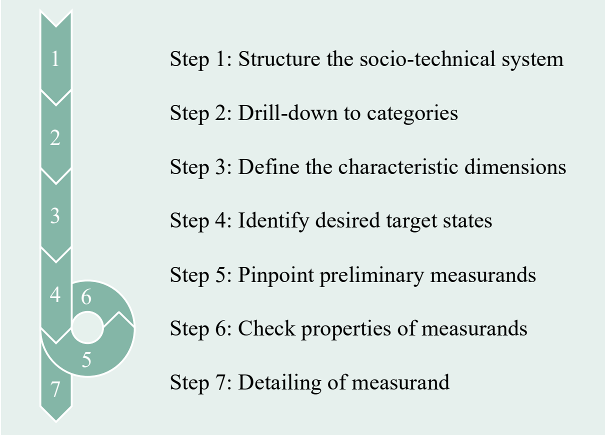

Figure 1: Framework Development Procedure

A basic theory to structure socio-technical systems is the fundamental MTO-model, which is already applied in similar cases such as the 'Dortmund Management Model' (Furmans and Wimmer, 2018). The MTO-model comprises socio-technical systems into human, technological and organizational subsystems.
Transferred, this framework is organized on the digitalization dimensions 'Man', 'Technology', and 'Organization'. Drilling into detail these dimensions can be subdivided into different categories.
The authors develop these categories by considering specialized literature. Based on leadership and human resource basic theories, e.g. theory of motivation (Niermeyer, 2007), the characteristics of the dimension man can be subdivided into the categories skills, willingness and leadership (see Niermeyer, 2007; Helldorff and Kahle, 2014; Boxall and Purcell, 2011). The dimension technology is clustered on the basis of the reviewed literature of digital technologies into the categories data acquisition, connectivity and integration, data analytics and human-machine interaction (Lackes and Siepermann, 2018; Panetta, 2018; Bonaty, 2018). The third dimension of the framework relates to literature about organizational theory (Laux and Liermann, 2005; Hatch, 2018). Subsequently, the authors categorized the organizational digitalization characteristics into strategy, financials, management and collaboration factors. In summary, 18 characteristics of digitalization related to supply chain planning context are elaborated.
Considering the existing maturity models, there is already a scientifically acknowledged definition of digitalization characteristics, which are utilized. Thus, the characteristic dimensions for measuring digitalization are derived from these publications. To gain a broad set of characteristics, all four maturity models previously introduced are analyzed and compared in detail. Therefore, each single maturity item is listed and assigned to a consolidated categorization.
In the next step, desired target states for each of these characteristics is defined. These are general goals of digitalization derived from the target vision of digitalization and industry 4.0 delivered by the previously analyzed maturity models.

In the fifth step, the authors defined preliminary measurands. The definition of measurands has substantial impact on the measurement significance (Petri *et al.*, 2015). Hence, they have to be aligned to the property intended to be measured in reference to the given goal. To find adequate measurands, the target state for each characteristic is reviewed. In doing so, several requirements must be fulfilled. According to Franceschini *et al.*, 2019b to ensure objectivity measurands are designed on a cardinal scale: interval or when possible ratio respective absolute scales. Another requirement in line with the research gap is understanding the logical connection between classical supply chain performance measurement and digitalization measurement. This is solved the following: An analysis of existing supply chain performance measurands in the literature delivers implications for the definition of indicators (Gunasekaran *et al.*, 2001, Gunasekaran *et al.*, 2004, Chae, 2009 Gunasekaran and Kobu, 2007, Shepherd and Günter, 2011). A correlation analysis of these performance indicators and the identified digitalization targets is performed. The final list of supply chain planning performance measurands is juxtaposed with the characteristic target states. Subsequently, measurands are derived from the insights of the correlation matrix and appropriated to measure the desired target state. To constrain the assessment effort, the number of measurands should be kept low. Consequently, the authors follow the principle of Occam's razor.
Finally, the most important requirements for the design of performance measurement systems have to be checked. Hence, the authors proceed an iterative process of indicator definition and properties check. Based on (Franceschini *et al.*, 2019a), the properties of the measurands are evaluated on plausibility and consistency of indicators. Hereby, the authors consider the factors meaningfulness, reliability and practical feasibility. The remaining indicators are assessed by professionals from the case company, but more cases are needed to verify the validity. The measurands are either accepted or revised by consensus.
To prepare the framework for application, the authors perform a final detailing. Besides the name of the measurand, a unique ID, a description, a formula, the unit of measure as well as the possible range and the targeted trend of the measurand is specified in line to the KPI description in ISO 22400 (ISO International Organization for Standardization, 2014).

Framework

Summarizing, the developed framework consists of three dimensions which are based on the definition of digitalization as transformation process of socio-technical system: 'Man', 'Technology' and 'Organization'. These dimensions are subdivided into eleven categories, which are represented by 18 characteristics based on analysis of existing assessment models from the literature. These characteristics can be measured by 22 measurands for the case of supply chain planning or more specific operational demand planning respecting the case study. These measurands are described by several items such as a name, an ID, a description, a scope, a formula, a unit of measure, a range and a desired trend. The concept is depicted in the Figure 2.

Application Procedure

The quantitative digitalization measurement framework (QDMF) can be applied to different scopes (see Figure 3). For the application in practice, the authors suggest the following application procedure:

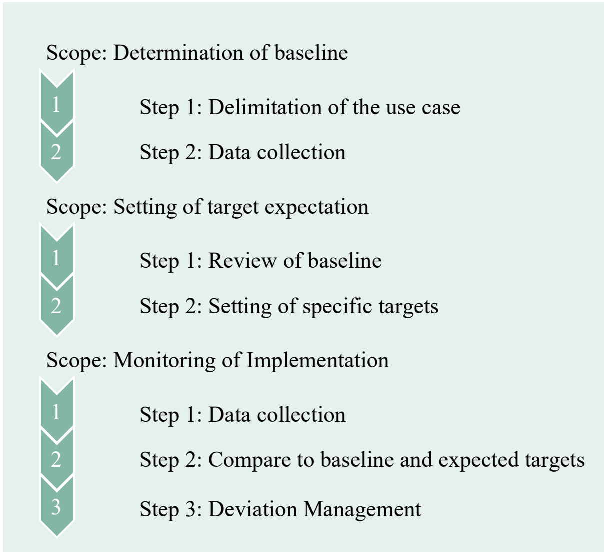

Figure 3: Scope and Application Procedure of QDMF

The QDMF can be used to determine the baseline for a digitalization project. This is the basis for potential benchmarking and the monitoring of the project progress. For that, the scope of the monitoring subject needs to be specified first. This requires the delimitation of the process which should be assessed and a description of the associated digitalization project. Afterwards, the collection of the relevant data for the assessment can be started. The data collection is executed by a survey method, as the digitalization measurement requires the knowledge of various experts and the acquisition of information that is usually not tracked yet. If the respective case is already situated in a highly digitalized environment, the surveys might be exchanged by data extraction from databases. For the moment, the authors propose structured interviews based on questionnaires with selected experts for the different dimensions: Whereas the assessment of the dimension 'Man' requires the knowledge of managers, project managers and HR experts, similar to the organizational dimension, the dimension 'Technology' also requires the knowledge of process and technical experts.
This data collection procedure can be reiterated either regularly or at specific milestones during the implementation of a digital technology. To extract the information

MAN

Category	Characteristic	Measurand	Description	Unit
skills	skill / awareness level	skill transfer participation	participation rate in related skill transfer measures (e.g. training)	%
	skill acquisition	training offering	number of training per relevant skill (e.g. technology, process)	number
willingness	change management	change managers	number of dedicated change managers per project	number
	change adoption	change initiation	number of improvement proposals per employee	number
leadership	ruling / objectives	job adaption rate	rate of job descriptions adapted	%
	decision-making	project decision time	project decision time	months

TECHNOLOGY

Category	Characteristic	Measurand	Description	Unit
data acquisition	data collection	acquisition capacity	data volume collected (e.g. customer data, product master data) per time period	MB/week
connectivity and integration	information exchange	system integration	number of systems / applications used per process	number
	digital model building	data currency	update frequency of data (vs. forecasting frequency)	1/week
		data volume	data volume available in the related database	GB
data analytics	(big) data analysis	analysis capacity	data points analyzed per planning item	number
		analysis frequency	planning frequency (vs. volatility)	1/week
	decision support / analysis automation	automation rate	rate of not manually adapted values	%
		machine forecast accuracy	forecast accuracy of the algorithm (vs. volatility)	%
		spreading width	interquartile range of the forecast accuracy	%
human-machine interaction	information provision	information effort	number of screens accessed per process	screens/planning item
	cooperation / collaboration of humans and machines	human-machine performance	human-machine system forecast accuracy (vs. volatility)	%

ORGANIZATION

Category	Characteristic	Measurand	Description	Unit
strategy	implementation status	target attainment	attainment of strategic digitalization targets in a project	%
financials	budget / investment	personnel deployment	number of full-time-equivalents spent per project	FTE
management	management level	management rate	frequency of digitalization project consideration by the management	1/month
collaboration	settings / principles	communication offering	rate of official communication channels offered per project	%
	cooperation / collaboration level	stakeholder involvement	number of stakeholders per project	number

Figure 2: Quantitative Digitalization Measurement Framework with Exemplary Measurands

from this assessment, the gathered data can be compared to previously assessed project states i.e. the baseline. For this the data for the project state is displayed in a structured manner and the absolute and relative changes of the measurands can be calculated. Furthermore, the data can be interpreted by the comparison to the initial target expectations, which can be defined at the beginning of the project. These expectations can be set by means of the QDMF through the review of the baseline, the benchmarking to similar projects and the experiences of experts. Nevertheless, to draw a conclusion of the results and manage deviations an estimation of an expert is recommended.

Case Validation

To validate the QDMF as a practical digitalization monitoring tool, the framework is applied on a specific use case in the field of supply chain planning at the Infineon Technologies AG. Infineon is one of the leading semiconductor manufacturers in Europe with production facilities all over the world. To manage its complex supply chains the company manages it following the generic SCOR-model (APICS, 2017). Within these SCOR-model the supply chain planning plays a central role. In this environment the authors decided for a digitalization project for the operational demand planning, which is important to balance demand and supply on a short-term basis. The investigated project comprises the implementation of a machine learning based algorithm for operational demand prediction. Therefore, available data bases are prepared to deliver sufficient data for the algorithm. The data is analyzed to identify the essential data for the demand prediction. An algorithm is set up to analyze this data using machine learning approaches to automatically generate a prediction of the future demand based on patterns from historical data. The project has four phases: development phase, pilot application phase, interims phase and productive phase. At date of the survey the project was at pilot phase, which means that a pilot algorithm is tested in particular departments.
Following the recommended application procedure, the authors measured all exemplary measurands (see figure 2) from the QDMF at the beginning of the project if data was available. As the assessment was performed in retrospect, the authors only surveyed specific target states, which were already determined for the project. In addition, the authors performed further interviews to get the available data for the current project state. The assessment and comparison of the measurands revealed the following results exemplarily:
In the dimension 'Man', the training offering and the skill transfer participation was measured. The assessment disclosed an increase of relevant trainings through the project, which means that skill transfer is sufficiently managed as all trainings for the affected process were already adapted or developed. The participation in these newly developed trainings was still at 0%, as the project was in an early project phase at date of assessment. Hence, this measurand is more important in later project phases. Apart from that, the change managers' evaluation of the measurands showed that there were no dedicated change managers. Thus, the willingness to manage the change through the digitalized process was relatively low, yet. As professional change management is essential for a successful change process, it shows that there is still room for improvement in this project.
In the dimension 'Technology', especially the measurands data volume, automation rate as well as the analysis capacity and the analysis frequency were targeted. As databases were prepared for the automation algorithm, the data volume increased by 5%. Furthermore, the analysis capacity increased by 1000% as the algorithm considers more data points then the prior standard process. In addition, the analysis frequency could be improved by 300% through the lowered manual effort. These measurands show the effect of the project from a technological point of view. Whereas these measurands show the details, the main control parameter was the automation rate. The project targeted to reach an automation rate of 95% for the considered planning step. But the assessment showed only 77% automation rate could be accomplished within the current pilot algorithm, which means development work has to be continued to improve it for the desired target.
In the dimension 'Organization', for instance, the target attainment as well as the stakeholder involvement was measured. As only very little strategic targets were defined, the measurand target attainment is not fully conclusive, but the assessment showed that 85% of the strategic goals were already fulfilled. The number of stakeholder involved in the project increased by 100% during the project, showing the gained interest in general favored by the preliminary results.
The application of the QDMF to the use case shows, the framework is applicable for its design purpose in general. In particular, the results verify that the structure of the examined characteristics delivers comprehensive insights into different aspects of digitalization. Consequently, additional insights for effective management of digitalization can be given. For example, the assessment showed that there is a need for the establishment of a professional change management.
Withal these gained insights of quantitative digitalization measurement with objective performance, measurands underpin the subjective evaluation of the interviewed experts. Weaknesses within the project implementation and recommendations for future activities could be identified on a managerial as well on an operational-technical level. The monitoring of the technology dimension provides detailed indications on important requirements for future projects and the expectable effect of a technology in dedicated aspects of a socio-technical system.
Regarding the application procedure, the QDMF is largely appropriate to the selected case. Nevertheless, there are some hurdles to be taken to reach the goal of a general, applicable, quantitative digitalization monitoring tool.
In the case, several measurands are completely new and the required data is not tracked yet the acquisition takes time and effort, limiting the data availability. However, it

already points out white spots in the current monitoring: In the examination, dimensions differ a lot in terms of available data. Whereas the assessment of technological factors is very common within digitalization projects, organizational and people-oriented factors are widely not established yet. Crosschecks with other ongoing projects highlight that each use case has specifics, concluding that an interpretation layer for adaption of the QDMF is necessary. For instance, each type of project has individual target areas and therefore different methods and effects. Thus, it is sometimes not necessary to monitor all measurands within all projects. But it is important to consider all project aspects, when setting the targets and sub-targets of a digitalization project. Consequently, for the general application the authors recommend to review and pre-select the characteristics, which should be targeted within the project and the monitoring scope. In this, not only technological aspects should be selected, but also organizational and people related aspects. This brings along the opportunity to set specific measurable targets for each characteristic based on the proposed measurands. Making it short, the delimitation of the use case and the scope are crucial. Another hurdle is the limited explanatory power of the quantitative measurands. The application shows the quantitative digitalization measurement requires additional information to set measurands into context. The reference information can be delivered through several measures. On the one hand, the setting of targets for the specific measurand can be the point of reference. On the other hand, the necessary information can be revealed through the comparison with other projects. Besides that, the results can be interpreted through the contextual information from experts.

The third constraint of the approach determines the constrained application opportunity within the scope of the study. Currently, the framework is only be applied to one use case. It represents a typical digitalization project within the supply chain planning context. Hence, a first indication about the general validity of the concept is evaluated. Nevertheless, the validity of all particular measurands in all situations is finite. To verify the applicability and comparability, the research has to expanded to more cases. Thereby, not only classical technology-focused projects such as the actual use case should be investigated, but also organizational projects and projects targeting at the people perspective. This diversity of projects would complete the assessment of the validity of the framework and its measurands from all perspectives.

Overall, the use case application reveals that the provided measurands can only represent a proposal. There is still need to review the measurands for the applicability to the specific use case. For example, the assessment of the capacity planning might require measuring other outputs, i.e. capacity utilization, than the demand planning. Therefore, the integration of an interpretation layer states a potential enhancement of the QDMF. Nevertheless, the current framework gives a guideline for other applications in the field of supply chain planning. Additionally, the findings demonstrate the complexity to conceptualize a procedure to develop a general quantification criterion, which is also applicable for very specific use cases. Concluding, the research states the necessary groundwork for future applications and enhancements of the framework and delivers no final set of valid digitalization monitoring metrics.

CONCLUSION AND OUTLOOK

The study aimed at analyzing, how digitalization can be quantified within the context of supply chain planning.

Therefore, a quantitative digitalization measurement framework (QDMF) was developed and validated on a use case study on demand planning in the semiconductor industry. The approach states a contribution to bridge the research gap between the constrained applicability of existing supply chain performance metrics and digitalization assessments. In addition, the limited objectivity of digitalization assessment models in the current literature was tackled by underpinning the personal view of digitalization with quantitative measurands. Although the framework still has its limitations, an initial guideline for quantitative digitalization measurement can be given. As result, the study delivers the groundwork for more extensive investigations on this topic and shows the general feasibility of the concept of quantifying digitalization. Besides, the framework proves its capability to monitor the impact of digitalization projects on the categorical level. The application of the QDMF to a machine learning project for demand planning demonstrated, the effect of the technological implementation can be captured through the framework within various digitalization aspects. The comprehensiveness of the framework allows not only tracking the direct effect on the technological side, but also the accompanying personnel and organizational impact. Thus, the general effect and experiences regarding a digital technology can be recorded. Consequently, further applications will support the management in the definition of adequate digitalization targets and monitoring their attainment. As a consequence, digitalization can be managed more effectively.

One possibility offers the expansion of the analysis of the assessment result expanded by the valuation of target attainments and the benchmarking of different digitalization projects. Hereby, the meaningfulness of the quantitative measurands is expected to increase significantly. Besides that, adaptions for better practicability such as a reasonable preselection of assessed indicators for different types of digitalization projects might be a benefit, where an interpretation layer might be one solution. Another direction is the validation of the concept by the application on more projects even in other industries.

Coming to an end, all findings result in the conclusion that through the research within this study, progress is made on the target of showing how digitalization can be measured quantitatively. Also, the effect of the implementation of digital technologies on the different aspects of digitalization could be measured. But there are several research options for enhancement in the direction of a universal and practicable measurement framework with high validity.

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AUTHOR BIOGRAPHIES

TIM LAUER is responsible for R&D strategy processes at the Infineon Technologies AG. In addition, he conducts research on supply chain innovations focusing on digitalization and artificial intelligence. Thus, he writes his PhD in the field of human-AI system optimization at the Technical University of Dortmund.

MAXIMLIAN WOLF is an alumnus of the master program 'Engineering and Management' at the Munich University of Applied Sciences. He conducted research on supply chain digitalization in cooperation with the Infineon Technologies AG, which was part of his master thesis and the base for this publication.

JÖRG PUCHAN is Professor for Applied Computer Science at Munich University of Applied Sciences, Munich School of Engineering and Management. His main academic interests both in research and teaching are in the field of IT-management and business optimization.