MASTER

An integrated readiness and maturity model for Industry 4.0 (I4RMM)

Kaandorp, P.W.

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Department of Industrial Engineering & Innovation Sciences
Information Systems Research Group

An integrated readiness and maturity model for Industry 4.0 (I4RMM)

Master thesis

P.W. (Paul) Kaandorp
0903072

Supervisors:
dr.ir. I.T.P. (Irene) Vanderfeesten, TU/e
dr.ir. O. (Oktay) Türetken, TU/e
prof.dr.ir. P.W.P.J. (Paul) Grefen, TU/e
ir. J.L.M. (Hans) Kwaspen, Atos
ing. G.J. (Guido) van der Sluis, Atos

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Executive summary

Introduction

Industry 4.0 (I4.0) is here. This newest era of industrialization is still in its infancy in some manufacturing companies, though in others, the transformation to I4.0 is already well under way. In order to support organizations in their roadmap towards or during this new era, many different I4.0 readiness and maturity models have been proposed by academics and consultancy firms (Canetta et al., 2018). Although a great number of these modes are available, many models lack the empirical validation (Colli et al., 2018; Rauch et al., 2020; Santos and Martinho, 2019; Schumacher et al., 2019; Tarhan et al., 2015; Trotta and Garengo, 2019; Wagire et al., 2020), are often too diverse, too specifically focused, and underutilized (Pacchini et al., 2019; Trotta and Garengo, 2019). In addition, De Carolis et al. (2017); Mittal et al. (2018a) state that the conjunction of I4.0 readiness and I4.0 maturity models should be explored due to their current (unjustifiable) disconnection. Therefore, this research responded to this research gap by:

- performing a Systematic Literature Review (SLR) to obtain an extensive overview of the different I4.0 readiness and maturity assessment models proposed in the scientific literature;
- synthesizing an integrated model based on the existing models found in this SLR;
- improving and refining this integrated model by including expert opinion via a Delphi study;
- validating the integrated model by conducting a multiple-case study.

This integrated model is referred to as the Industry 4.0 Readiness Maturity Model (I4RMM), which aims to assess both I4.0 readiness and I4.0 maturity. Therefore, this model can be utilized to help organizations to prepare for the challenges and requirements of I4.0, while also helping organizations to identify improvement opportunities to achieve higher maturity levels in I4.0.

Research design

In developing the I4RMM, the Design Science Research (DSR) methodology by Hevner et al. (2004) was carefully followed, complemented by the Design Science Research Process (DSRP) model by Peffers et al. (2006). First, a literature review was performed to obtain an extensive overview of the proposed I4.0 readiness and maturity models in the academic literature. Based on a rigorous analysis of these models, a first blueprint of the I4RMM was synthesized. This initial blueprint contained ten organizational dimensions which were deemed to be highly important when measuring I4.0 readiness and maturity. In addition, these levels contained two readiness levels (R0-R1) and four maturity levels (M0-M3), as synthesized from the literature. Subsequently, a Delphi study was executed consisting of four rounds with nine domain experts to refine and further develop the I4RMM, while securing its relevance and validity. Finally, following the guidelines of Yin (2017), a multiple-case study was conducted to evaluate the model on completeness, validity, and usability. In addition, a Technology Acceptance Model (TAM) survey—as proposed by Davis (1989); Moody (2003); Venkatesh and Davis (2000)—was employed to further evaluate the model on perceived usefulness, perceived-ease-of-use, and intention-to-use.

Industry 4.0 Readiness Maturity Model

The final I4RMM assesses eight organizational dimensions on I4.0 readiness and I4.0 maturity, ranging from technological to non-technological dimensions. These dimensions are:

Technology The *technology* dimension relates to the extent to which I4.0 technologies are implemented and used in the organization.

Operations The *operations* dimension relates to the extent to which manufacturing operations (production, storage, quality test, and maintenance) are formally documented organized, robust, and repeatable (De Carolis et al., 2017).

Strategy & Vision The *strategy & vision* dimension relates to the extent to which the strategy and vision currently adopted by companies are aimed towards I4.0.

Culture & Competencies The *culture & competencies* dimension relates to the extent to which all people of an organization are competent (due to adequate training and recruitment), and willing to support the implementation of I4.0 technologies and innovation.

Process The *process* dimension relates to the extent to which organization (support) processes of production and maintenance are self-configurable, self-optimized, and simplified.

Connectivity & Integration The *connectivity & integration* dimension relates to the extent to which an IT/cloud infrastructure is in place to accommodate vertical or horizontal integration across the value chain.

Products & Services The *products & services* dimension relates to the extent to which products are individualized and product characteristics can be customer specific (smart products). In addition, it assesses the extent to which an organization offers data-driven services and customer integration (smart services and servitization).

Collaboration The *collaboration* dimension relates to the extent to which formal channels are enabled for employees and collaboration partners to share information and work together, as well as institutional structures and systems that allow collaborative behavior.

Each dimension contains three possible readiness levels (R0-R2) and four maturity levels (M0-M3), from which one can be selected after careful consideration. These levels are consecutive in nature, which means that I4.0 readiness must first be determined before identifying a maturity level. Organizations can use the I4RMM to self-assess their I4.0 readiness and I4.0 maturity, and to identify improvement opportunities based on their as-is assessment. Due to the fact that the model does not offer a prioritization in dimensions, organizations can choose and design their own improvement paths as they seem fit. Figure 1 presents the complete I4RMM.

Evaluation

Following the DSR method, the developed artifact was evaluated by applying it in a real business environment i.e. manufacturing companies that seek to assess their I4.0 status. This evaluation took place in the form of a multiple-case study, with the goal to evaluate the model on completeness, validity, and usability. Three cases were selected based on their industry. The first case organization operates in the high-tech manufacturing industry, and the second and third in the pharmaceutical and automotive industry respectively.

The case studies were performed as focus groups during planned assessment sessions. The participants were selected based on their work experience, so that they would be able to make a sensible assessment of the organization. During the assessment session, the participants were asked to choose an appropriate level for each dimension of the model. Only a single decision for each dimension was provided after group discussion. During these assessments, the researcher acted as an observer and took notes of the procedures. After all the dimensions were assigned to readiness or maturity levels, the results were aggregated. To conclude the case studies, the participants (*n=6*) were asked to individually fill out an online survey based on the TAM. This survey was developed based on the works of Davis (1989); Moody (2003); Venkatesh and Davis (2000) and assessed the I4RMM on perceived usefulness, perceived ease-of-use, and intention-to-use.

Conclusions

This research extends the body of knowledge on the academic literature of I4.0 assessment methodologies by providing an operational model that can be utilized to assess both I4.0 readiness and maturity. In addition, this research addresses the industrial need for a structured methodology to assess these concepts.

The I4RMM solves the research gap introduced by De Carolis et al. (2017); Mittal et al. (2018a) by introducing a model that can be used to assess both concepts of I4.0 readiness and I4.0 maturity. Furthermore, the model was validated after a multiple-case study and performed well in a conducted TAM survey, in which the overall view of the I4RMM was very positive. In conclusion, the I4RMM provides a unique solution to assess I4.0 readiness and maturity, while concurrently broadening the knowledge base on readiness and maturity models that can be used in the domain of I4.0.

The practical relevance has been demonstrated during the case studies. According to these results, the model is perceived to be useful and the intention-to-use is high. In addition, the model can be employed for three purposes. First, the model can be utilized to assess the as-is state of an organization regarding the I4.0 proceedings. Here, the model can help organizations to optimally prepare for the challenges and requirements of I4.0, or provide decision-making support during the digital transformation of an organization. Second, the model can be utilized to identify the to-be state of organizations. These ambition readiness or maturity levels can be compared to the as-is state, followed by the development of an improvement path. Third, the model could be utilized by several organizations to perform a benchmarking study. This study could provide valuable insight in the average I4.0 readiness and maturity levels of different manufacturing companies operating in different industries.

This research includes several limitations, which can be addressed in future research. First, it could be possible that some academic publications were missed during the literature collection procedure of the SLR, therefore excluding potential valuable input to the first iteration of the I4RMM. Future research could revisit the performed literature review to determine if all essential publications are included. Second, during the development of the model, a consensus was not reached regarding the dimensions. Therefore, future research could reconsider the selection of dimensions of the final model. Third, limitations of the model were identified concerning the model its completeness, validity, and usability. Specifically, the comprehensibility of the conjunction of I4.0 readiness and maturity, and the limited usability in the pharmaceutical industry. Respectively, future research could try to make the concepts of readiness and maturity more distinct, and future research could work on adjusting or extending the model to be applicable to specific industries. Alternatively, future research could alter the I4RMM to make it general applicable (across all industries). Both research paths will improve the overall applicability of the model. In addition, the absence of sub-dimensions could limit the general utilization of the model. Therefore, future research could revise these dimensions to identify sub-dimensions. Furthermore, the number of case studies can be considered as a limitation. Hence, a larger (diverse) sample size is necessary for a strong validation of the model. Therefore, future research could extend the multiple-case study with more cases. Finally, longitudinal evaluation studies could be performed to assess the performance of a business before, during, and after applying and using the I4RMM.

Industry 4.0 Readiness Maturity Model - I4RMM

Dimension	Definition	Readiness			Maturity			
		R0 Unprepared	R1 Planned	R2 Ready	M0 Incomplete	M1 Performed	M2 Managed	M3 Defined
Technology	The extent to which I4.0 technologies are implemented and used.	No presence of assets that enable data collection, transfer, and generation.	Planned to buy new technology that enables data collection, transfer and generation.	There are assets available that enable data collection, transfer, and generation.	There are assets available and used for data access and data visualization.	There are assets available and used for data analysis, and communicating the results to the user.	There are assets available that are acting autonomously according to information received after an analytic process.	The assets deployed across the supply chain can interact together and reconfigure themselves to optimize performance.
Operations	The extent to which manufacturing operations (production, storage, quality, test, and maintenance) are formally documented, supported by I4.0 paradigms, and enable continuous improvement and optimization.	No manufacturing operations have been documented.	The manufacturing operations are partly documented, and there are plans to finalize the documentation.	All manufacturing operations are well documented, deployed and monitored.	The manufacturing operations are defined, deployed and monitored with documented standards and partly supported by software tools.	The manufacturing operations are defined, deployed and monitored and fully supported by software tools and executed with possibly repeatable results in normal situations.	The manufacturing operations are defined, deployed and monitored across all organizational groups, and their executions are repeatable and monitored with software tool supports.	The manufacturing operations are focused on continuous improvement and optimization.
Strategy & Vision	The extent to which the strategy and vision currently adopted by companies are aimed towards I4.0, including the acknowledgement of an I4.0 roadmap.	There is no awareness regarding the digital transformation, and I4.0 strategy and vision are lacking.	There is a willingness and interest towards the digital transformation. I4.0 strategy and vision are being developed but there is great uncertainty on how to approach I4.0.	There is a clear I4.0 strategy and vision in place.	I4.0 strategy and vision have been formally implemented in at least one functional area.	I4.0 strategy and vision are expanded to include more than one functional area.	I4.0 strategy and vision are expanded to include all functional areas.	I4.0 strategy and vision are refreshed and updated automatically if necessary (monthly).
Culture & Competencies	The extent to which all people of all departments are competent (due to adequate training and recruitment of HRM) and support the implementation of I4.0 technologies and innovation.	The organizational culture is not open to innovation, nor are there in-house or external competencies related to digital manufacturing.	The organizational culture is open to innovation, but there are no in-house or external competencies available to approach digital manufacturing.	The organizational culture is open to innovation and there are in-house or external competencies available related to digital manufacturing, and these can be utilized when needed.	An inclusive culture is (partly) in place by involving workforce in vision development. People are being recruited with digitization competencies.	People are educated to develop the ability to exploit connected data systems. Production staff proactively coordinates digital insights and knowledge sharing.	Suppliers, users, and other stakeholders meet up to improve shared group understanding of production processes. Data analysts and data scientists are recruited to optimize production.	A culture of continuous smart factory innovation is in place covering the complete organization. Specialized roles and responsibilities are geared toward predictable production.
Process	The extent to which companies support departments collaboration, machine and system integration with the help of I4.0 technologies. This includes self- optimization, self-configuration, standardization and simplification of processes of production, maintenance, and support processes.	No processes have been explicitly defined.	The processes are partly defined, and there are plans in place to define all processes.	All processes are defined, simplified, standardized, and are being executed.	Defined processes are completed with the support of digital tools.	Digitized processes and systems are securely integrated across all hierarchical levels (machines & workers - boardroom).	Integrated processes and systems are automated, with limited human intervention.	Automated processes and systems are actively analyzing and reacting to data, enabling continuous process improvements.
Connectivity & Integration	The extent to which an IT/ cloud infrastructure is in place to accommodate vertical or horizontal integration across the value chain.	The IT infrastructure is poorly documented and designed, and provides no flexibility in extending it.	The IT infrastructure is partly documented and designed, and there are plans in place to increase its flexibility to extend it in the future.	The IT infrastructure is well documented and designed, and provides enough flexibility to extend towards I4.0 technology requirements. In addition, the IT department resources are aligned to support future extensions.	The IT infrastructure is not standardized but all the different modules can communicate with each other.	The IT infrastructure is not fully integrated but is based on a number of recognized standards and when new modules have to be developed, this is done accordingly.	The IT infrastructure is based on a commonly agreed set of standards and new modules are developed accordingly, enabling interoperability.	The IT infrastructure in the whole supply chain is based on standards that allow plug and play inter-organization real-time communication, enabling interoperability and scalability.
Products & Services	The extent to which products are individualized and product characteristics can be customer specific (smart products), and the extent towards offering data-driven services and customer integration (smart services and servitization).	Product development or services are not digitally supported.	There are plans to explore digital support of product development and services, but additional help is required.	Product development or services are partly digitally supported.	Products offer digital features and services are continuously digitally supported.	Products offer connectivity features and little differentiation. Data-driven services offer little customer integration.	Products offer responsive features and can be largely customized. Data-driven services offer customer integration.	Products can be completely customized and feature all smart product functionalities, and many products are being servitized. Data-driven services are fully integrated with the customer.
Collaboration	The extent to which formal channels are enabled for employees and collaboration partners to share information and work together, as well as institutional structures and systems that allow collaborative behavior.	Communication and information sharing across teams happen on an informal basis.	There are plans to formalize the current channels used for communication and information sharing, but additional help is required.	Formal channels are established for communication and information sharing across teams.	Formal channels are established to allow teams to work together on discrete tasks and projects.	Teams are empowered by the organization to make adjustments that will facilitate cooperation on discrete tasks and projects.	Teams are empowered by the organization to share resources on both discrete and longer-term tasks and projects.	Formal channels are established to enable dynamically-forming teams to work on cross-functional projects with shared goals and resources.

Figure 1: Industry 4.0 Readiness Maturity Model (I4RMM)

Preface

This is it, the end of the line. I am proud and thrilled to present this thesis to you, which represents my final chapter of my time at the Eindhoven University of Technology. What a journey it has been, from Building Engineering to Industrial Engineering, to where I am right now. The end of my student life is just around the corner, and a new exciting chapter is about to begin. Looking back, I cherish all the friendships that I made, the inspiring events that I participated in, and the unforgettable moments that I will always hold close to my heart.

Although I was obliged to only work from home due to the COVID-19 pandemic, I was never alone on this scientific journey. Therefore, I would like to take the opportunity to thank those who have contributed significantly to this master thesis.

First, I would like to thank Irene Vanderfeesten as my first university supervisor. As cliché as it may sound, I could not have wished for a better mentor. Your cheerfulness and enthusiasm really made a positive impact on me. I look back on countless interesting and inspiring discussions, and a fantastic collaboration overall. I sincerely wish you all the best, and hope more students get the opportunity to benefit from your excellent mentorship. In addition, I would like to thank Oktay Türetken and Paul Grefen for their time and feedback as my second and third university supervisor respectively.

Second, I would like to thank Hans Kwaspen and Guido van der Sluis as my company supervisors. Your wholehearted support for my project meant the world to me. The expertise and passion you guys hold and shared, inspired me immensely throughout the project. Although we have never physically met due to the pandemic, you guys made me feel part of the team, and I will never forget that. In addition, I would like to thank all the participants of the Delphi study, who contributed significantly to the final artifact of my project.

Last but definitely not least, I would like to thank my family and friends. My parents and sister for their unconditional support during my complete educational journey. Without you, I would have never been able to do the things that I did, and to achieve what I have achieved, I love you guys.

My friends mean the world to me, I could write a thesis ten times the length of this one containing all the adventures and stories we shared. I would like to thank the 'Helpdesk' for the innumerable studying sessions at MetaForum, and 'TBKater' for the infinite amount of my most cherished memories. Without you guys, this journey would have been unimaginable. Let us toast to many new adventures, to more years of happiness in good health, and let us toast to a new chapter!

Thank you!

Paul Kaandorp
Eindhoven, April 2021

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List of Acronyms

AM	Adoption Model
CPS	Cyber Physical System
DSR	Design Science Research
DSRP	Design Science Research Process
EC	Exclusion Criteria
I4.0	Industry 4.0
I4RMM	Industry 4.0 Readiness Maturity Model
IoT	Internet of Things
IS	Information Systems
JIF	Journal Impact Factor
MM	Maturity Model
PLM	Product Lifecycle Management
RM	Readiness Model
SLR	Systematic Literature Review
SQ	Search Query
TAM	Technology Acceptance Model

Chapter 1

Introduction

Industry 4.0 (I4.0) was introduced by professor Wolfgang Wahlster during the Hannover Fair in 2011. He suggested that firms must be in shape for the fourth Industrial Revolution that is being driven by the internet. I4.0 goes by many names, it is also known as 'Smart Manufacturing' in the United States, 'Smart Factory' in Asia (most noticeably: South-Korea), and 'Industrie 4.0' in Germany (Mittal et al., 2020). These labels all convey the same message of a new era of industrialization, in which traditional manufacturing and industrial practices are further automated using modern smart technology. I4.0 can be described as a new organizational model based on the implementation of I4.0 technologies (e.g. Internet of Things (IoT), Cyber Physical System (CPS)) that enable horizontal and vertical integration across the entire value chain, leading to the improvement of organizational performance. This increased organizational performance can be both internal and external. Internal improvements may be increased efficiency, productivity, and reduced costs. External improvements may yield a better market position compared to the competition, and better customer service.

For example, companies in the pharmaceutical industry may benefit from I4.0 to accelerate drug production (Thomsen, 2020). At the time of writing (April 2021), the wold is facing the COVID-19 pandemic. Its inhabitants are eagerly waiting for an effective vaccine, as it is the only sustainable way to prevent the disease. There is immense pressure on pharmaceutical companies to accelerate its mass production, to provide sufficient vaccines for the whole world. However, at the same time, there must be absolutely no compromise on quality and reliability. To conform to these high requirements, each stage of the vaccine manufacturing process could be equipped with IoT sensors. These sensors make it possible to collect diverse sets of rich data to understand exactly what is happening in real-time. By combining this data with physical, chemical and biological models, it is possible to build a 'digital twin' of the complete vaccine production process. This digital twin works as a live replica of all physical processes, and can be used to optimize every production stage, or simulate any change in the manufacturing setup to test the effects. By using machine learning techniques, predictive and prescriptive models, new insights can be generated into all aspects of COVID-19 vaccine production. Hence, I4.0 can help pharmaceutical organizations in their decision-making to optimize their drug production. This is one of many examples in which I4.0 can help companies to improve organizational performance. Therefore, increasingly more companies are interested in successfully joining this new industrial revolution and reaping its benefits.

However, companies do not seem to have the knowledge or expertise in-house to help make them structural decisions in their I4.0/digital transformation. Therefore, to support companies in their roadmap towards this new era, many different I4.0 readiness and maturity models have been proposed by academics and consultancy firms (Canetta et al., 2018). These models are used as an evaluative and comparative basis for improvement, and to derive an informed approach for increasing the capability of a specific area within an organization (de Bruin et al., 2005). They offer a methodology for companies to analyze their status quo of I4.0 readiness and maturity through a dedicated assessment instrument. According to Bley et al. (2020), an awareness of the maturity level is necessary in order to recognize improvement potentials and to stimulate a continuous improvement process. Moreover, companies are enabled to make better substantiated decisions in their I4.0 proceedings, ultimately leading to—the discussed—organizational benefits.

Currently, a vast variety exists of different readiness and maturity assessment models. Therefore, making it challenging for companies to choose the right model, that fits their needs and available resources to employ it. Furthermore, many models lack the empirical validation (Colli et al., 2018; Rauch et al., 2020; Santos and Martinho, 2019; Schumacher et al., 2019; Tarhan et al., 2015; Trotta and Garengo, 2019; Wagire et al., 2020), and are often too diverse, too specifically focused, and underutilized (Pacchini et al., 2019; Trotta and Garengo, 2019). Furthermore, the terms 'readiness' and 'maturity' seem to have caused confusion in the scientific community. According to De Carolis et al. (2017), readiness and maturity are relative and related, but different (Pacchini et al., 2019). In this research, 'readiness' is described as the level of preparedness (or readiness) of the conditions, attitudes, and resources, at all levels of an organization, **before** engaging in I4.0 proceedings. In addition, 'maturity' is described as the level of maturity of the conditions, attitudes, and resources at all levels of an organization **while** engaging in I4.0. This perceived difference has led to a segmentation of assessment tools. Mittal et al. (2018a) claim that this segmentation is causing a negative disconnection between maturity and self-assessment readiness models, and suggest that integrating these models could eliminate this disconnection. However, De Carolis et al. (2017) state that there is no established approach or framework to combine these assessment methods.

To summarize, the manufacturing industry is in need of a structured, validated I4.0 assessment model to help them in their decision making before or during their digital transformation. The science community provides a great collection of these I4.0 readiness and maturity assessment models. However, these models are underutilized and different authors argue the need of integrating and standardizing these I4.0 assessment models. Therefore, the following problem statement is given by combining the practical relevance and academic research gaps:

> *Companies in practice lack the knowledge, expertise and methodology to make a sensible assessment of their I4.0 readiness and maturity. Science has produced a great number of readiness and maturity models but these are too diverse, too specifically focused, and underutilized. Therefore, the problem is that there is no comprehensive I4.0 readiness-maturity assessment model that helps companies in their decision-making before and during their I4.0 transformation.*

Following this problem statement, the objective of this research is to develop a new assessment model that assesses both I4.0 readiness and I4.0 maturity. This model aims to help businesses in the manufacturing industry in their decision-making during or before their I4.0 transformation. Therefore, the research objective is:

> *To develop and evaluate a new integrated I4.0 readiness-maturity assessment model for companies in the manufacturing industry.*

This research attempts to reach this goal by:

- performing a Systematic Literature Review (SLR) to obtain an extensive overview of the different I4.0 readiness and maturity assessment models proposed in the scientific literature;
- synthesizing an integrated model based on the existing models found in this SLR;
- improving and refining this integrated model by including expert opinion via a Delphi study;
- validating the integrated model by conducting a multiple-case study.

This new integrated solution is named the Industry 4.0 Readiness Maturity Model (I4RMM); providing a first attempt in merging the entities of I4.0 readiness and I4.0 maturity.

In developing the I4RMM, the Design Science Research (DSR) methodology as proposed by Hevner et al. (2004) was carefully followed. First, a systematic review was conducted of a significant number of existing I4.0 readiness and maturity assessment models, as proposed by the scientific community. Based on an extensive analysis and synthesis of these models, an initial version of the I4RMM was developed. This initial version consisted of a set of key dimensions that are deemed important to be measured, to adequately assess I4.0 readiness and maturity. Afterwards, a Delphi study was performed consisting of four rounds with nine field experts to improve and refine the I4RMM, ensuring its relevance and validity. To evaluate the new I4RMM, a multiple-case study was conducted. These case-studies tested the model on completeness, validity, and usability. Finally, a Technology Acceptance Model (TAM) survey was employed to test the model on perceived usefulness, perceived ease-of-use, and intention-to-use.

The remainder of this thesis follows the publication schema of Gregor and Hevner (2013), to aim for maximum impact in emphasizing significant contribution to the knowledge base. In chapter 2, the theoretical background is provided by presenting the SLR. In chapter 3, the deployed research approach is elaborated. In chapter 4, the final I4RMM is described in detail, and chapter 5 presents the results of the model evaluation. Finally, the most important findings are restated in chapter 6, including limitations and topics for future research.

Chapter 2

Literature review

This chapter provides an overview of the Systematic Literature Review (SLR) that was performed in August 2020 (Appendix G). The objective of this literature study was to get an extensive overview of the available Industry 4.0 (I4.0) readiness, maturity, and adoption assessment models. Synthesis of this analysis provided the first blue-print of an integrated I4.0 readiness and maturity assessment model i.e. the Industry 4.0 Readiness Maturity Model (I4RMM).

First, the research method for the SLR is described. Second, the I4.0 phenomena is defined using the literature, followed by I4.0 readiness and maturity assessment models. Fourth, an overview of these models is presented. Fifth, the theoretical framework of the new integrated solution is described. Finally, the chapter concludes with a summary of the main findings of the SLR.

2.1 Research method

A SLR was conducted to obtain a better understanding of the available I4.0 readiness, maturity, and adoption models. During this review, it was observed that I4.0 adoption models were completely different in structure and usage compared to the readiness and maturity models. Therefore, these adoption models were neglected from the final synthesis. This synthesis focused on integrating the reviewed I4.0 readiness and maturity assessment models in a new integrated meta-model for the domain of I4.0. The literature study followed the guidelines and activities as defined by Keele et al. (2007); Okoli (2015). These guidelines are aimed for conducting SLRs in software engineering. Hence, making it a relatively good fit with the topic of I4.0 which is characterized by emerging engineering technology. To ensure that this SLR can be reproduced as accurate as possible, it is important to specify and carefully document the steps of the methodology. First, scientific literature was collected using a literature collection strategy, leading to a long-list. Second, this long-list was reduced to a short-list by using the literature selection strategy. Finally, the publications in the short-list were carefully studied, analyzed, and synthesized. Figure 2.1 presents a visual overview of the procedure and its refinement steps.

The literature collection strategy elaborates on the used search engines and search terms. To obtain an extensive overview of the available models, multiple (complementary) search engines were used. These search engines were selected from the database list of the university. This list was filtered on the research areas of 'computer sciences' and 'industrial engineering and management sciences'. In addition, a combination of search engines were used to include both journal articles and conference proceedings. Finally, the search engines ScienceDirect, Web of Science, and IEEE Xplore were used to provide a reasonably complete overview of the topic at hand.

Search terms construct the Search Queries (SQs) which were executed in the search engines. These search terms were derived from composed research questions in the SLR. Synonyms and

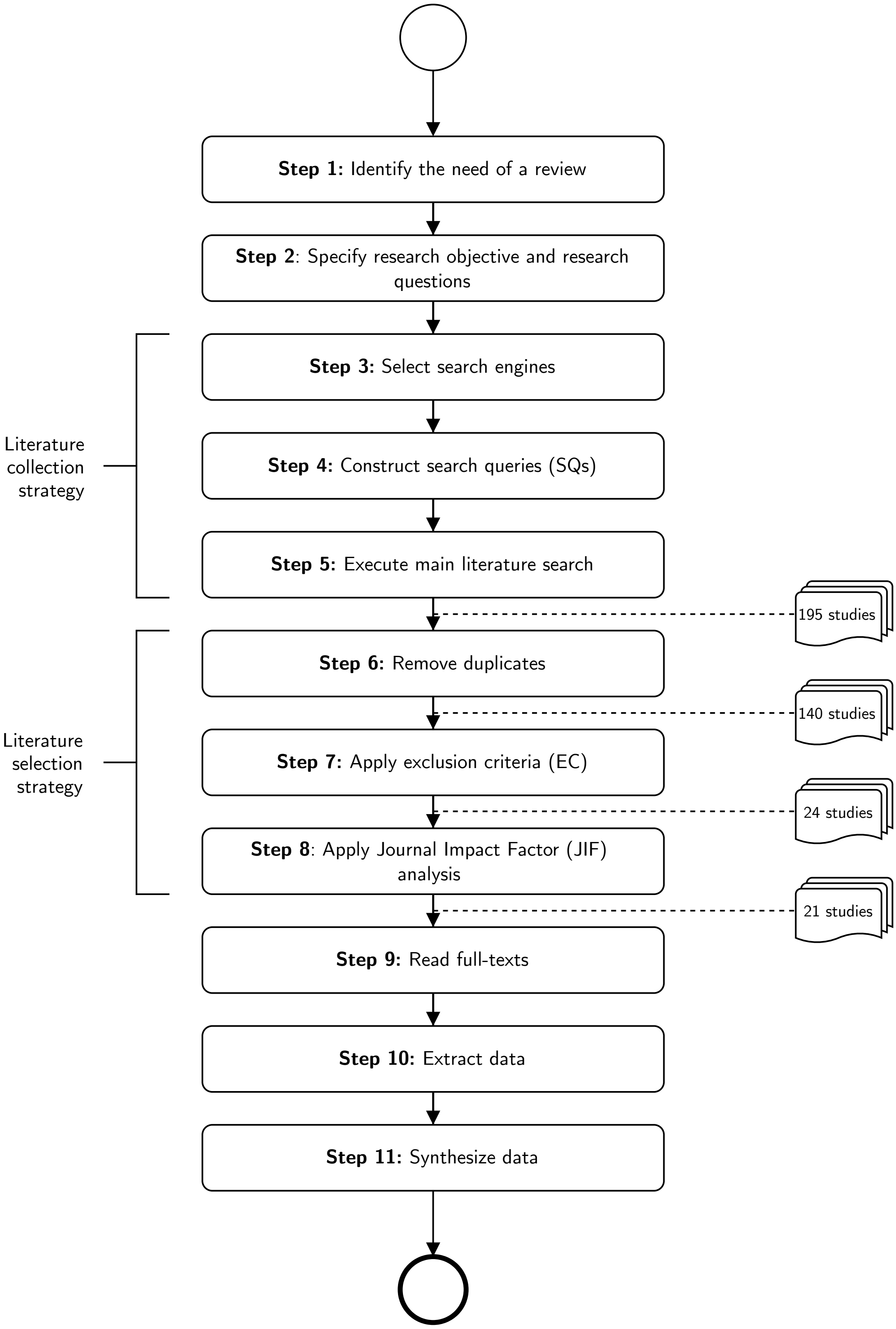

Figure 2.1: SLR: procedure and refinement steps

variants of search terms were identified using the online American dictionary of Merriam-Webster (Merrian-Webster, 2020), and by using field terminology/knowledge. After establishing the search terms, the SQs were constructed using `AND` and `OR` operators. First, the title, abstract, and keywords (*TITLE-ABS-KEY*) of publications were searched for the right context and domain i.e. I4.0. Second, the title (*TITLE*) of the publication was exclusively searched for the assessment type (readiness, maturity, and adoption) and model typology. Therefore, the outcome was a list of publications merely focusing in-depth on the different assessment models in the domain of I4.0. To summarize, the following SQs were used—in ScienceDirect, Web of Science, and IEEE Xplore—to find publications about I4.0 **readiness**, **maturity**, and **adoption** assessment models respectively:

SQ1 *TITLE-ABS-KEY(iot* `OR` *iiot* `OR` *"internet of things"* `OR` *"industry 4.0"* `OR` *"smart manufacturing"* `OR` *"smart factory")* `AND` *TITLE(**readiness*** `AND` *(model* `OR` *assessment* `OR` *framework* `OR` *evaluation*))

SQ2 *TITLE-ABS-KEY(iot* `OR` *iiot* `OR` *"internet of things"* `OR` *"industry 4.0"* `OR` *"smart manufacturing"* `OR` *"smart factory")* `AND` *TITLE(**maturity*** `AND` *(model* `OR` *assessment* `OR` *framework* `OR` *evaluation*))

SQ3 *TITLE-ABS-KEY(iot* `OR` *iiot* `OR` *"internet of things"* `OR` *"industry 4.0"* `OR` *"smart manufacturing"* `OR` *"smart factory")* `AND` *TITLE(**adoption*** `AND` *(model* `OR` *assessment* `OR` *framework* `OR` *evaluation*))

These SQs were used to find all publications after 2011, in which the concept of I4.0 was first introduced. This led to a long-list of 195 publications, concluding the literature collection strategy.

Consequently, the literature selection strategy started with removing the duplicates, reducing the long-list to 140 publications. Afterwards, several Exclusion Criteria (EC) were enforced to identify the most relevant publications (Table 2.1). According to Keele et al. (2007), EC are essential in removing publications that are irrelevant in answering the composed research questions. These criteria were applied after carefully studying the titles and abstracts of the publications. After applying the EC, the long-list was reduced from 140 to 24 publications. Finally, a Journal Impact Factor (JIF) analysis was conducted to ensure that only the publications of the highest quality would be included. Publications with a JIF below 1.0 were omitted as they were clear outliers. Hence, three articles were deducted from the short-list, leading to the final short-list of 21 publications. Table 2.2 presents this final short-list divided in the assessment types: Readiness Models (RMs), Maturity Models (MMs), and Adoption Models (AMs).

Table 2.1: SLR: exclusion criteria

Index	Description
EC1	Full text not accessible.
EC2	Not written in English or Dutch.
EC3	Does not present a model (or framework, assessment, evaluation) to represent (or explain, assess, evaluate) readiness, maturity, or adoption of I4.0 technologies.
EC4	Does not present a model that is applicable in a manufacturing environment.
EC5	Does not present a model that is built upon a too specific case study and cannot be generalized.

Table 2.2: SLR: final short-list

ID	Type	Publication
1	RM	Jung, K., Kulvatunyou, B., Choi, S., and Brundage, M. P. (2016). An overview of a smart manufacturing system readiness assessment. In *IFIP Advances in Information and Communication Technology*, volume 488, pages 705–712. Springer New York LLC

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Table 2.2—continued from previous page

ID	Type	Publication
2	RM	Pacchini, A. P. T., Lucato, W. C., Facchini, F., and Mummolo, G. (2019). The degree of readiness for the implementation of Industry 4.0. *Computers in Industry*, 113:103125
3	RM	Rajnai, Z. and Kocsis, I. (2018). Assessing industry 4.0 readiness of enterprises. In *SAMI 2018 - IEEE 16th World Symposium on Applied Machine Intelligence and Informatics Dedicated to the Memory of Pioneer of Robotics Antal (Tony) K. Bejczy, Proceedings*, volume 2018-Febru, pages 225–230. Institute of Electrical and Electronics Engineers Inc
4	MM	Canetta, L., Barni, A., and Montini, E. (2018). Development of a Digitalization Maturity Model for the Manufacturing Sector. In *2018 IEEE International Conference on Engineering, Technology and Innovation, ICE/ITMC 2018 - Proceedings*. Institute of Electrical and Electronics Engineers Inc
5	MM	Colli, M., Berger, U., Bockholt, M., Madsen, O., Møller, C., and Wæhrens, B. V. (2019). A maturity assessment approach for conceiving context-specific roadmaps in the Industry 4.0 era. *Annual Reviews in Control*, 48:165–177
6	MM	Colli, M., Madsen, O., Berger, U., Møller, C., Wæhrens, B. V., and Bockholt, M. (2018). Contextualizing the outcome of a maturity assessment for Industry 4.0. *IFAC-PapersOnLine*, 51(11):1347–1352
7	MM	De Carolis, A., Macchi, M., Kulvatunyou, B., Brundage, M. P., and Terzi, S. (2017). Maturity Models and tools for enabling smart manufacturing systems: Comparison and reflections for future developments. In *IFIP Advances in Information and Communication Technology*, volume 517, pages 23–35. Springer New York LLC
8	MM	Leyh, C., Schäffer, T., Bley, K., and Forstenhäusler, S. (2017). Assessing the IT and software landscapes of industry 4.0-enterprises: The maturity model SIMMI 4.0. In *Lecture Notes in Business Information Processing*, volume 277, pages 103–119. Springer Verlag
9	MM	Lin, W. D., Low, M. Y., Chong, Y. T., and Teo, C. L. (2019). Application of SIRI for Industry 4.0 Maturity Assessment and Analysis. In *IEEE International Conference on Industrial Engineering and Engineering Management*, pages 1450–1454. IEEE Computer Society
10	MM	Mittal, S., Khan, M. A., Romero, D., and Wuest, T. (2018a). A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs)
11	MM	Mittal, S., Romero, D., and Wuest, T. (2018b). Towards a smart manufacturing maturity model for SMEs (SM3E). In *IFIP Advances in Information and Communication Technology*, volume 536, pages 155–163. Springer New York LLC
12	MM	Rauch, E., Unterhofer, M., Rojas, R. A., Gualtieri, L., Woschank, M., and Matt, D. T. (2020). A maturity level-based assessment tool to enhance the implementation of industry 4.0 in small and medium-sized enterprises. *Sustainability (Switzerland)*, 12(9):3559
13	MM	Santos, R. C. and Martinho, J. L. (2019). An Industry 4.0 maturity model proposal. *Journal of Manufacturing Technology Management*
14	MM	Schumacher, A., Erol, S., and Sihn, W. (2016). A Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises. In *Procedia CIRP*, volume 52, pages 161–166. Elsevier B.V
15	MM	Schumacher, A., Nemeth, T., and Sihn, W. (2019). Roadmapping towards industrial digitalization based on an Industry 4.0 maturity model for manufacturing enterprises. In *Procedia CIRP*, volume 79, pages 409–414. Elsevier B.V
16	MM	Sjödin, D. R., Parida, V., Leksell, M., and Petrovic, A. (2018). Smart Factory Implementation and Process Innovation. *Research-Technology Management*, 61(5):22–31
17	MM	Trotta, D. and Garengo, P. (2019). Assessing Industry 4.0 Maturity: An Essential Scale for SMEs. In *Proceedings of 2019 8th International Conference on Industrial Technology and Management, ICITM 2019*, pages 69–74. Institute of Electrical and Electronics Engineers Inc
18	MM	Wagire, A. A., Joshi, R., Rathore, A. P. S., and Jain, R. (2020). Development of maturity model for assessing the implementation of Industry 4.0: learning from theory and practice. *Production Planning and Control*, pages 1–20
19	AM	Mittal, S., Khan, M. A., Purohit, J. K., Menon, K., Romero, D., and Wuest, T. (2020). A smart manufacturing adoption framework for SMEs. *International Journal of Production Research*, 58(5):1555–1573
20	AM	Ehie, I. C. and Chilton, M. A. (2020). Understanding the influence of IT/OT Convergence on the adoption of Internet of Things (IoT) in manufacturing organizations: An empirical investigation. *Computers in Industry*, 115:103166
21	AM	Tripathi, S. (2019). System Dynamics perspective for Adoption of Internet of Things: A Conceptual Framework. In *2019 10th International Conference on Computing, Communication and Networking Technologies, ICCCNT 2019*. Institute of Electrical and Electronics Engineers Inc

2.2 Defining Industry 4.0

The manufacturing industry is experiencing a significant change labeled as 'the fourth industrial revolution'. While all the authors of Table 2.2 acknowledge this revolution, there seems to be no agreement about its definition (Leyh et al., 2017; Trotta and Garengo, 2019; Wagire et al., 2020). According to Hofmann and Rüsch (2017), I4.0 still *"lacks a precise, generally accepted definition"*. The fact that this revolution is also named differently across the world, does not help towards reaching a coherent definition. According to Mittal et al. (2020), I4.0 is also known as 'Smart Manufacturing' in the United States, 'Smart Factory' in Asia (most noticeably: South-Korea), and 'Industrie 4.0' in Germany. In this research, the name Industry 4.0 (I4.0) will be used.

For the definition of I4.0, existing definitions were first assessed. For example, according to Trotta and Garengo (2019), *"Industry 4.0 is a new organizational model based on the implementation of several* ***technologies*** *(i.e. Cloud, Additive Manufacturing, Cyber Security, Big Data Analytics, Simulation, Augmented Reality, Horizontal and Vertical Integration) that work together for the* ***improvement*** *of organizational* ***performance****"*. Pacchini et al. (2019) state that *"I4.0 is an* ***integrated*** *set of intelligent production systems and advanced information* ***technologies*** *that are based on sets of* ***integrated*** *software systems"*. Finally, Li et al. (2017) claim that *"I4.0 is a set of* ***technologies*** *based on the digitization and* ***interconnection*** *of all production units present within an economic system"*. From these three definitions, the following recurring themes can be identified:

- Technologies
- Improvement
- Integration

Using these themes, I4.0 could be initially defined as the phenomenon of using **technologies** to improve the **integration** of people, objects, and systems into the value chain (Rajnai and Kocsis, 2018) with the objective to improve organizational **performance**. However, this initial interpretation of I4.0 is relatively vague and is in need of some refinements.

Technology is a broad term. According to Merrian-Webster (2020), technology can be defined as: *"a manner of accomplishing a task especially using technical processes, methods, or knowledge"*. In I4.0, these technical methods differ or are evolved from previous industrial revolutions. Moreover, one could argue these methods define I4.0. According to Pacchini et al. (2019); Santos and Martinho (2019), the adoption of I4.0 is enabled by I4.0 enabling technologies i.e. Internet of Things (IoT), Big Data, Cloud Computing, Cyber Physical System (CPS), Autonomous Robot, Additive Manufacturing, Augmented Reality (Pacchini et al., 2019; Santos and Martinho, 2019; Trotta and Garengo, 2019). In addition, Santos and Martinho (2019) argue that the attributes related to these technologies are intrinsically linked to CPS and IoT, and can be summarized in digitalization, connectivity, interoperability, adaptability, scalability, efficiency, predictive capability, reconfigurability. Note that some of these attributes can be linked to the integration theme of the initial interpretation of I4.0.

Integration is one of most important characteristics of I4.0. According to Leyh et al. (2017), horizontal and vertical integration across the entire value chain is vital in adopting the concept of I4.0. Complementing the technological attributes of Santos and Martinho (2019), Leyh et al. (2017) introduce the concept of connecting the physical world to the virtual world. In this integration, the authors claim that all process steps of the engineering are digitized and interconnected, to share and distribute information along the vertical and the horizontal value chains.

This extensive integration leads to organizational improvements. According to Rajnai and Kocsis (2018), this new level of organization and control forms a real-time optimized, self-organizing system. In addition, Santos and Martinho (2019) state that completely new solutions and services will emerge because of this integration, generating new business opportunities. For example, emerging concepts such as mass customization and business servitization can make great use of I4.0 technologies. Moreover, Pacchini et al. (2019) argue that I4.0 is on a path with no return and will become a competitive challenge for companies interested in long-term survival with adequate performance. In conclusion, the use of I4.0 technologies can enable horizontal and vertical integration across the entire value chain, leading to an increase of organizational performance. This increased organizational performance can be both internal and external. Internal improvements may be increased efficiency, productivity, and reduced costs. External improvements may yield a better market position compared to the competition, and better customer service. Based on the literature, I4.0 in this research is defined as follows:

Definition 2.2.1. I4.0 Industry 4.0 (I4.0) is a new organizational model based on the implementation of I4.0 technologies (e.g. IoT, Big Data Analytics) that enable horizontal and vertical integration across the entire value chain, leading to the improvement of organizational performance.

2.3 Defining I4.0 readiness and maturity

In order to support companies in their roadmap towards I4.0, readiness and maturity assessment models offer a methodology to analyze their status quo through a dedicated assessment instrument (Canetta et al., 2018). With these obtained insights, companies are able to make better substantiated decisions in their I4.0 proceedings. Therefore, increasing the chance of successfully joining the I4.0 movement, and ultimately achieving—the discussed—organizational benefits. These assessment models help companies to prepare for the challenges and requirements of I4.0, and guide companies in reaching higher adoption levels of I4.0, and are respectively distinguished as:

- I4.0 readiness assessment models
- I4.0 maturity assessment models

These readiness and maturity assessments have been proposed to guide organizations through their maturing process or transformation phases in a more effective and efficient way (Wagire et al., 2020). However, the difference between the terms 'readiness' and 'maturity' is discussed by many researchers. For example, the publication of Mittal et al. (2018a) refer to readiness models as maturity models. In contrast, Pacchini et al. (2019); Schumacher et al. (2016) claim that readiness is different from maturity, and that these terms cannot be used as synonyms. Pacchini et al. (2019) propose readiness as the state in which the organization is ready to accomplish a task, and maturity as the level of evolution that an organization has accomplished with respect to that task. Schumacher et al. (2016) claim that the difference between readiness and maturity is that *"readiness assessments take place* ***before*** *engaging in the maturing process whereas maturity assessment aims for capturing the* ***as-it-is*** *state whilst the maturing process"*. Therefore, underlining the difference in timing. The confusion between these terms and their assessments may be explained due to their relation to each other (De Carolis et al., 2017). For example, the results of a readiness assessment could be used as a baseline for a maturity assessment. Therefore, it is important to provide definitions of both readiness and maturity assessments, since the understanding of these terms and models may vary within the same field of expertise.

According to Benedict et al. (2017), a readiness assessment can evaluate the preparedness of capabilities towards a goal. In addition, a more comprehensive definition is given by Mittal et al. (2018a), who define readiness assessments as *"evaluation tools to analyze and determine the level of preparedness of the conditions, attitudes, and resources, at all levels of a system, needed for achieving its goal(s)"*. Moreover, De Carolis et al. (2017) define readiness assessments as tools to measure the capability of a manufacturing firm to deploy I4.0 enablers.

Maturity models are defined by Santos and Martinho (2019) as conceptual structures that define the maturity of a determined interest area of study. Mittal et al. (2018a) state that maturity models should help individuals or entities to reach a more sophisticated maturity level in people/culture, process/structures and/or objects/technologies following a step-by-step continuous improvement process. Finally, De Carolis et al. (2017) define maturity models as how well a manufacturing firm has employed I4.0 enablers. In order to provide clarity and agreement about the terms 'readiness' and 'maturity' in this research. Two adapted definitions of I4.0 readiness and maturity are presented based on the definitions of De Carolis et al. (2017); Mittal et al. (2018a):

Definition 2.3.1. I4.0 readiness The level of preparedness of the conditions, attitudes, and resources, at all levels of an organization, before engaging in I4.0 proceedings.

Definition 2.3.2. I4.0 maturity The level of maturity of the conditions, attitudes, and resources at all levels of an organization while engaging in I4.0 proceedings.

2.4 Overview extracted models

Table 2.3 presents an overview of the analyzed models from the literature study. In total, 26 models from 21 scientific publications were analyzed. From these models, six models were focused on I4.0 readiness, and 20 models on I4.0 maturity. In addition, three publications introduced I4.0 adoption models. However, these models will be neglected—as previously mentioned—due to their completely different structure and usage.

The overview also states the purpose of the model. According to de Bruin et al. (2005), a maturity model can have three different purposes:

- Descriptive
- Prescriptive
- Comparative

Descriptive maturity models only present the current maturity state, whereas prescriptive models also indicate how to achieve higher maturity levels. Finally, comparative models are more quantitative in nature, and are able to compare similar practices across organizations, to benchmark maturity within industries. Therefore, comparative maturity models are also referred to as benchmarking models. As can be seen in Table 2.3, all the models are descriptive in nature, and six and four models have additional prescriptive and comparative features respectively.

All the models were assessing dimensions. These dimensions describe what aspects should be measured to adequately assess I4.0 readiness and maturity. Figure 2.2 presents a word cloud of the extracted dimensions (total of n=*134*) from the studied I4.0 readiness and maturity models. Note that 'Technology' seems to be the most frequent recurring dimension.

Figure 2.2: SLR: word cloud of extracted dimensions, n=*134*

Table 2.3: SLR: overview extracted I4.0 readiness and maturity assessment models

	Index	Model name	Author(s)/institution	Model purpose	# Dimensions	# Levels	Measurement method
Readiness	1	SMSRL	Jung et al. (2016)	Descriptive, comparative	4	n.a.	Counting measures, activity maturity scoring schemes, incidence scoring schemes
	2	I4.0 readiness model	Pacchini et al. (2019)	Descriptive, comparative	8	4 (L0-L3)	Interviews
	3	IMPULS	IMPULS Foundation	Descriptive	6	6 (L0-L5)	Questionnaires
	4	DREAMY	De Carolis et al. (2017)	Descriptive, prescriptive	4	5 (L1-L5)	Interviews
	5	SIRI	Lin et al. (2019)	Descriptive	10	6 (L0-L5)	Interviews, questionnaires, focus groups
	6	I4.0 readiness model	Akdil et al. (2018)	Descriptive	3	4 (L0-L3)	Questionnaires
Maturity	1	PwC I4.0 maturity model	PwC	Descriptive	7	4 (L1-L4)	n.a.
	2	Acatech I4.0 maturity model	acatech	Descriptive	4	6 (L1-L6)	Questionnaires
	3	Digital Maturity Model 4.0	Forrester	Descriptive	4	4 (L1-L4)	Questionnaires
	4	Digitalization Maturity Model	Canetta et al. (2018)	Descriptive, comparative	5	4 (L1-L4)	Questionnaires
	5	360DMA	Colli et al. (2019)	Descriptive	5	6 (L0-L5)	Questionnaires, workshops
	6	MOM	De Carolis et al. (2017)	Descriptive, comparative	8	6 (L0-L5)	Questionnaires
	7	SIMMI	Leyh et al. (2017)	Descriptive, prescriptive	4	5 (L1-L5)	Interviews
	8	Connected Enterprise Maturity	Rockwell Automation	Descriptive, prescriptive	4	n.a.	n.a.
	9	Three-stage maturity model	Ganzarain and Errasti (2016)	Descriptive	3	5 (L1-L5)	n.a.
	10	Smartness Assessment Framework	Lee et al. (2017)	Descriptive	4	5 (L1-L5)	n.a.
	11	I4.0 maturity model	Gökalp et al. (2017)	Descriptive	5	6 (L0-L5)	n.a.
	12	AMM	Scremin et al. (2018)	Descriptive	3	n.a.	Interviews
	13	SM^{3}E	Mittal et al. (2018b)	Descriptive	5	5 (L1-L5)	n.a.
	14	I4.0 maturity model	Rauch et al. (2020)	Descriptive, prescriptive	4	5 (L1-L5)	Questionnaires
	15	I4.0 maturity model	Santos and Martinho (2019)	Descriptive	5	6 (L0-L5)	Questionnaires
	16	I4.0 maturity model	Schumacher et al. (2016)	Descriptive	9	5 (L1-L5)	Questionnaires
	17	I4.0 realization model	Schumacher et al. (2019)	Descriptive, prescriptive	8	4 (L1-L4)	Questionnaires
	18	I4.0 maturity model	Sjödin et al. (2018)	Descriptive	3	4 (L1-L4)	n.a.
	19	I4.0 maturity model	Trotta and Garengo (2019)	Descriptive	5	5 (L1-L5)	Questionnaires
	20	I4.0 maturity model	Wagire et al. (2020)	Descriptive, prescriptive	7	4 (L1-L4)	Questionnaires

The number of dimensions per model ranged from three to a maximum of ten dimensions, with an average number of 5.269 dimensions. Figure 2.3 presents a frequency diagram of the number of dimensions per model. It can be observed that most models in the literature measure four, five, and three dimensions (from respectively eight, six, and four assessed models out of a total of 26 models).

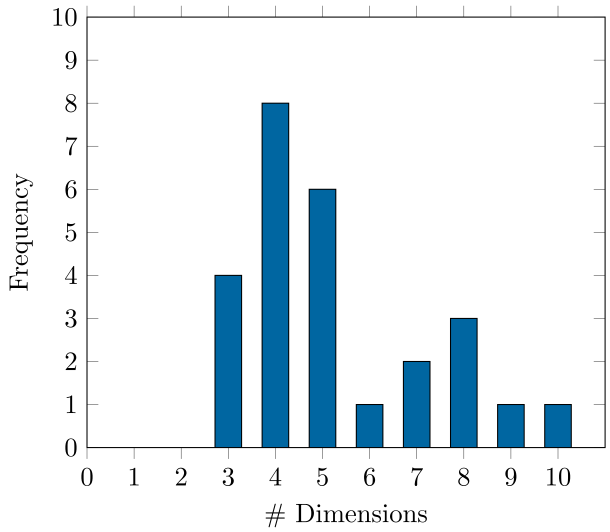

Figure 2.3: SLR: frequency diagram of # dimensions per model

In addition, Table 2.3 presents the number of levels of each analyzed model. The dimensions are adequately assigned to these readiness or maturity levels or stages. These levels range from level zero (L0) or level one (L1) to a maximum of level six (L6). In addition, the levels are often labeled with relatable names. For example, the proposed I4.0 maturity model of Mittal et al. (2018b) introduces the levels novice (L1), beginner (L2), learner (L3), intermediate (L4), and expert (L5). According to this example, these levels indicate a kind of progression: where a higher level stands for a higher maturity or readiness state.

Finally, the generated overview presents the different measurement method(s) used by the extracted I4.0 readiness and maturity models. Questionnaires were used the most due to their self-assessment capability. They are relatively easy to understand and to use. The second most-used measurement method is interviews. During these interviews, experts of companies are asked about different dimensions to determine a readiness or maturity level in collaboration with the interviewee. Focus groups and workshops were also used, but only for complementing interviews and questionnaires.

After analyzing the different models, three recurring shortcomings were identified. First, Pacchini et al. (2019); Trotta and Garengo (2019) argue that many models focus too heavily on technology, and lack other important dimensions. They discuss that non-technology factors are just as important, or even more crucial. Second, during the evaluation of the models of Colli et al. (2018); De Carolis et al. (2017); Rauch et al. (2020), it was observed that the assessment models were deemed to be too resource-intensive when executing them. There is a challenging trade-off between the size of the measurement method e.g. number of questions of a questionnaire, and the associated accuracy of the model. Finally, due to the novelty of the models of Colli et al. (2018); Rauch et al. (2020); Santos and Martinho (2019); Schumacher et al. (2019); Trotta and Garengo (2019); Wagire et al. (2020), the authors claim that the models need more evaluation and case-studies to assure validity.

2.5 Theoretical framework I4RMM

The previous section provided an overview of the available I4.0 readiness and maturity models proposed by the scientific community. From this analysis, the following needs were recognized:

- The need for an integrated I4.0 readiness and maturity model to face the disconnection between these assessment types.
- The need for model validation due to their relative novelty.

This section provides the initial Industry 4.0 Readiness Maturity Model (I4RMM) including the design choices to satisfy the first need.

The initial model aims to measure both I4.0 readiness and maturity, to provide guidance to manufacturing organizations in their I4.0 proceedings. After the model has been completely developed and validated, organizations could use the model to assess their I4.0 status, and identify possible improvement opportunities to improve this status. Respectively, this can be described as a descriptive and prescriptive model purpose (de Bruin et al., 2005). To achieve this model purpose, the I4RMM must contain the following components (Fraser et al., 2002):

- a number of dimensions;
- a number of levels;
- a descriptor for each level i.e. label;
- a generic description or summary of the characteristics of each level as a whole;
- a description of each level per dimension.

In addition, the initial I4RMM will use a 'continuous' representation, to allow organizations to focus on improving capability in a specific dimension (Fraser et al., 2002). Therefore, different dimensions may be scored on different levels. The reason for this design choice has to do with the intended audience of the model, which is rather broad i.e. manufacturing organizations. These manufacturing organizations can be of different sizes, industries, and focus. By using a 'continuous' representation, the initial model provides flexibility to organizations to choose their own improvement path(s), to organize improvement procedures that best meets the agenda of the organization.

2.5.1 Dimensions

According to de Bruin et al. (2005), the identification of domain components i.e. dimensions, can be achieved through an extensive literature review. Therefore, the initial version of the I4RMM was built using the dimensions found in the previous section.

In constructing this version, the goal was to achieve an extensive base model. This base model aims to include all facets of an organization i.e. including both organizational and technological factors, that are deemed to be important to measure when assessing I4.0 readiness and maturity. Hence, making the model versatile in use and utilization. These dimensions were determined by applying inductive coding as proposed by Chandra et al. (2019). In total, 35 and 99 dimensions were extracted from the readiness and maturity assessment models respectively (total of n=*134*). These dimensions were aggregated and labeled with a code on a first level. For example, the dimensions *"cloud computing"* (Pacchini et al., 2019), *"IT"* (Jung et al., 2016), and *"smart manufacturing technology"* (Wagire et al., 2020) were labeled with 'Technology', to describe a certain theme. Another example was to label the dimensions of *"leadership competency"* (Lin et al., 2019), *"employees"* (Schumacher et al., 2019), and *"workforce"* (Santos and Martinho, 2019) with 'People' to describe a more non-technological theme. The appendix of Appendix G presents the complete list of the dimensions with their associated codes. This method also complements the approach from Rajnai and Kocsis (2018), to bundle indicators in thematic groups. Table 2.4 presents the final collection of coded dimensions with their frequency, including a description based on the literature. The descriptions were adapted from multiple publications, as indicated in the table. Table 2.5 presents the mapping of these dimensions on the extracted models.

According to de Bruin et al. (2005), the identification of sub-dimensions is recommended for complex domains, enabling richer analysis of maturity results. However, the authors also argue that a literature review is unlikely to provide sufficient information to populate this layer of detail. This was also observed during the SLR, in which almost no (recurring) sub-dimensions could be identified. Therefore, the initial version of the I4RMM focuses on the main dimensions as presented in Table 2.4. To avoid absolute exclusion of potential sub-dimensions, these sub-components were further explored in a Delphi study (subsection 3.3.3).

Table 2.4: SLR: results of coded dimensions in order of frequency, *n=134*

Index	Dimension code	#	Description
1	Technology	32	The extent to which I4.0 technologies are implemented and used (Canetta et al., 2018; Mittal et al., 2020; Schumacher et al., 2019; Trotta and Garengo, 2019).
2	Operations	23	The extent to which processes are decentralized and make use of I4.0 paradigms e.g. agile manufacturing systems, and monitoring and decision systems (Rauch et al., 2020; Schumacher et al., 2016).
3	Strategy & Organization	23	The extent to which the strategy currently adopted by companies is related to I4.0 implementation, including the acknowledgement of an I4.0 roadmap (Schumacher et al., 2016, 2019; Trotta and Garengo, 2019; Wagire et al., 2020).
4	People	15	The extent to which people are competent and open to new I4.0 technologies, and the extent to which HRM practices support I4.0 implementation (Rauch et al., 2020; Schumacher et al., 2016; Sjödin et al., 2018; Trotta and Garengo, 2019).
5	Products & Services	14	The extent to which products are individualized and product characteristics are flexible. This also includes product tracking, management of products' lifecycle, and data driven services and product data usage (Canetta et al., 2018; Leyh et al., 2017; Mittal et al., 2018a; Schumacher et al., 2016, 2019; Trotta and Garengo, 2019).
6	Process	12	The extent to which companies support departments collaboration, machine and system integration with the help of I4.0 technologies. This includes self-optimization and self-configuration of processes of production, maintenance, and support processes (Canetta et al., 2018; Santos and Martinho, 2019; Schumacher et al., 2019; Sjödin et al., 2018; Wagire et al., 2020).
7	Integration	6	The extent to which vertical and horizontal integration is in place across the value chain (Leyh et al., 2017; Lin et al., 2019; Rajnai and Kocsis, 2018).
8	Culture	5	The extent to which the culture is open to innovation enabled by I4.0 (Santos and Martinho, 2019; Schumacher et al., 2016; Wagire et al., 2020).
9	Connectivity	3	The availability of infrastructural elements needed for data transmission inside and outside the organization (Colli et al., 2019, 2018; Lin et al., 2019).
10	Collaboration	1	The extent to which formal channels are enabled for employees to share information and work together, as well as institutional structures and systems that allow collaborative behavior (Lin et al., 2019).

Table 2.5: SLR: mapping dimensions on extracted I4.0 readiness and maturity assessment models

	Index	Model name	Author(s)/institution	Technology	Operations	Strategy & Organization	People	Products & Services	Process	Integration	Culture	Connectivity	Collaboration
Readiness	1	SMSRL	Jung et al. (2016)	x	x	x						x	
	2	I4.0 readiness model	Pacchini et al. (2019)	x									
	3	IMPULS	IMPULS Foundation	x	x	x	x	x					
	4	DREAMY	De Carolis et al. (2017)	x	x	x			x				
	5	SIRI	Lin et al. (2019)	x		x	x			x		x	x
	6	I4.0 readiness model	Akdil et al. (2018)			x		x	x				
Maturity	1	PwC I4.0 maturity model	PwC	x	x	x		x		x	x		
	2	Acatech I4.0 maturity model	acatech	x		x		x			x		
	3	Digital Maturity Model 4.0	Forrester	x		x		x			x		
	4	Digitalization Maturity Model	Canetta et al. (2018)	x		x	x	x	x				
	5	360DMA	Colli et al. (2019)	x	x	x		x				x	
	6	MOM	De Carolis et al. (2017)		x								
	7	SIMMI	Leyh et al. (2017)	x				x		x			
	8	Connected Enterprise Maturity	Rockwell Automation	x					x				
	9	Three-stage maturity model	Ganzarain and Errasti (2016)										
	10	Smartness Assessment Framework	Lee et al. (2017)	x	x	x			x				
	11	I4.0 maturity model	Gökalp et al. (2017)	x	x	x			x				
	12	AMM	Scremin et al. (2018)		x	x		x					
	13	SM^{3}E	Mittal et al. (2018b)			x	x	x	x				
	14	I4.0 maturity model	Rauch et al. (2020)	x	x	x					x		
	15	I4.0 maturity model	Santos and Martinho (2019)		x	x	x	x	x				
	16	I4.0 maturity model	Schumacher et al. (2016)	x	x	x	x	x			x		
	17	I4.0 realization model	Schumacher et al. (2019)	x		x	x	x	x				
	18	I4.0 maturity model	Sjödin et al. (2018)	x			x		x				
	19	I4.0 maturity model	Trotta and Garengo (2019)	x	x	x	x	x					
	20	I4.0 maturity model	Wagire et al. (2020)	x		x	x		x				

2.5.2 Levels & labels

To complete the initial framework, both readiness and maturity levels must be added to the discussed dimensions. According to the literature review, the levels indicate a kind of progression. A higher readiness and maturity level must indicate a higher level of preparedness (Definition 2.3.1) and maturity (Definition 2.3.2) respectively.

The readiness levels aim to capture the starting-point and allow for initializing the development process (Schumacher et al., 2019). To integrate these readiness levels with the maturity levels, and to avoid a simple combination of two models. Two readiness levels were designed to assess the level of preparedness, needed to successfully engage in I4.0. These levels are based on Definition 2.3.1, which was synthesized from the literature.

- R0 *Unprepared*: the organizational dimension is not prepared i.e. does not have the sufficient conditions, attitudes or resources to successfully engage in its digital transformation.
- R1 *Ready*: the organizational dimension is fully ready to start its digital transformation.

According to de Bruin et al. (2005), and complemented by the extracted models, a common design principle is to represent maturity as a number of cumulative stages (*n=5*) where higher stages build on the requirements of lower stages, with level five representing high maturity and level one low maturity. However, the authors state that the number of stages may vary from model to model, as long as the final stages are distinct and well-defined. Furthermore, de Bruin et al. (2005) argue that the model design needs an appropriate balance between a complex reality and model simplicity. For example, a model that is oversimplified may not adequately reflect the complexities of the domain and may not provide sufficient meaningful information to the audience. However, a model that is too complicated may limit interest or create confusion. Therefore, due to the inclusion of—the discussed—two readiness levels, the researcher decided to limit the number of maturity levels to four distinct stages. Hence, attempting a balance between domain complexity and model simplicity by generating six different levels in total (diverging with one level from the common design principle).

To complement the 'continuous representation' design choice, the capability level structure as proposed by CMMI Product Team (2010) was adopted. These four levels provide an evolutionary path to performance improvement. Each level builds on the previous level by adding new functionality or rigor resulting in increased capability. According to the SLR, many final stages are aimed towards continuous improvement and optimization e.g. (Jung et al., 2016; Leyh et al., 2017; Lin et al., 2019). Therefore, this initial model adopts this direction, by adapting the generic capability level descriptions as proposed by CMMI Product Team (2010). Finally, for consistency: the first level uses the same suffix as the first readiness level:

- M0 *Incomplete*: incomplete approach to meeting the intent of the dimension or minimal effort in I4.0 paradigms.
- M1 *Performed*: complete set of practices to meet the full intent of the dimension in at least one functional area.
- M2 *Managed*: complete set of practices that address the full intent of the dimension in all functional areas.
- M3 *Defined*: focuses on continuous improvement and optimization.

Finally, by combining the synthesized dimensions and levels and labels, a blue-print of the I4RMM was created. Figure 2.4 presents this blue-print.

	Readiness		Maturity			
Dimension	**R0** Unprepared	**R1** Ready	**M0** Incomplete	**M1** Performed	**M2** Managed	**M3** Defined
Technology	...	...	...	...	...	...
Operations	...	...	...	...	...	...
Strategy & Organization	...	...	...	...	...	...
People	...	...	...	...	...	...
Products & Services	...	...	...	...	...	...
Process	...	...	...	...	...	...
Integration	...	...	...	...	...	...
Culture	...	...	...	...	...	...
Connectivity	...	...	...	...	...	...
Collaboration	...	...	...	...	...	...

Figure 2.4: SLR: blue-print I4RMM

Note that the unique level descriptions have not been formalized yet in this blue-print. Before constructing these heavy dimension-dependent descriptions, the dimensions were first validated by conducting a Delphi study (subsection 3.3.3).

2.6 Conclusion

In section 2.3, the similarities and differences between the terms 'readiness' and 'maturity' are discussed. To summarize that discussion: readiness and maturity are relative and related (De Carolis et al., 2017), but different (Pacchini et al., 2019). This perceived difference leads to a segmentation of assessment models in 'readiness assessments', and 'maturity assessments'. Therefore, producing a vast variety of different models.

However, when briefly analyzing the measured dimensions of these tools, it becomes clear that the models do not assess entirely different aspects. For example, the readiness models of Akdil et al. (2018); De Carolis et al. (2017); Jung et al. (2016); Rajnai and Kocsis (2018) and maturity models of Gökalp et al. (2017); Rauch et al. (2020); Santos and Martinho (2019); Wagire et al. (2020) all measure organizational, and technological dimensions. In addition, all mentioned models are similar in structure. They all have a scoring mechanism, ranging from either level zero or level one (L0, L1 respectively) to level five or level six (L5, L6 respectively).

Mittal et al. (2018a) complement this observation and identified the research gap of the current disconnection between I4.0 maturity and readiness models. The authors claim that there is a current disconnection, where maturity models do not include a readiness assessment. Moreover, De Carolis et al. (2017) acknowledge that some assessment methodologies are merging, but state the need for an established approach or framework to combine these assessment methods. Furthermore, Mittal et al. (2018a) argue that a unique method is needed that allows integrating self-assessing approaches for evaluating the current level of I4.0 readiness and maturity. Therefore, this research project aims to develop and evaluate a first attempt in integrating I4.0 readiness and maturity models in a new solution: the Industry 4.0 Readiness Maturity Model (I4RMM).

Based on the results of the literature review, the SLR provided a synthesized blue-print of this I4RMM. This blue-print consists of ten organizational dimensions with two readiness and four maturity levels. The next chapter will elaborate on further development and refinement of this model.

Chapter 3

Method

This chapter provides an overview and explanation of the used research methods. The research project follows the Design Science Research (DSR) paradigm as proposed by Hevner et al. (2004). Using this paradigm and the results of the SLR, an initial version of the Industry 4.0 Readiness Maturity Model (I4RMM) is presented, and further developed and refined using an extensive Delphi study.

First, the DSR methodology is presented. Second, the initial version of the I4RMM is established. Finally, the structure and the results of the Delphi study are presented.

3.1 Design Science Research (DSR)

Figure 3.1 presents how this research is structured around the Design Science Research framework. The Design Science Research (DSR) methodology by Hevner et al. (2004) is fundamentally a problem-solving paradigm in Information Systems (IS) research. This IS research is motivated by a single (or multiple) business need(s) from what is called the 'environment'. This environment defines the problem space in which the phenomena of interest resides (Hevner et al., 2004), and provides relevance of the IS research. The business need was established with help from senior consultants of Atos, in which they argued that companies in practice lack the knowledge, expertise, and methodology to make a sensible assessment of their I4.0 readiness and maturity.

Given such a business need, IS research is conducted in two complementary phases. Design science addresses research through the building and evaluation of artifacts designed to meet the identified business need (Hevner et al., 2004). In this research, the final artifact will be the Industry 4.0 Readiness Maturity Model (I4RMM), aiming to help companies assessing their I4.0 readiness and maturity. The I4RMM will be evaluated by using a multiple-case study, and a Technology Acceptance Model (TAM) survey (chapter 5).

The 'knowledge base' provides the raw materials from and through which IS research is accomplished (Hevner et al., 2004). This knowledge base is composed of prior IS research and provides existing theories, methods, and models that are used in the building phase of the research study. Therefore, rigor is achieved by successfully applying existing foundations and methods. In this research project, the knowledge base consists of the results of the SLR, and provides a need for the I4RMM from a scientific perspective. Finally, the contribution of the IS research is assessed as the artifact is applied to the business need in an appropriate environment, and as the artifact functions as an addition to the knowledge base for further research and practice (Hevner et al., 2004).

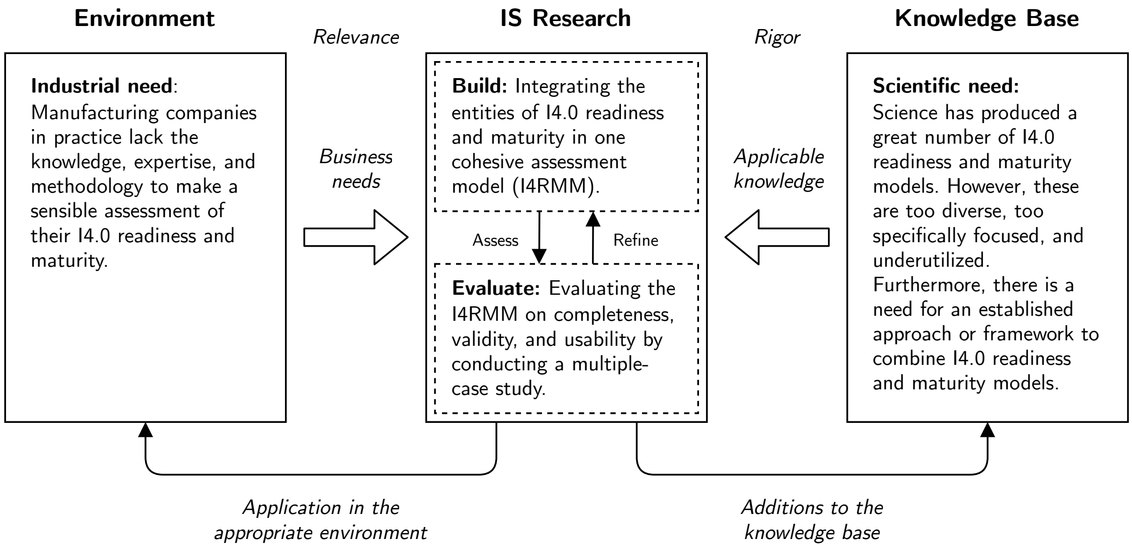

Figure 3.1: DSR framework (Hevner et al., 2004) applied for this research

3.1.1 Design Science Research Process (DSRP)

In addition to the DSR, this research follows the Design Science Research Process (DSRP) model as proposed by Peffers et al. (2006). These authors proposed a model which can be used for the production and presentation of design science research in IS. It gives a better understanding of the course of activities that are needed to successfully conduct DSR. Their process model consists of the following six activities in a nominal sequence:

1. Problem identification and motivation
2. Objectives of a solution
3. Design and development
4. Demonstration
5. Evaluation
6. Communication

Figure 3.2 presents the DSRP for this research project. First, the problem and its importance were identified in the SLR. Second, the objectives of the solution aim to tackle the found research gaps. Third, the initial version of the artifact (I4RMM) was proposed as a synthesized model that integrates elements found in the academic literature. Subsequently, this model was used as a base-model, and further developed by conducting an extensive Delphi study. Fourth, the efficacy of the artifact to solve the problem was demonstrated with case studies. Fifth, the artifact was evaluated on completeness, validity, and usability based on the results of the multiple-case study. Finally, the project was communicated in this master thesis, following the publication schema of Gregor and Hevner (2013).

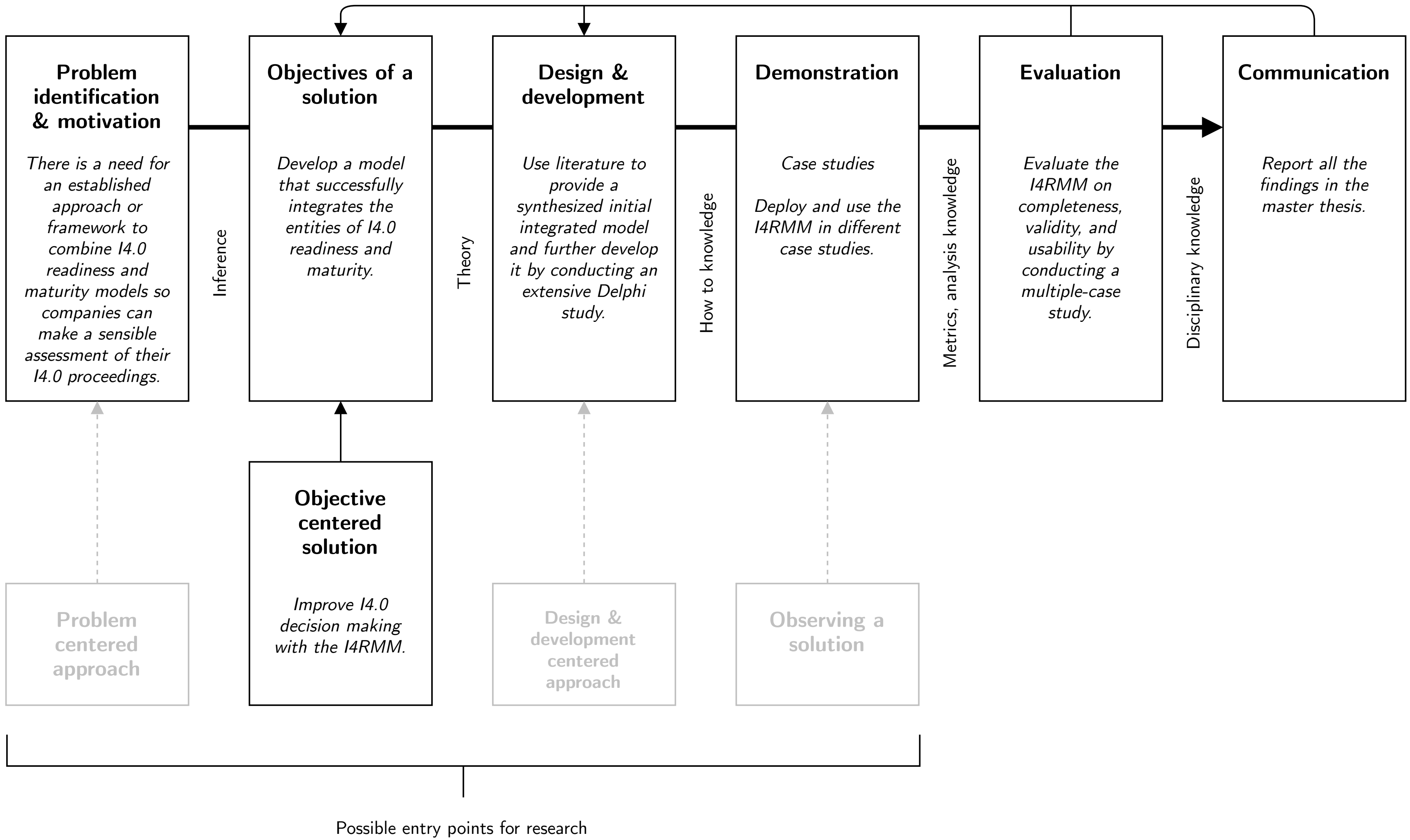

Figure 3.2: DSRP model (Peffers et al., 2006) applied for this research

3.2 Initial version of the I4RMM

The initial version of I4RMM was provided in the previous chapter. In which a blue-print was synthesized based on a literature review. This literature review presented an overview of the available I4.0 readiness and maturity models that have been presented in the academic literature. The blue-print consists of ten organizational dimensions with two readiness and four maturity levels. Table 3.1 presents the dimensions of the initial I4RMM. This model was used as input for the Delphi study, in which the model was further refined and developed.

Table 3.1: I4RMM: initial version including dimensions and descriptions

Index	Dimension code	Description
1	Technology	The extent to which I4.0 technologies are implemented and used (Canetta et al., 2018; Mittal et al., 2020; Schumacher et al., 2019; Trotta and Garengo, 2019).
2	Operations	The extent to which processes are decentralized and make use of I4.0 paradigms e.g. agile manufacturing systems, and monitoring and decision systems (Rauch et al., 2020; Schumacher et al., 2016).
3	Strategy & Organization	The extent to which the strategy currently adopted by companies is related to I4.0 implementation, including the acknowledgement of an I4.0 roadmap (Schumacher et al., 2016, 2019; Trotta and Garengo, 2019; Wagire et al., 2020).
4	People	The extent to which people are competent and open to new I4.0 technologies, and the extent to which HRM practices support I4.0 implementation (Rauch et al., 2020; Schumacher et al., 2016; Sjödin et al., 2018; Trotta and Garengo, 2019).
5	Products & Services	The extent to which products are individualized and product characteristics are flexible. This also includes product tracking, management of products' lifecycle, and data driven services and product data usage (Canetta et al., 2018; Leyh et al., 2017; Mittal et al., 2018a; Schumacher et al., 2016, 2019; Trotta and Garengo, 2019).
6	Process	The extent to which companies support departments collaboration, machine and system integration with the help of I4.0 technologies. This includes self-optimization and self-configuration of processes of production, maintenance, and support processes (Canetta et al., 2018; Santos and Martinho, 2019; Schumacher et al., 2019; Sjödin et al., 2018; Wagire et al., 2020).
7	Integration	The extent to which vertical and horizontal integration is in place across the value chain (Leyh et al., 2017; Lin et al., 2019; Rajnai and Kocsis, 2018).
8	Culture	The extent to which the culture is open to innovation enabled by I4.0 (Santos and Martinho, 2019; Schumacher et al., 2016; Wagire et al., 2020).
9	Connectivity	The availability of infrastructural elements needed for data transmission inside and outside the organization (Colli et al., 2019, 2018; Lin et al., 2019).
10	Collaboration	The extent to which formal channels are enabled for employees to share information and work together, as well as institutional structures and systems that allow collaborative behavior (Lin et al., 2019).

3.3 Model refinement via Delphi study

According to de Bruin et al. (2005), the Delphi technique *"includes the identification of a panel of industry experts from whom information about a specific topic is solicited through the iterative completion of a number of surveys"*. This technique is suited for this research due to its exploratory nature. Moreover, Delphi studies are considered beneficial when research is:

- dealing with complex issues (Okoli, 2015);
- seeking to combine views to improve decision making (Bass, 1970);
- aiming to contribute to an incomplete state of knowledge (Delbecq et al., 1975).

This research recognized these issues in the development of an integrated I4.0 readiness and maturity model, making it a suitable research method. The Delphi study helped to elicit industry expert opinion to ensure the validity and relevance of the I4RMM during development.

3.3.1 Setup

The Delphi study consisted of four rounds with nine I4.0 domain experts to gather information, use that information to develop the model, and to evaluate the development steps and to finalize the I4RMM. These I4.0 domain experts were formed as a Delphi panel. This panel selection procedure will be elaborated in the next subsection.

In each round, the researcher asked the Delphi panel to (re)-evaluate a specific component of the I4RMM. These components can be distinguished into:

1. I4RMM: dimensions
2. I4RMM: levels & labels

The first component was assessed in rounds 1-2, and the second component in rounds 3-4. For each round, the researcher asked the Delphi panel to evaluate the respective model component by participating in an online survey hosted in Microsoft Forms. In this survey, the Delphi panel members were asked to vote on each element of the respective component e.g. to vote on the 'Technology' dimension. During voting, the participants could choose out of the following options:

- Stay
- Change
- Can go

The first option 'Stay' implies that the participant agrees with the current element and its form e.g. agrees with the inclusion of the 'Technology' dimension and its definition, and that the element does not require any change. The second option 'Change' implies that the participant argues that the element can stay in the model, though it requires an alteration e.g. the definition of the 'Technology' dimension should be refined. The final option: 'Can go' implies that the participant disagrees with the current element and argues that the element should be omitted completely from the model e.g. the 'Technology' dimension is not important to measure and should be removed from the I4RMM. When the participants chose either the 'Change' or 'Can go' option, they were required to fill in an explanation of their reasoning. After all the members of the Delphi panel completed the survey, the researcher consolidated the results and this formed the end of the round.

In the subsequent round, the researcher provided a result sheet to the participants. The objective of this result sheet was twofold:

- to inform the participants about the results of the previous round;
- to inform the participants about the new iteration of the I4RMM based on the results of the previous round.

All the shared results were anonymized. For this subsequent round, the researcher encouraged the panel members to study these results before engaging in the round. Afterwards, the researcher asked the Delphi panel to (re-)evaluate this new iteration of the model, using the same 'Stay, Change, Can Go' voting system. This technique makes the development procedure transparent, by informing all the Delphi panel members of each new model iteration and allow them to react on it.

The first round of the respective component was exploratory in nature (round 1 and round 3). This means that the Delphi panel members were asked to suggest new (sub-)elements, or altering the structure of the elements or model component, as they see fit. The second and final round of the respective component (round 2 and round 4) were aimed to reach a consensus about this component. This consensus means that a majority of the panel members opt for the 'Stay' option for all the elements discussed in a round. In the academic literature, no firm rule is provided of when consensus is reached (Powell, 2003). Therefore, the researcher quantified the majority needed to agree on a model element in order for it to be included. Hence, 80% of the panel must have voted 'Stay', in order for it to be included in the final model. Table 3.2 presents an overview of the Delphi rounds as they were executed in this research. Figure 3.3 presents a visual overview of the Delphi study, and how it is positioned in this complete research endeavor.

Table 3.2: Delphi: rounds overview

Round	I4RMM component	Round type	Provided result sheet
1	Dimensions	Exploratory	n.a.
2	Dimensions	Consensus	Results round 1
3	Levels & labels	Exploratory	Results round 2
4	Levels & labels	Consensus	Results round 3

The complete Delphi study duration was 8 weeks. The study started after the kick-off meeting on 16 November 2020, and the final Delphi round closed on 13 January 2021. Each round lasted one week. The researcher communicated all the proceedings to the Delphi panel by mail and Circuit (digital work environment). If the answers or motivations by the Delphi panel were unclear to the researcher, the researcher contacted the individual Delphi panel members and asked for an elaboration. This was done to make sure that all feedback was processed and handled correctly.

3.3.2 Panel selection

The participants of the Delphi study were grouped in a panel. These members of the panel were selected based on the guidelines of Delbecq et al. (1975). According to the authors, it is unrealistic to expect effective participation unless the respondents:

1. feel personally involved in the problem;
2. have pertinent information to share;
3. are motivated to include the Delphi task in their schedule of competing tasks;
4. feel that aggregation of judgments of the panel will include information which they too value and to which they would not otherwise have access.

The first two items suggest that participants must have a deep interest and understanding of the issues, and have important knowledge or experience to share (Delbecq et al., 1975; Okoli, 2015). For this research project, the goal was to select industry experts on I4.0 with an understanding of readiness or maturity models. Their experience with I4.0 projects proved to be very valuable, as they have a deep understanding of requirements and challenges that companies are facing when engaging in I4.0. The third and fourth item (motivation and interest in outcome) were established during initial contact with the participants. According to Delbecq et al. (1975), most respondents will fully participate in the Delphi study after a detailed and personal introduction. Therefore, at the start of the Delphi study, the researcher organized a kick-off meeting and invited the panel members. The goal of this meeting was twofold: to explain the motivation and importance of the research, and to explain the procedures of the Delphi study. Hence, convincing the participants of the importance of the Delphi study objectives and the importance of their participation. The researcher invited 13 industry experts to the kick-off meeting, of whom 10 persons accepted the invitation and joined the meeting. From these 10 experts, the panel was created of nine participants (differed between rounds due to availability issues). According to Okoli (2015), the recommended party size for a Delphi study is 10-18 people. However, due to scoping restrictions, the researcher decided to start the Delphi study with nine participants. Table 3.3 presents an overview of the composition of the expert panel.

Table 3.3: Delphi: panel overview

Index	Function	Work experience in the domain of I4.0
1	I4.0/PLM Business Consultant	>8 years
2	Business & Technology Consultant I4.0/IoT	>8 years
3	Global Manufacturing Presales	>8 years
4	PLM Business Consultant/Project Manager	>8 years
5	I4.0/MES Consultant	>8 years
6	Principal Consultant	>8 years
7	PLM/IoT Consultant	4-8 years
8	I4.0/MES Consultant	2-4 years
9	I4.0/MES Consultant	<2 years

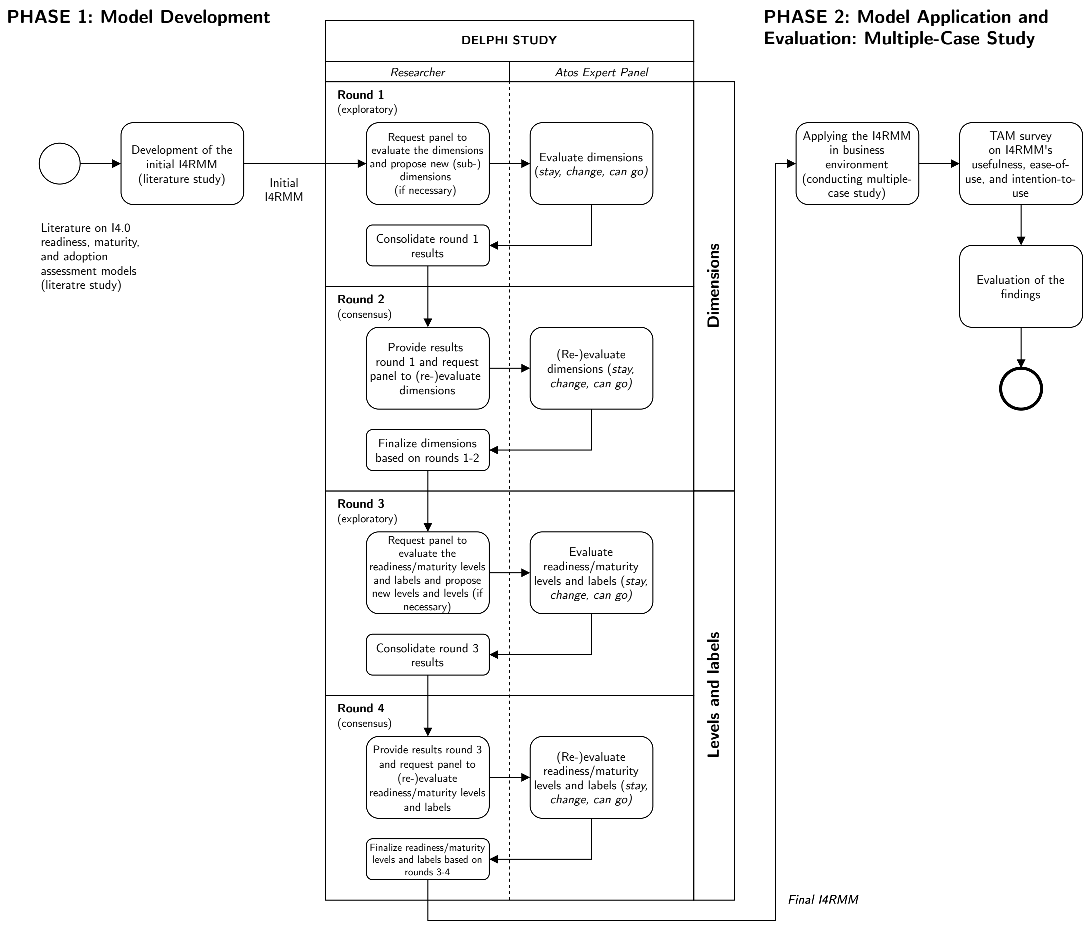

Figure 3.3: Delphi: rounds overview

3.3.3 Round 1: Dimensions (exploratory)

The goal of the first round was to evaluate the initial model (Table 3.1) with regards to its structure, dimensions, and its definitions. As suggested by Powell (2003), the first round was exploratory in nature. Therefore, the Delphi panel was explicitly asked to think about—and if possible: suggest—alternative dimensions, sub-dimensions, and structural changes. Appendix A.2 presents the Microsoft Forms that was used to collect the data from the first round, and Appendix A.3 presents the result sheet i.e. the outcome of the first round.

Based on the feedback from the Delphi panel (number of participants: nine), the researcher further developed the model by:

- refining definitions of five dimensions;
- altering the structure by merging two sets of dimensions.

These changes led to a new version of the I4RMM, which was used as input for the second Delphi round.

3.3.4 Round 2: Dimensions (consensus)

The goal of the second round was to reach a consensus regarding the dimensions and their definitions of the I4RMM. Therefore, this round was confirmative in nature.

Before the start of the second round, the results of the first round were shared with the Delphi panel (Appendix A.3). The participants were asked and encouraged to study these results and investigate the new version of the I4RMM (Appendix B.1). After the panel members got familiar with the new iteration, the researcher asked the Delphi panel to (re-)evaluate the I4RMM, using the same 'Stay, Change', Can go' voting mechanism. Appendix B.2 presents the Microsoft Forms that was used to collect the data from the second round. Appendix B.3 presents the results of this round.

Based on the feedback from the Delphi panel (number of participants: eight), the researcher further developed the model by:

- refining definitions of four dimensions;
- renaming one dimension name for clarity purposes.

These changes led to a new version of the model, and finalized the dimensions of the I4RMM. Finally, a consensus was reached on six out of eight dimensions i.e. a minimum of 80% of the Delphi panel voted for 'Stay' for the respective dimension. Although the dimensions were finalized in this round, the Delphi panel was still able to provide feedback on the dimensions in the subsequent rounds. This was done due to the fact that the dimensions were such an integral part of the complete I4RMM, and were heavily related to the levels and labels of the model. Furthermore, two out of eight dimensions were not agreed on. Therefore, including the dimensions in the subsequent rounds provided the Delphi panel more time to reach this consensus.

3.3.5 Round 3: Levels & labels (exploratory)

The goal of the third round was to evaluate the I4RMM including its levels and labels. In the previous round, the researcher finalized the list of dimensions. Based on these dimensions, the blue-print of the I4RMM as presented in Figure 2.4 was revised. Figure 3.4 presents this updated blue-print. Subsequently, the literature from the SLR was revisited to obtain the unique level descriptions for the I4RMM. These descriptions were altered to fit the definitions as they were defined by the Delphi panel. Appendix C presents an overview of the adapted level descriptions using the found literature.

This round was exploratory in nature. Therefore, the Delphi panel was explicitly asked to think about—and if possible: suggest—alternative levels and structural changes. Appendix C.1 presents

	Readiness		Maturity			
Dimension	**R0** Unprepared	**R1** Ready	**M0** Incomplete	**M1** Performed	**M2** Managed	**M3** Defined
Technology	...	...	...	...	...	...
Operations	...	...	...	...	...	...
Strategy & Vision	...	...	...	...	...	...
Culture & Competencies	...	...	...	...	...	...
Process	...	...	...	...	...	...
Connectivity & Integration	...	...	...	...	...	...
Products & Services	...	...	...	...	...	...
Collaboration	...	...	...	...	...	...

Figure 3.4: Delphi: revised blue-print I4RMM

the I4RMM including the initial theoretical levels and labels. The researcher asked the Delphi panel to evaluate this iteration of the model by filling in the associated Microsoft Forms (Appendix C.2). Appendix C.3 presents the results of this round.

Based on the feedback from the Delphi panel (number of participants: eight), the researcher further developed the model by:

- refining a great number of level descriptions (for a detailed overview: Appendix C.3);
- adding an additional intermediate readiness level 'Planned'.

These changes led to a new version of the I4RMM (Appendix D.1), which was used as input for the fourth and final Delphi round.

3.3.6 Round 4: Levels & labels (consensus)

The goal of the fourth and final round was to reach a consensus regarding the levels and labels of the I4RMM. Therefore, this round was confirmative in nature.

The results of the previous round were shared with the Delphi panel (Appendix C.3). Similar to round 2, the participants were asked and encouraged to study these results and investigate the new iteration of the I4RMM (Appendix D.1). After the panel members got familiar with the new version, the researcher asked the Delphi panel to (re-)evaluate the I4RMM, by filling in the associated Microsoft Forms (Appendix D.2). Appendix D.3 presents the results of this round.

Based on the feedback from the Delphi panel (number of participants: eight), the researcher further developed the model by:

- refining the unique level descriptions;

These changes led to a new and final version of the I4RMM. This version can be found in Appendix E and is discussed in the next chapter. To conclude, all levels and labels were agreed on, and a consensus was reached by the Delphi panel i.e. a minimum of 80% of the Delphi panel voted 'Stay' for all the level descriptions.

Chapter 4

Industry 4.0 Readiness Maturity Model (I4RMM)

This chapter presents the final I4RMM that resulted from the Delphi study. First the structure and dimensions will be presented, followed by a discussion of the different readiness and maturity levels. Finally, the chapter will conclude with an elaboration on how the I4RMM can be utilized in practice for assessing I4.0 readiness and maturity.

4.1 Structure and dimensions

Figure 4.1 depicts a visual representation of the high-level structure and scope of the I4RMM. The I4RMM assesses eight dimensions: *technology*, *operations*, *strategy & vision*, *culture & competencies*, *process*, *connectivity & integration*, *products & services*, and *collaboration*. Each dimension is represented by a unique icon that can be easily recognized. Note that all dimensions are divided in equal segments. Therefore, the I4RMM does not offer a prioritization and allows the organization to choose its own desired improvement path.

The dimensions can then be assessed on I4.0 readiness and maturity by choosing the appropriate readiness or maturity level. The I4RMM incorporates three readiness levels and four maturity levels. Each level consists of:

- a label;
- a generic description of the level as a whole;
- a description of each level per dimension.

The readiness levels (R0-R2) assess the minimum requirements needed for an organization to successfully engage in I4.0:

R0 *Unprepared*: the organizational dimension is not prepared i.e. does not have the sufficient conditions, attitudes or resources to successfully engage in its digital transformation.

R1 *Planned*: the organizational dimension is not completely prepared but has activities planned to improve their readiness.

R2 *Ready*: the organizational dimension is fully ready to start its digital transformation.

The maturity levels (M0-M3) provide an evolutionary path to performance improvement. Each level builds on the previous levels by adding new functionality or rigor resulting in increased capability:

M0 *Incomplete*: incomplete approach to meeting the intent of the dimension or minimal effort in I4.0 paradigms.

M1 *Performed*: complete set of practices to meet the full intent of the dimension in at least one functional area.

M2 *Managed*: complete set of practices that address the full intent of the dimension in all functional areas.

M3 *Defined*: focuses on continuous improvement and optimization.

The following sections introduce the dimension descriptions and unique readiness and maturity level descriptions.

Figure 4.1: I4RMM: visualization of the dimensions

4.1.1 Technology

The *technology* dimension relates to the extent to which I4.0 technologies are implemented and used in the organization. This comprises of assets that make it possible to collect, transfer, and generate digital data. Examples of these assets are cloud technology, mobile devices on shop floor, sensors for data collection, additive manufacturing, utilization of robots (Colli et al., 2019; Schumacher et al., 2019). The readiness levels aim to assess the current assets that are available to collect, transfer, and generate data. Subsequently, the maturity levels aim to assess the utilization of these assets (Figure 4.2).

Readiness			Maturity			
R0 Unprepared	R1 Planned	R2 Ready	M0 Incomplete	M1 Performed	M2 Managed	M3 Defined
No presence of assets that enable data collection, transfer, and generation.	Planned to buy new technology that enables data collection, transfer and generation.	There are assets available that enable data collection, transfer, and generation.	There are assets available and used for data access and data visualization.	There are assets available and used for data analysis, and communicating the results to the user.	There are assets available that are acting autonomously according to information received after an analytic process.	The assets deployed across the supply chain can interact together and reconfigure themselves to optimize performance.

Figure 4.2: I4RMM: technology levels

4.1.2 Operations

The *operations* dimension relates to the extent to which manufacturing operations (production, storage, quality test, and maintenance) are formally documented organized, robust, and repeatable (De Carolis et al., 2017). The higher the level, the more efficient an organization operates and fewer problems arise at the operations management level. The readiness levels aim to asses the documentation, deployment, and monitoring status of manufacturing operations. The maturity levels aim to assess the extent to which these operations are supported by IT (Figure 4.3).

Readiness			Maturity			
R0 Unprepared	R1 Planned	R2 Ready	M0 Incomplete	M1 Performed	M2 Managed	M3 Defined
No manufacturing operations have been documented	The manufacturing operations are partly documented, and there are plans to finalize the documentation.	All manufacturing operations are well documented, deployed and monitored.	The manufacturing operations are defined, deployed and monitored with documented standards and partly supported by software tools.	The manufacturing operations are defined, deployed and monitored and fully supported by software tools and executed with possibly repeatable results in normal situations.	The manufacturing operations are defined, deployed and monitored across all organizational groups, and their executions are repeatable and monitored with software tool supports.	The manufacturing operations are focused on continuous improvement and optimization.

Figure 4.3: I4RMM: operations levels

4.1.3 Strategy & Vision

The *strategy & vision* dimension relates to the extent to which the strategy and vision currently adopted by companies are aimed towards I4.0. This includes awareness regarding the digital transformation and its impact on the organization (Schumacher et al., 2016; Trotta and Garengo, 2019; Wagire et al., 2020). The readiness levels aim to assess the existence of an I4.0 strategy and vision. The maturity levels aim to assess the (organization-wide) implementation of these plans (Figure 4.4).

Readiness			Maturity			
R0 Unprepared	R1 Planned	R2 Ready	M0 Incomplete	M1 Performed	M2 Managed	M3 Defined
There is no awareness regarding the digital transformation, and I4.0 strategy and vision are lacking.	There is a willingness and interest towards the digital transformation. I4.0 strategy and vision are being developed but there is great uncertainty on how to approach I4.0.	There is a clear I4.0 strategy and vision in place.	I4.0 strategy and vision have been formally implemented in at least one functional area.	I4.0 strategy and vision are expanded to include more than one functional area.	I4.0 strategy and vision are expanded to include all functional areas.	I4.0 strategy and vision are refreshed and updated automatically if necessary (monthly).

Figure 4.4: I4RMM: strategy & vision levels

—*continued on next page*—

4.1.4 Culture & Competencies

The *culture & competencies* dimension relates to the extent to which all people of an organization are competent (due to adequate training and recruitment), and willing to support the implementation of I4.0 technologies and innovation. This includes open innovation, inclusive culture, and digitization competencies (Colli et al., 2019; Sjödin et al., 2018). The readiness levels aim to assess the acknowledgment of open innovation, and the existence of required digital manufacturing competencies. The maturity levels focus on using these competencies to achieve continuous smart factory innovation (Figure 4.5).

Readiness			Maturity			
R0 Unprepared	R1 Planned	R2 Ready	M0 Incomplete	M1 Performed	M2 Managed	M3 Defined
The organizational culture is not open to innovation, nor are there in-house or external competencies related to digital manufacturing.	The organizational culture is open to innovation, but there are no in-house or external competencies available to approach digital manufacturing.	The organizational culture is open to innovation and there are in-house or external competencies available related to digital manufacturing, and these can be utilized when needed.	An inclusive culture is (partly) in place by involving workforce in vision development. People are being recruited with digitization competencies.	People are educated to develop the ability to exploit connected data systems. Production staff proactively coordinates digital insights and knowledge sharing.	Suppliers, users, and other stakeholders meet up to improve shared group understanding of production processes. Data analysts and data scientists are recruited to optimize production.	A culture of continuous smart factory innovation is in place covering the complete organization. Specialized roles and responsibilities are geared toward predictable production.

Figure 4.5: I4RMM: culture & competencies levels

4.1.5 Process

The *process* dimension relates to the extent to which organization (support) processes of production and maintenance are self-configurable, self-optimized, and simplified. This includes the extent to which processes are defined, digitized, integrated, and automated (Lin et al., 2019). The readiness levels aim to assess the number of processes that are defined, simplified, and standardized. The maturity levels aim to assess to what extent the processes have been digitized, integrated, and automated (Figure 4.6).

Readiness			Maturity			
R0 Unprepared	R1 Planned	R2 Ready	M0 Incomplete	M1 Performed	M2 Managed	M3 Defined
No processes have been explicitly defined.	The processes are partly defined, and there are plans in place to define all processes.	All processes are defined, simplified, standardized, and are being executed.	Defined processes are completed with the support of digital tools.	Digitized processes and systems are securely integrated across all hierarchical levels (machines & workers - boardroom).	Integrated processes and systems are automated, with limited human intervention.	Automated processes and systems are actively analyzing and reacting to data, enabling continuous process improvements.

Figure 4.6: I4RMM: process levels

4.1.6 Connectivity & Integration

The *connectivity & integration* dimension relates to the extent to which an IT/cloud infrastructure is in place to accommodate vertical or horizontal integration across the value chain. This includes the documentation, design, standardization, integration, and interoperability of the used IT/cloud infrastructure (Colli et al., 2019; Lin et al., 2019). The readiness levels aim to assess the documentation and flexibility of the IT/cloud infrastructure. The maturity levels aim to assess the standardization, integration, and interoperability of the IT/cloud infrastructure (Figure 4.7).

Readiness			Maturity			
R0 Unprepared	R1 Planned	R2 Ready	M0 Incomplete	M1 Performed	M2 Managed	M3 Defined
The IT infrastructure is poorly documented and designed, and provides no flexibility in extending it.	The IT infrastructure is partly documented and designed, and there are plans in place to increase its flexibility to extend it in the future.	The IT infrastructure is well documented and designed, and provides enough flexibility to extend towards I4.0 technology requirements. In addition, the IT department resources are aligned to support future extensions.	The IT infrastructure is not standardized but all the different modules can communicate with each other.	The IT infrastructure is not fully integrated but is based on a number of recognized standards and when new modules have to be developed, this is done accordingly.	The IT infrastructure is based on a commonly agreed set of standards and new modules are developed accordingly, enabling interoperability.	The IT infrastructure in the whole supply chain is based on standards that allow plug and play inter-organization real-time communication, enabling interoperability and scalability.

Figure 4.7: I4RMM: connectivity & integration levels

—*continued on next page*—

4.1.7 Products & Services

The *products & services* dimension relates to the extent to which products are individualized and product characteristics can be customer specific (smart products). In addition, it assesses the extent to which an organization offers data-driven services and customer integration (smart services and servitization). This includes digital, connectivity, responsive, and customization features of products and services (Canetta et al., 2018; Leyh et al., 2017; Santos and Martinho, 2019). The readiness levels aim to assess the extent to which products and services are digitally supported. The maturity levels aim to assess the utilization of smart products, smart services, and servitization (Figure 4.8).

Readiness			Maturity			
R0 Unprepared	R1 Planned	R2 Ready	M0 Incomplete	M1 Performed	M2 Managed	M3 Defined
Product development or services are not digitally supported.	There are plans to explore digital support of product development and services, but additional help is required.	Product development or services are partly digitally supported.	Products offer digital features and services are continuously digitally supported.	Products offer connectivity features and little differentiation. Data-driven services offer little customer integration.	Products offer responsive features and can be largely customized. Data-driven services offer customer integration.	Products can be completely customized and feature all smart product functionalities, and many products are being servitized. Data-driven services are fully integrated with the customer.

Figure 4.8: I4RMM: products & services levels

4.1.8 Collaboration

The *collaboration* dimension relates to the extent to which formal channels are enabled for employees and collaboration partners to share information and work together, as well as institutional structures and systems that allow collaborative behavior. The readiness levels aim to assess the establishment of formal communication channels. The maturity levels aim to assess the level of team empowerment Figure 4.9.

Readiness			Maturity			
R0 Unprepared	R1 Planned	R2 Ready	M0 Incomplete	M1 Performed	M2 Managed	M3 Defined
Communication and information sharing across teams happen on an informal basis.	There are plans to formalize the current channels used for communication and information sharing, but additional help is required.	Formal channels are established for communication and information sharing across teams.	Formal channels are established to allow teams to work together on discrete tasks and projects.	Teams are empowered by the organization to make adjustments that will facilitate cooperation on discrete tasks and projects.	Teams are empowered by the organization to share resources on both discrete and longer-term tasks and projects.	Formal channels are established to enable dynamically-forming teams to work on cross-functional projects with shared goals and resources.

Figure 4.9: I4RMM: collaboration levels

4.2 Using the I4RMM

Organizations can use the I4RMM to self-assess their I4.0 readiness and I4.0 maturity, and identify improvement opportunities based on their assessment. In addition, organizations can use the I4RMM in collaboration with their partners, who may have more experience and a better understanding of I4.0 practices. The latter could especially be beneficial for organizations who are eager to start their digital transformation, yet are unfamiliar with I4.0 terminology and concepts.

It is recommended to choose a group of participants with different functions in an organization when using the I4RMM. Due to the broad scoping of the model i.e. ranging from strategical dimensions from a management level to operational dimensions from a shopfloor level, it is important that varied employees perform the assessment. In addition, de Bruin et al. (2005) recommends to deploy the model within entities that are independent of the model development, to provide wider acceptance and improve the standardization of the model.

The assessment can take place as a focus group or during a workshop. It is recommended to introduce the participants to the I4RMM beforehand. This could be realized by sharing documentation or employing an online assessment tool. During the focus group or workshop, the participants are asked to individually (to avoid group-think) assess the different dimensions based on the as-is situation of the organization. After all the participants completed their assessment, it is recommended to initiate a discussion and attempt to arrive at a consensus. After this consensus has been reached and all the levels have been determined, the results should be properly documented. Subsequently, a new assessment should take place assessing the to-be state of the organization. In this assessment, the organization should determine the ambition levels that it seeks to achieve. After all the levels have been determined, an improvement path can be formed by analyzing the gap between the as-is situation, and the desired state of the different dimensions. This improvement path could include the proposal of use-cases and best practices to achieve these ambition levels. Finally, the model can be utilized to enable benchmarking. The collected data can then be used to compare the as-is and to-be state of an organization with the average industry levels. This could further motivate organizations to reach higher readiness and maturity levels in I4.0.

Chapter 5

Evaluation

This chapter presents the evaluation of the developed I4RMM. Following the DSR, the new artifact should be evaluated in a real business environment (Hevner et al., 2004) i.e. manufacturing companies that seek to assess their I4.0 status. This evaluation took place in the form of a multiple-case study, with the goal to evaluate the model on completeness, validity, and usability (Yin, 2017). In addition, a survey based on the Technology Acceptance Model (TAM) by Davis (1989); Moody (2003) was conducted to evaluate the model on perceived usefulness, ease-of-use, and intention-to-use.

First, the general evaluation setup is presented, followed by a detailed description of the case studies and their results. Finally, the complementary results of the TAM survey are presented.

5.1 Evaluation setup

For the evaluation of the I4RMM, a multiple-case study design was followed. According to Yin (2017), multiple-case study designs have distinct advantages over single-case study designs. The evidence from multiple cases is often considered more compelling. In addition, analytic conclusions independently arising from two or more cases, will be more powerful than those coming from a single-case alone (Yin, 2017). In order to assure consistency, a case study protocol was defined and followed. According to Yin (2017), such a protocol is essential when performing a multiple-case study. The protocol contains a set of substantive questions to be used in collecting the case study evidence. In addition, the protocol contains the procedures and general rules to be followed when performing a case study. Therefore, it keeps the researcher targeted on the topic of the case study, and the preparation of the protocol forces the researcher to anticipate problems, including the way the case study reports are to be completed. The case study protocol consists of the following four sections (adapted from Yin (2017)):

A Overview of the case study
B Data collection procedures
C Protocol questions
D Tentative outline for the case study report

Overall, the protocol is a way of increasing the reliability of the case study and is intended to consistently guide the data collection (Yin, 2017). The complete case study protocol is documented in Appendix F.1.

The case studies were performed as focus groups during so-called assessment sessions. In these sessions, the researcher asked the case study participants to try to use the I4RMM to evaluate their organization on I4.0 readiness or maturity. In addition, the researcher asked at least two people to be present from the organization, to initiate discussion during the sessions. Moreover, multiple perspectives can increase the accuracy of the I4.0 readiness or maturity assessment. However, the focus in these case studies was on the completeness, validity, and usability of the I4RMM, rather than on the precision of the selected I4.0 readiness or maturity level. The assessment sessions were planned by the researcher as online focus groups with a duration of 1.5 hours and consisted of:

- Introduction by the researcher (0.5 hours)
  - Introduction research topic
  - Introduction I4RMM
  - Explanation case study setup i.e. procedures
- Assessment session (1.0 hour)

To increase the effectiveness of the assessment session, all the assessment material including the complete I4RMM was sent to the participants 1-2 weeks prior to the meetings. In addition, a 'hands-on' experience was provided by the researcher three days prior to the meeting. This experience consisted of a Microsoft Forms in which the participants could assign levels to the dimensions of the I4RMM. Here, the objective was to encourage the participants to already get familiar with the model, and think of its application within their organization. None of the participants fully submitted their assessments. However, they did browse through it to familiarize themselves with it. Appendix F.2 presents this 'hands-on' experience.

During the assessment session, the participants were asked to choose an appropriate level for each dimension of the I4RMM. Only a single decision for each dimension was provided after group discussion. During these assessments, the researcher acted as an observer and made notes of the procedures. Furthermore, the researcher collected feedback on the completeness, validity, and usability of the model. After all the dimensions were assigned to readiness or maturity levels, the results were aggregated. In addition, a short report was compiled and shared with the participants for each case study summarizing the main findings. These reports are included in Appendix F.

To conclude a case study, the participants were asked to fill out a short survey which further evaluated the I4RMM. The survey was built using a set of statements from the Technology Acceptance Model (TAM) as proposed and further developed by Davis (1989) and Venkatesh and Davis (2000) respectively. The TAM is a commonly referred theory that can predict the acceptance and use of design artifacts. According to Moody (2003), the TAM has been *"the most influential"* and has advantages in *"parsimony, IT, specificity, and strong theoretical basis and empirical support"*. There are three primary constructs in TAM (Davis, 1989):

- perceived usefulness;
- perceived ease-of-use;
- intention-to-use.

First, perceived usefulness refers to the *"the degree to which a person believes that using a particular system would enhance his or her job performance"* (Davis, 1989). Second, perceived ease-of-use refers to *"the degree to which a person believes that using a particular system would be free of effort"* (Davis, 1989). Finally, intention-to-use refers to the *"extent to which a person intends to use a particular system"* or design artifact (Moody, 2003).

All constructs were operationalized using multiple indicators which have been rigorously evaluated for reliability and validity (Davis, 1989). For this research, the measurement scales from Venkatesh and Davis (2000) were adapted. Therefore, the survey comprised of four questions for perceived usefulness, four questions for perceived ease-of-use, and two questions for intention-to-use (total of ten questions). In addition, as proposed by Moody (2003), the questions were changed in wording to fit the use of the method to this specific research endeavor. Furthermore, half of the items per construct were negated to avoid monotonous responses (Moody, 2003). Each question used a five-point Likert scale, ranging from one (strongly disagree) to five (strongly agree). Appendix F.3 presents the TAM survey as it was employed.

To conclude, Figure 5.1 depicts the evaluation setup of the I4RMM.

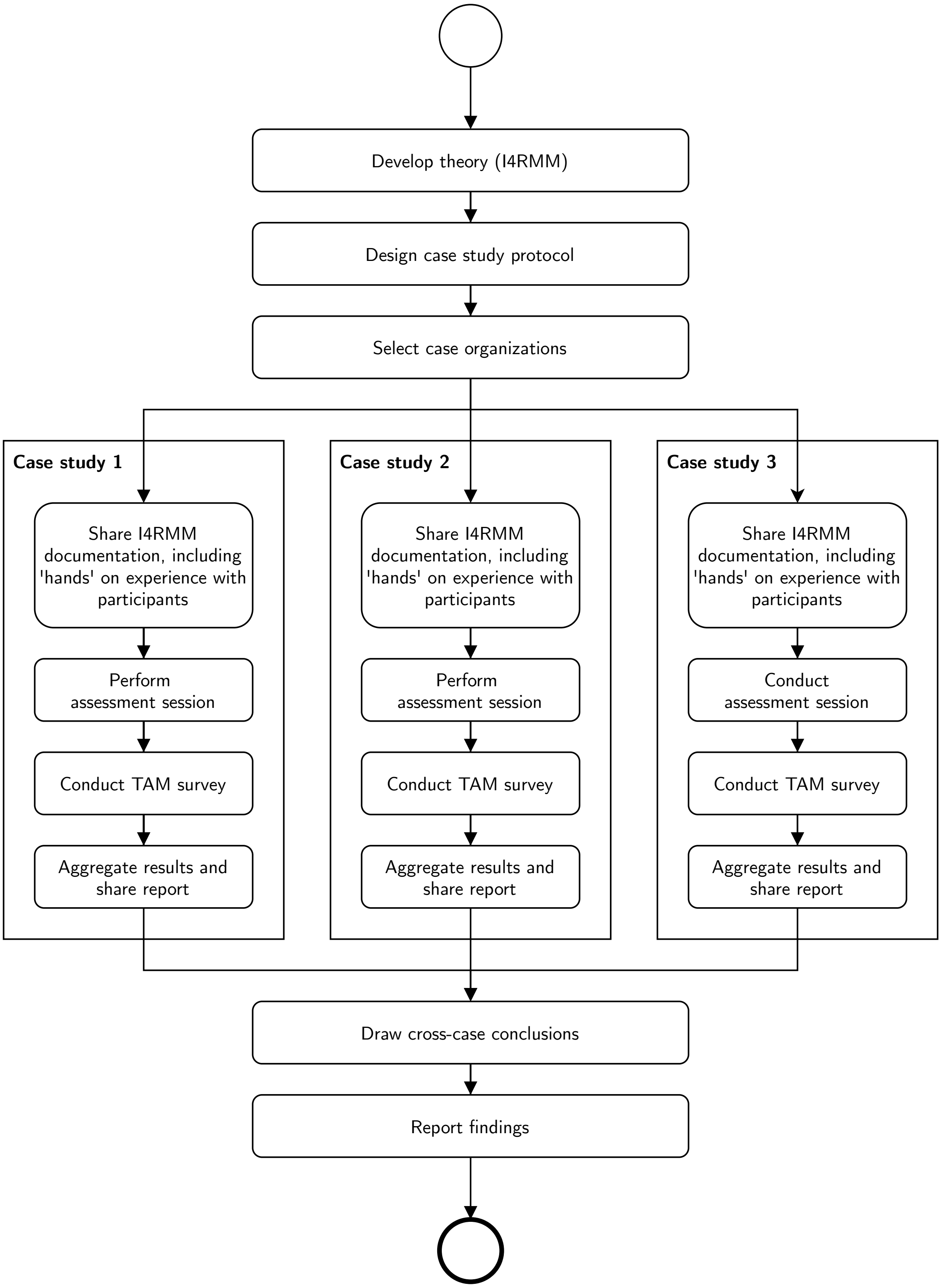

Figure 5.1: Evaluation: setup and procedures

5.2 Multiple-case study

According to Yin (2017), each case must be carefully selected so that the individual case either predict similar results or predict contrasting results but for anticipatable reasons. For this multiple-case study, the cases were selected to predict contrasting results i.e. organizations were selected from different industries. During the Delphi study and the development of the I4RMM, it was suggested that the model may not be widely applicable due to different challenges and requirements from different industries (Appendix B.3). Therefore, the case organizations were adequately selected to test this hypothesis.

The first company (company A) chosen for the case study is headquartered in Europe, and operates in discrete high-tech manufacturing. It employs more than 24,700 employees and operates in over 16 countries worldwide. The company designs and manufactures lithography machines. The second company (company B) is headquartered in Europe and operates in the pharmaceutical industry. It employs more than 2,000 employees and operates on four continents. The company is a manufacturer of medicines and vaccines. The third company (company C) is headquartered in Europe and operates in the automotive industry. It employs more than 9,400 employees and operates worldwide. The company is a commercial vehicle manufacturer. Table 5.1 summarizes the case organizations.

Table 5.1: Multiple-case study: case organizations

Company	Industry	Region	Headquarter	Company size
A	High-tech manufacturing	Global	Europe	+24,700 employees
B	Pharmaceutical	Global	Europe	+2,000 employees
C	Automotive	Global	Europe	+9,400 employees

The next sections will present the results of the case studies including the observations made by the researcher, and the results of the assessment. All the observations and comments made by the participants were anonymized. For some dimensions, the motivations and discussions for the level assignments were omitted due to confidentiality reasons.

5.2.1 Case study 1: company A

This assessment was conducted by three case study participants in a focus group setting. The participants have been senior business consultants for Product Lifecycle Management (PLM) for company A, and have a good understanding of the organization due to their long-term experience and association with the company. Ideally, the case study would have been performed with employees of the case organization. However, due to practical and logistical reasons, the business consultants for company A were asked to participate in the case study. First, the observations by the researcher are presented including the level assignments for all dimensions. Finally, an overview of the complete assessment is given in Figure 5.2.

Structure I4RMM First, the researcher observed that the difference between the concepts of I4.0 readiness and I4.0 maturity was somewhat unclear to the participants. The name of the model suggests that both concepts are assessed, but it was unclear that only one level should be selected as final verdict. The researcher explained that the levels are consecutive i.e. a company must first pass the readiness assessment before an appropriate maturity level can be selected. In other words, if a dimension is deemed to be a mature (levels M0-M3), the dimension is also immediately classified as level R2 (ready). Hence, the participants suggested to make this structurally visual, so that it becomes clear you are always in level R2 when a dimension is assigned to one of the maturity levels. In addition, the suggestion was made to alter the labels of the levels. The continuation from level R2 to level M0 seems unnatural, due to the number suffix. This could be solved by continuing the maturity levels suffix from the final readiness levels i.e. R0-R1-R2-M3-M4-M5-M6.

However, the participants were unsure if this alteration would improve understandability of the model. Finally, it was suggested to include a glossary of terminology used in the model, to increase consistency and understandability.

Technology According to the participants, the number of machines/assets that hold valuable data is varying. Some machines may even be classified as level M2 or M3, while other physical entities may not reach the maturity levels. However, the participants agreed that the majority could be assessed as level M2. Level M3 was not recognized due to the missing deployment across the supply chain. Therefore, the participants agreed on the level M2.

Operations The participants commented that the starting sentence of the level descriptions of levels M0-M3 is very repetitive. It was suggested to change the word order, to improve readability. Furthermore, the participants argued that the difference between the different levels should be more distinct in an eye-sight. In the current form, the complete level descriptions must be carefully read to identify the differences. It was suggested to work with bullet points or with keywords e.g. keeping the top sentence (introductory sentence of the level) and include the qualifications under it. Finally, the level M1 was assigned without any noteworthy discussion.

Strategy & Vision No specific comments were made about this dimension. Without any noteworthy discussion, the participants agreed on level M1.

Culture & Competencies According to the participants, *culture & competencies* seems like a misfit. They argued that competencies are not related to organizational culture, and suggested to replace 'competencies' with 'people'. To complement this observation, the definition of the dimension was deemed to be too focused on competencies. The participants suggested to add the effect of cultural influence or cultural behavior to both the definition and the respective readiness and maturity levels. In addition, it was observed that the readiness levels were focused on culture and the maturity levels on competencies. However, both constructs should be assessed on readiness and maturity. Furthermore, the participants discussed the challenges coming from working in an international environment. Therefore, they argued to include this phenomenon in the I4RMM. Moreover, it was suggested to add business change management to both readiness and maturity levels i.e. the flexibility of people to change and adopt new technologies. This suggestion complements the earlier argument to replace 'competencies' with 'people'. Finally, the level M2 was assigned without any noteworthy discussion.

Process The description of level M1 was confusing i.e. *"...machines & workers - boardroom..."*. Due to the ampersand and dash, the participants experienced readability issues with this description. With regards to the level assessment, an interesting discussion was started. The participants argued that company A can be seen as a fast growing company, therefore, processes are constantly being added. In addition, not all the processes are carefully followed and executed. In some cases, the deadline of delivering a product was more important than following the processes leading to that final product. Therefore, the participants agreed on level R1.

Connectivity & Integration The participants agreed that the level allocation should be high. During the COVID-19 pandemic, company A proved to be highly adaptable to accommodate vertical and horizontal integration using a stable IT infrastructure. Therefore, the participants agreed on the level M2 without any noteworthy discussion.

Products & Services According to the participants, products and services should be two separate dimensions due to their independence. It was argued that—in the current form—it is near impossible to assign a level e.g. if smart products are developed but servitization is not applied. These concepts can be developed independently and the current model does not take this into account. With regards to the level assignment, the participants assessed the products aspect of the organization. Company A provides little (but some) differentiation in their products. Therefore, the level M1 was assigned.

Collaboration The participants argued that security and compliance rules could be a nice addition to the current level descriptions. Furthermore, it was stated that *"...institutional structures..."*

in the dimension definition was too vague and should be refined. In addition, one participant suggested to alter the labels of the levels to appropriately reflect the different dimension stages. With regards to the level assignment, a quick consensus was reached on the level M3. The participants agreed that company A is highly advanced in this dimension. The COVID-19 pandemic also proofed this e.g. by smoothly continuing collaboration in the organization while working from home. Finally, the level M3 was assigned.

Final comments In conclusion, the participants stated that the I4RMM could be very useful for both small-medium companies that want to enter their digital transformation, and bigger companies who are already proceeding in I4.0. However, the readiness levels could be less interesting to the latter, as was experienced in this case organization. In addition, the participants argued that the distinction between readiness and maturity must be made more explicit in the model e.g. the difference between levels R2 and M0 is very subtle, and an important distinction must be made. Furthermore, it was suggested to explore benchmarking opportunities. By creating a comparative model, the results of the assessment could immediately be compared to the competition. This could help decision-making and prioritizing improvement paths of specific organizational dimensions.

Finally, Figure 5.2 presents the results of the assessment for company A.

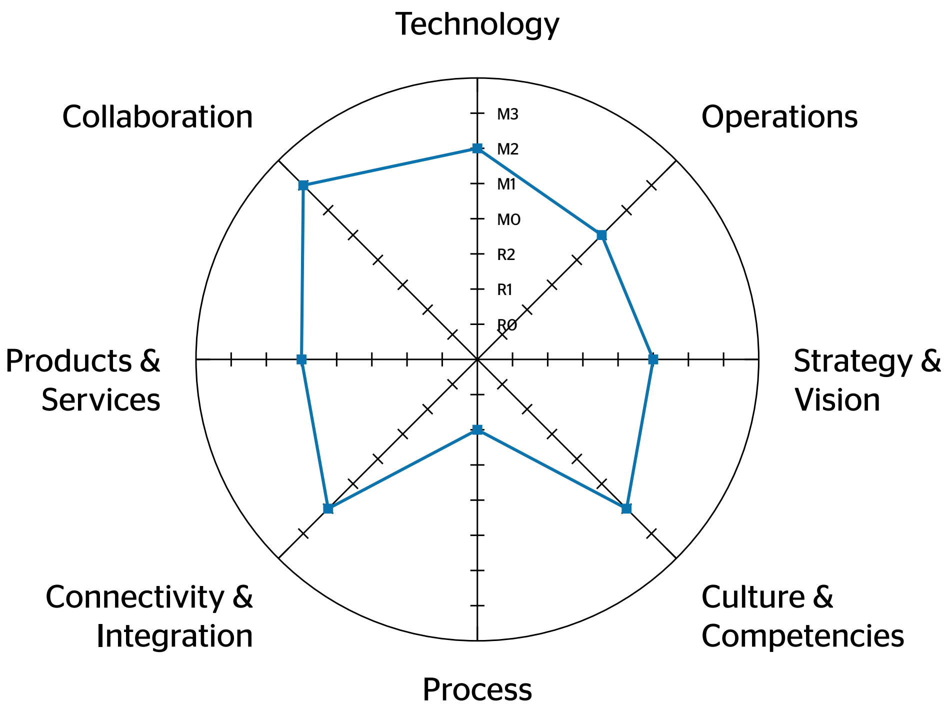

Figure 5.2: Evaluation: results I4RMM assessment company A

As can be seen in Figure 5.2, the organization scores relatively high for most dimensions, except *process*. It may be recommended to company A to revise its process management. In specific, to ensure that all processes (of production, maintenance, and support) are defined and more importantly: carefully followed, to reach a higher maturity level in this dimension.

5.2.2 Case study 2: company B

This assessment was conducted by two case study participants in a focus group setting. The participants are senior business consultants in IoT for company B. First, comments about the general structure and usage of the I4RMM are presented, followed by observations for each individual assessed dimension. Finally, an overview of the complete assessment is given in Figure 5.3.

Structure I4RMM First, the participants were unsure from which perspective they should perform the assessment with the I4RMM. It was argued that the different perspectives of IT and operations could lead to different assessment results. In other words: business and operations are not always synchronously developed. Furthermore, complementing the case study of company A, it was again suggested to include a glossary of used terminology to increase understandability and consistency. Finally, the dimensions relevance of the dimensions of different industries should be explored and made explicit e.g. by using weighting factors.

Technology The participants stated that the definition of *"...I4.0 technologies..."* in the dimension definition is missing. It was suggested to include examples of these technologies to make the definition more comprehensible. Furthermore, as previously discussed, it was unclear from which perspective (business versus operations) the dimension should be assessed. Therefore, the participants agreed that the level M1 should be assigned from an operations perspective, and level R1 from a business perspective.

Operations With regards to the level assignment, the participants were discussing whether the dimension should be on level M1 or M2. Finally, the participants agreed that the level of software tools is lower than mentioned in level M2. Therefore, the level M1 was assigned.

Strategy & Vision According to the participants, no vision is being developed with regards to I4.0. Alternatively, I4.0 paradigms are followed from operational problems regarding shipments. However, there seems to be an awareness and willingness of the digital transformation by company B. Therefore, the participants agreed on level R0.

Culture & Competencies According to the participants, the description of level R0 should be hedged. The current form: *"...organizational culture is **not** open to innovation..."* is invalid. The participants argued that this statement does not apply to any organization (of any size). It was suggested to hedge the sentence in: *"...organizational culture is **poorly** open to innovation..."*. Furthermore, it was argued that elements of the maturity levels of this dimensions were not necessarily evolutionary items of each other i.e. they could be treated independently. Therefore, the participants stated that the descriptions should be further refined. With regards to the level assignment, the participants recognized a culture open to innovation. Especially during a track & trace project, affecting all organizational layers from production to distribution. However, the participants could not make an informed decision about the maturity stage. Therefore, the level R2 was assigned.

Process The participants argued that the current description of level M0 is too mature, its description should be toned down to adequately represent its level i.e. not **all** processes are completed with the support of digital tools, only **partially**. Furthermore, the participants agreed that the processes have been strictly defined—as is mandatory in the pharmaceutical industry—yet not all processes are strictly executed and followed. It was observed that many processes are susceptible to failure, due to the heavy dependence on human interaction. Therefore, the participants agreed on the level R2.

Connectivity & Integration No specific comments were made about this dimension. The level M1 was assigned without any noteworthy discussion.

Products & Services According to the participants, this dimension is not relevant for this case organization and industry. In the pharmaceutical industry, there is a great amount of strict regulations posed by the government. Therefore, it legally impossible to offer 'customer specific' products. In addition, there is no market-pull or demand for these customization options, making this dimension irrelevant for this organization. However, in the current form, the dimension cannot be neglected. Therefore, it was suggested to introduce weighting factors to the I4RMM, to exclude level assignments of irrelevant dimensions. However, to complete the assessment, the level R1 was selected by the participants.

Collaboration It was highly advised to revise the the term 'team empowerment'. According to the participants, there is a difference when 'team empowerment' entails that teams can bring up new initiatives or that teams can also (independently) execute these new initiatives. In the pharmaceutical industry, the latter would be impossible due to strict regulations and laws. Therefore, making 'team empowerment' irrelevant to assess in the current form of the I4RMM. Therefore, the level M0 was assigned (one level before the introduction to team empowerment), as formal channels are established to allow teams to work together.

Finally, Figure 5.3 presents the results of the assessment session for company B.

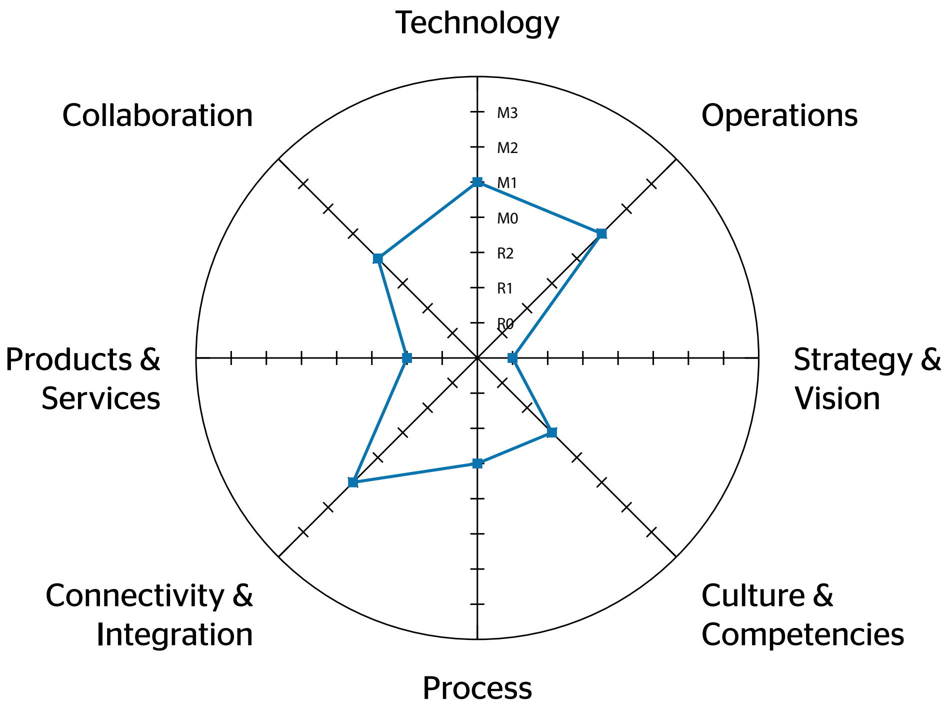

Figure 5.3: Evaluation: results I4RMM assessment company B

As can be seen in Figure 5.3, the dimension *strategy & vision* scores the lowest with level R0. Therefore, it is highly recommended to company B to start developing a strategy and vision aimed towards I4.0, to better guide the organization in its digital transformation. Once these are in place, it is important that both strategy and vision are adopted by all areas in the organization, and that they are refreshed and updated continuously.

5.2.3 Case study 3: company C

This assessment was conducted by two case study participants in a focus group setting. Both participants are I4.0 consultants for company C, helping the organization in their digital transformation. First, general comments regarding the structure of the I4RMM are presented, followed by comments for each individual assessed dimension. Finally, an overview of the complete assessment is given in Figure 5.4.

Structure I4RMM The participants shared a few concerns with regards to the scoping of the I4RMM. It was argued that the results of the assessments are heavily dependent on the focused department within an organization. Some departments may be further developed than others. For example, the difference between the work scheduling, preparation, and production departments were significant according to the participants. Therefore, assigning a overall readiness or maturity level for the complete organization was challenging. It was suggested to acknowledge departmental differences in the model.

Technology According to the participants, the term 'supply chain' in level M3 should be refined or clarified. This complements the observation from previous case studies, in which a glossary of terminology was suggested to be added. In the current form, it was unclear whether the 'supply chain' definition would include or exclude production processes. According to the participants, company C in its completeness could be assigned to level R2. However, the maturity level is very dependent on different departments within company C. The participants argued that no assets are available that act autonomously. Therefore, they agreed on the level M1.

Operations The participants argued that this dimension may lead to different assessment outcomes when different factories of the case organization are assessed. Therefore, it was perceived difficult to choose one level for the case organization as a whole. Furthermore, the participants suggested that the maturity levels should be expanded, either by introducing new (higher) maturity levels, or by altering the level descriptions. However, the participants acknowledged the existence of continuous improvement projects within company C, based on the operations data that the company collects. Therefore, the level M3 was assigned.

Strategy & Vision The participants acknowledged the willingness and interest towards I4.0 by company C. However, a clear vision is missing. Therefore, the participants agreed on the level R1.

Culture & Competencies According to the participants, company C is involved in the coordination of digital insights and knowledge sharing. However, this is not always the case throughout the complete organization. Yet, the participants did agree on level M1.

Process The definition of the dimension was perceived to be vague, specifically: *"...departments collaboration..."*. It was unclear if this aimed at collaboration between departments or collaboration within departments. Furthermore, it was suggested to revise the flow of the sentence to enhance readability. With regards to the level assignment, the participants stated that not all processes have been standardized. In addition, there are many (undocumented) exceptions. Therefore, the level R1 was assigned, to clearly indicate that not **all** processes have been defined, simplified, and standardized.

Connectivity & Integration As discussed earlier, the term 'supply chain' is too broad. It was suggested to improve the model by specifying sub-areas of the supply chain. For example, multiple IT/cloud infrastructures could be utilized in these different sub-areas. Therefore, it is unwise to aggregate these and attempt to select a general readiness/maturity level. In addition, the participants also stated that business could be interested in I4.0 proceedings for only one specific sub-area. Therefore, the model would be better applicable if a specification could be utilized. According to the participants, not all IT infrastructure is well documented and designed, therefore, they vouched for level R1.

Products & Services According to the participants, the dimension should be split up in two dimensions as they are two different (independent) entities. Therefore, it was rather difficult to choose one readiness or maturity level i.e. the case organization its product individualization is very high, while the organization is not really engaged in smart services or servitization. However, when assigning a level from a products perspective, the level M2 was assigned. Company C is in the automotive industry, and—according to the participants—can offer plenty of customization options of the vehicles to its customers.

Collaboration The participants argued that the extent to which collaboration could be acknowledged under the movement of I4.0 is unclear. It would help to provide examples or use-cases where I4.0 paradigms or technologies really affect the collaboration of a organization and between organizations. The example of co-engineering was given. With regards to the level assignment, the participants argued that not all communication and information sharing is formally implemented. For example, the communication between the factory, engineering departments, and product design departments could be vastly improved. Therefore,the level R0 was assigned.

Finally, Figure 5.4 presents the results of the assessment using the I4RMM for company C.

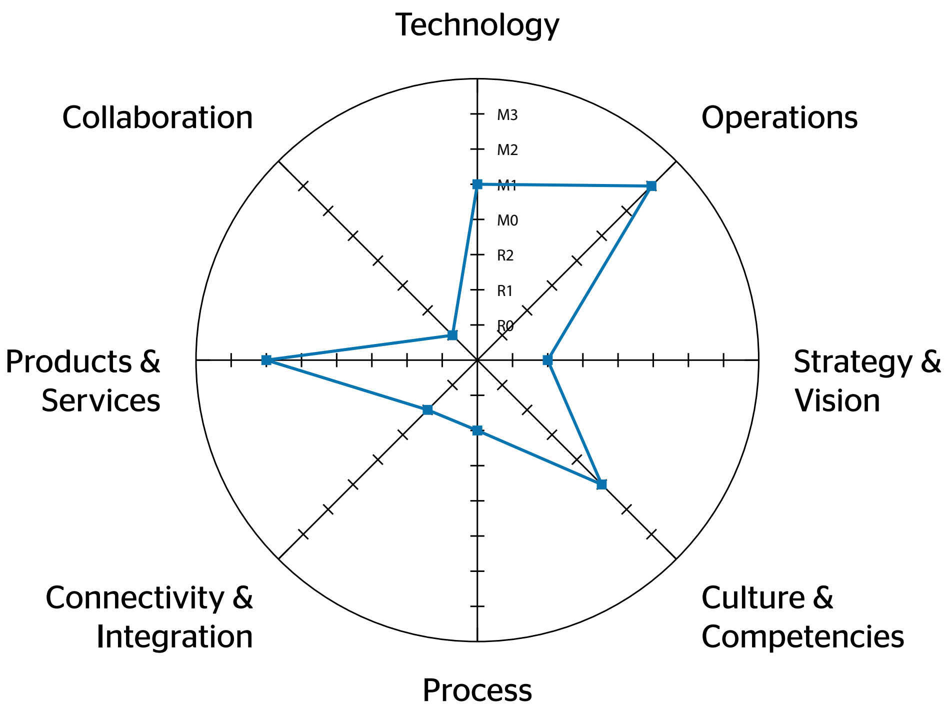

Figure 5.4: Evaluation: results I4RMM assessment company C

As can be seen in Figure 5.4, the organization scores relatively low on *collaboration*, *strategy & vision*, *connectivity & integration*, and *process*. According to these results, company C does not seem to be ready for their digital transformation (at this point). It is recommended to revise collaborative behavior, connectivity features, process management, and the strategy and vision of the organization, to ensure a smooth transition into I4.0.

5.3 Cross-case conclusions

Figure 5.5 presents an overview of the I4RMM assessment results of the performed case studies. It can be observed that some dimensions scored quite similar, while others scored significantly different. This could be explained due to the fact that the companies operate in different industries. These different industries could focus on different organizational dimensions. Hence, some dimensions may be further developed than others due to strategical—industry specific—decisions. It would be interesting to conduct more case studies in future research, and applying the I4RMM in different companies from the same industry. In this multiple-case study, the most important made observation was that some dimensions were irrelevant for assessing I4.0 when using the model in a specific industry. In particular: the pharmaceutical industry. This industry is bound by strict legislation and laws concerning the manufacturing of pharmaceutical products. These rules restrict the opportunities of exploring customer specific product characteristics and customer integration. Therefore, it is (legally) impossible to assign a readiness or maturity level to the dimension of *products & services*, causing the dimension to become irrelevant. However, this dimension could perfectly be assessed for the other two companies in the semiconductor and automotive industry.

The current form of the I4RMM is designed to assess I4.0 for **all** manufacturing organizations. However, this multiple-case study showed that it may not always be possible to assess all dimensions of the model for all organizations of all industries. Hence, more research is needed to identify all (ir)relevant dimensions of the I4RMM based on the industry of the organization.

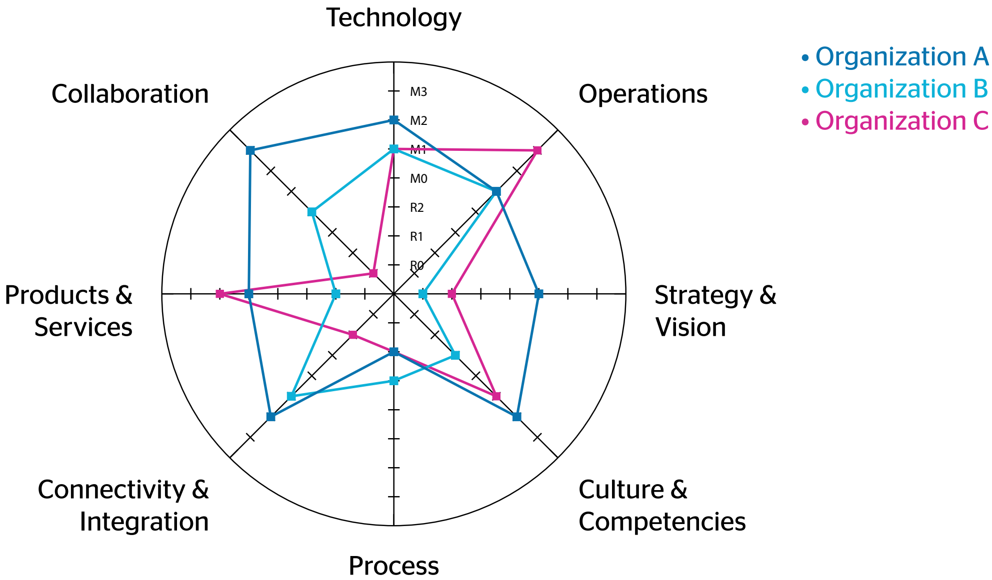

Figure 5.5: Evaluation: results I4RMM assessments companies A,B, and C

Finally, using the case study protocol, the main findings of the multiple-case study can be categorized as evaluation items on the model its completeness, validity, and usability. A summary of these items are presented in Table 5.2.

Table 5.2: Multiple-case study: results

	Completeness	Validity	Usability
Case study 1	• It lacks a glossary of used terminology. • Business change management and the effect of cultural influence is missing in the *culture & competencies* dimension. • Security and compliance is missing in the *collaboration* dimension.	• For the *culture & competencies* dimension, readiness levels are focused on culture and maturity levels are focused on competencies. The dimension is not cohesively assessed. • *Products & services* should be two separate dimensions. The dimension cannot be accurately assessed in its current form.	• The concepts of I4.0 readiness and maturity were unclear i.e. whether both entities are assessed in the model or only one entity. • The difference between the different levels should be more distinct. • The continuation from level R2 to level M0 seems unnatural, due to the number suffix.
Case study 2	• It lacks a glossary of used terminology. • Weighting factors or a relevance indication is missing in the model.	• Two different perspectives IT/OT are not always synchronized in an organization. Therefore, is it important to make a decision from which perspective the model assesses the dimensions. • The dimension *products & services* is irrelevant in the pharmaceutical industry due to strict regulations and laws.	
Case study 3	• The highest maturity level of *operations* should be expanded by introducing new (higher) maturity levels, or by altering the current level descriptions.	• Different factories or departments may lead to different assessment outcomes, it is difficult to assess a organization in its completeness. • *Products & services* should be two separate dimensions.	• The extent to which collaboration could be acknowledged under I4.0 is unclear.

5.4 Technology Acceptance Model (TAM) survey

The TAM survey was sent to the participants of the case study directly after the assessment session. In this survey, the participants were asked their opinion about the perceived usefulness, perceived ease-of-use, and intention-to-use of the I4RMM. In total, six people participated in the case study i.e. two participants per case study.

Figure 5.6 depicts the results of the TAM survey. The overall view is positive on the measured constructs, indicating that the overall attitude towards the I4RMM is positive. However, the results of the second question stand out. This question assesses the difficulty in which organizations can comprehend the concepts of I4.0 readiness and maturity in this model. Complementing the observations from the first case study, these concepts may be difficult to interpret and use. For new iterations of this model, I4.0 readiness and maturity must be made very clear. Their definitions and relation to each other could be refined and clarified, to improve the perceived usefulness of measuring both concepts.

Perceived usefulness	Q01	I think the I4RMM provides an effective solution to the problem of assessing Industry 4.0 in organizations.
	Q02	Readiness and maturity represented in this way would be difficult for users and stakeholders to understand.*
	Q03	Overall, I found the I4RMM in this experiment to be useful.
	Q04	Using the I4RMM would make it difficult to communicate readiness/maturity of Industry 4.0 to users and other stakeholders.*
Perceived ease-of-use	Q05	Learning to use the I4RMM to assess Industry 4.0 would be easy for me.
	Q06	I found the way readiness/maturity is represented as unclear and difficult to understand.*
	Q07	It would be easy for me to become skillful at using the I4RMM to assess Industry 4.0.
	Q08	Overall, I found the I4RMM for assessing Industry 4.0 difficult to use.*
Intention-to-use	Q09	I would prefer to use the I4RMM to assess Industry 4.0 in the future.
	Q10	I would definitely not use the I4RMM to assess Industry 4.0.*

** The items marked with * are in negative form and their results are reversed in the graph.*

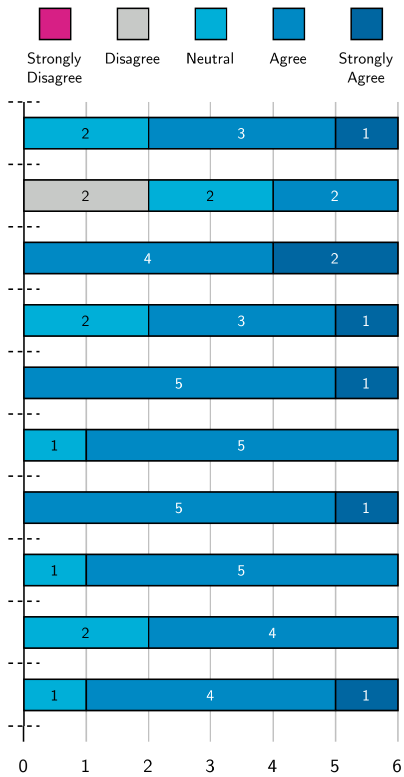

Figure 5.6: Evaluation: results TAM survey of I4RMM

Chapter 6

Conclusions

This chapter presents the conclusions which can be drawn from this research endeavor. It follows the DSR paradigm by presenting the contributions to the knowledge base and to the environment (Hevner et al., 2004). Furthermore, the limitations of the research project are acknowledged, and recommendations for future research are discussed.

This research endeavor introduced a readiness maturity model for assessing the concepts of I4.0 readiness and I4.0 maturity of organizations operating in the manufacturing domain. By including both readiness and maturity, this research developed a comprehensive assessment model that can be utilized by organizations before and during their I4.0 proceedings. The model can be used to determine the current readiness level, in which the minimum organizational requirements are assessed that are needed to successfully engage in I4.0. In addition, the maturity levels aim to assess the as-is state of organizations in their digital transformation, and help organizations to identify improvement opportunities to achieve higher maturity levels in I4.0.

The elements of the initial model were synthesized from a broad range of I4.0 maturity and readiness models as presented in the academic literature. This initial model was further developed and refined through a Delphi study of four rounds with nine domain experts. Subsequently, this resulted in the Industry 4.0 Readiness Maturity Model (I4RMM).

Finally, this research artifact was evaluated by applying the I4RMM in a business environment. This was realized by conducting a multiple-case study with three case organizations, in which the I4RMM was used to assess the organization its I4.0 readiness and I4.0 maturity. The case organizations were selected on industry, to enable a cross-case analysis. During the case studies, the model was evaluated on completeness, validity, and usability. In addition to the case studies, a Technology Acceptance Model (TAM) survey was held to research the model its perceived usefulness, perceived ease-of-use, and intention-to-use. The overall view of the I4RMM was positive on these measured constructs. However, multiple improvement opportunities were identified during the evaluation concerning the model its applicability for specific industries, the conjunction of I4.0 readiness and maturity, and overall refinement opportunities.

6.1 Contributions to Knowledge Base

This research extends the body of knowledge on the academic literature of I4.0 assessment methodologies by providing an operational model that can be utilized to assess both I4.0 readiness and maturity.

The study addresses the research gap introduced by De Carolis et al. (2017); Mittal et al. (2018a). These authors claim that there is a current disconnection between I4.0 maturity and readiness models. In addition, the authors state the need for an established approach or framework to combine these assessment methods, including both perspectives of I4.0 readiness and maturity. The I4RMM solves this gap by introducing a model that can be used to assess both concepts. Furthermore, the model was validated after a multiple-case study and performing a TAM survey, in which the overall view of the I4RMM was positive. In conclusion, the I4RMM provides a unique solution to assess I4.0 readiness and maturity, while concurrently broadening the knowledge base on readiness and maturity models that can be used in the domain of I4.0.

6.2 Contributions to Environment

This research addresses the industrial need for a structured methodology to assess I4.0 readiness and maturity. The practical relevance has been demonstrated during the application of the I4RMM in the case studies. According to these results, the model is perceived to be useful and easy-to-use. The I4RMM can be employed for three purposes.

First, the model can be utilized to assess the as-is state of the organization regarding the proceedings of I4.0. The I4RMM can identify the minimum organizational requirements that are needed to successfully engage in I4.0 by selecting the appropriate readiness level. This can help organizations to optimally prepare for the challenges and requirements of I4.0. Furthermore, the model can provide insight in current maturity levels of organizational dimensions. These levels provide better understanding to organizations regarding their current state in their digital transformation.

Second, the model can be utilized to assess the to-be state of organizations regarding their proceedings in I4.0. Organizations can use the model to determine their ambition readiness or maturity levels. Furthermore, a gap analysis could be conducted between the as-is state and the to-be state of the organizational dimensions. This gap analysis could identify improvement opportunities by comparing the different unique readiness/maturity level descriptions.

Finally, by utilizing the model for several organizations, it is possible to perform a benchmarking study. This benchmarking study could provide valuable insight in the average I4.0 readiness and maturity levels of different manufacturing companies operating in different industries.

6.3 Limitations and future research

This research includes several limitations, which can be addressed in future research. The most important limitations are presented and possibilities and recommendations for future research are shared.

Theory: completeness The first limitation deals with the completeness of the performed literature review. This literature review analyzed and synthesized 26 I4.0 readiness and maturity models. Based on this synthesis, a first iteration of the I4RMM was developed. The literature selection procedures was carefully performed. However, it could be possible that some academic publications were missed during the literature collection procedure, therefore excluding potential valuable input to the first iteration of the model. Future research should revisit the performed literature review to determine if all essential publications are included.

Delphi study According to Delbecq et al. (1975); Okoli (2015), the recommended panel size of a Delphi study is between 10-18 participants. However, in this study, nine domain experts participated. In addition, the Delphi rounds aim to reach a certain consensus between the participants. In the academic literature, no firm rule is provided of when this consensus is reached (Powell, 2003). For this study, the consensus was based on a 80% response-rate for the option 'Stay' for a specific model item. However, the study proceeded with round 3 although a consensus was not reached for all the dimensions of round 2 i.e. 2/8 dimensions were not agreed on. This could have had an impact on the intention-to-use and/or acceptance of the new model, since users may disagree with the selected dimensions.

I4RMM: completeness Although the Delphi study did investigate sub-dimensions, the final I4RMM does not contain sub-dimensions. However, the additional layer of detail can enable richer analysis of maturity results and could improve the ability to present maturity results in a way that meets the need of the targeted audience (de Bruin et al., 2005). Therefore, it can increase the utility of the model. Hence, future research should revise these dimensions and explore the ability to define sub-dimensions. For example, the *products & services* dimension should be split up—according to the multiple-case study—and could be re-defined as possible sub-dimensions. During the development of the I4RMM, participants of the Delphi study and the case studies vouched for a quantitative extension of the model. For example, the inclusion of weighting factors could prioritize the dimensions and their improvement paths. Furthermore, the different level descriptions could be quantified to eliminate potential disagreements on the level selection procedure. These features could be explored in future research. In addition, the model is lacking a glossary of used terminology, to ensure consistency and understandability. Finally, themes such as change management, the effect of cultural influence, and security and compliance are missing in the dimensions of the model. Future research should revise and explore these themes.

I4RMM: validity During the multiple-case study, several limitations were discovered regarding the unique level descriptions of the I4RMM. For example, the level descriptions of the *culture & competencies* dimension were not cohesively formulated, in which the levels did not accurately represent evolutionary items i.e. readiness levels were focused on culture and maturity levels were focused on competencies. Future research could try to improve the model its validity by improving these descriptions. Furthermore, the *products & services* dimension should be split up in two separate dimensions. In the current form, the dimension cannot be accurately assessed. In addition, the capability level labels from CMMI Product Team (2010) were adopted for the I4RMM. However, these labels could be improved to give a better indication of the intent of the stage. For example, the level 'defined' could be updated to 'optimized' to better reflect the continuous improvement and optimization characteristic of the level. Future research should revise these labels to improve them. Furthermore, the maturity levels as proposed by CMMI Product Team (2010) should be explored, as a replacement for the capability level structure as is currently adopted. These maturity levels would bring an additional level to the model, potentially providing richer analysis of maturity results.

I4RMM: usability From the start, this research attempted to develop a model that can be utilized by companies of different sizes operating in the manufacturing domain. However, during the evaluation of the model, it was observed that this broad scoping led to applicability issues in specific industries i.e. irrelevant dimensions in the pharmaceutical industry. Therefore, future research could work on adjusting or extending the model to be applicable to these specific industries. Alternatively, future research could alter the I4RMM to make it general applicable (across all industries). Both research paths will improve the applicability of the model, and therefore, increase its adoption by the environment. Another limitation was identified during the multiple-case study. In some cases, the participants were confused by the concepts of I4.0 readiness and maturity and their conjunction. It was unclear whether both concepts were assessed, or only one. This could be visually solved by improving the current structure of the model i.e. clarifying that the readiness level R2 is always applied when selecting an appropriate maturity level (M0-M3). Future research could attempt to improve the model its structure to increase its usability and comprehensibility regarding the concepts of readiness and maturity. Furthermore, the addition of a glossary of used terminology was suggested to increase consistency and understandability for those who seek to utilize the I4RMM.

I4RMM: evaluation Finally, a few limitations can be identified regarding the evaluation of the developed artifact. First, the number of case studies can be considered as another limitation. The multiple-case study comprised of three case studies with organizations from different industries. However, a larger (diverse) sample size is necessary for a strong validation of the model. Second, due to practical and logistical reasons, the multiple-case study was conducted with business consultants of the case organizations (externals). The evaluation of the model could be further reinforced by case studies with employees of the case organizations (internals). Future research should try to conduct these internal case studies. Third, the performed evaluation was focused on the descriptive purpose of the model and its completeness, validity, and usability. However, future research could be performed to evaluate the prescriptive and comparative (benchmarking) features of the model. For example, longitudinal evaluation studies could be performed to assess the performance of a business before, during, and after applying and using the I4RMM.

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Appendix A

Delphi round 1: dimensions

This appendix contains detailed information about the first Delphi round which was exploratory in nature. The goal of this round was to evaluate the initial model with regards to its structure, dimensions, and its definitions. Furthermore, additional (sub-)dimensions were explored.

This appendix contains the following:

A.1 I4RMM: round 1
A.2 Microsoft Forms: round 1
A.3 Result sheet: round 1

First, Appendix A.1 presents the base model for this round, which originated from the Systematic Literature Review (Appendix G). Second, Appendix A.2 presents the Microsoft Forms which was used to gather information from the Delphi panel. Finally, Appendix A.3 presents the results of this survey, including the model alterations that were made based on these results.

A.1 I4RMM: round 1

Table A.1: I4RMM: round 1

Index	Dimension code	Description
1	Technology	The extent to which I4.0 technologies are implemented and used (Canetta et al., 2018; Mittal et al., 2020; Schumacher et al., 2019; Trotta and Garengo, 2019).
2	Operations	The extent to which processes are decentralized and make use of I4.0 paradigms e.g. agile manufacturing systems, and monitoring and decision systems (Rauch et al., 2020; Schumacher et al., 2016).
3	Strategy & Organization	The extent to which the strategy currently adopted by companies is related to I4.0 implementation, including the acknowledgement of an I4.0 roadmap (Schumacher et al., 2016, 2019; Trotta and Garengo, 2019; Wagire et al., 2020).
4	People	The extent to which people are competent and open to new I4.0 technologies, and the extent to which HRM practices support I4.0 implementation (Rauch et al., 2020; Schumacher et al., 2016; Sjödin et al., 2018; Trotta and Garengo, 2019).
5	Products & Services	The extent to which products are individualized and product characteristics are flexible. This also includes product tracking, management of products' lifecycle, and data driven services and product data usage (Canetta et al., 2018; Leyh et al., 2017; Mittal et al., 2018a; Schumacher et al., 2016, 2019; Trotta and Garengo, 2019).
6	Process	The extent to which companies support departments collaboration, machine and system integration with the help of I4.0 technologies. This includes self-optimization and self-configuration of processes of production, maintenance, and support processes (Canetta et al., 2018; Santos and Martinho, 2019; Schumacher et al., 2019; Sjödin et al., 2018; Wagire et al., 2020).
7	Integration	The extent to which vertical and horizontal integration is in place across the value chain (Leyh et al., 2017; Lin et al., 2019; Rajnai and Kocsis, 2018).
8	Culture	The extent to which the culture is open to innovation enabled by I4.0 (Santos and Martinho, 2019; Schumacher et al., 2016; Wagire et al., 2020).
9	Connectivity	The availability of infrastructural elements needed for data transmission inside and outside the organization (Colli et al., 2019, 2018; Lin et al., 2019).
10	Collaboration	The extent to which formal channels are enabled for employees to share information and work together, as well as institutional structures and systems that allow collaborative behavior (Lin et al., 2019).

Figure A.1: I4RMM: round 1

A.2 Microsoft Forms: round 1

Industry 4.0 Readiness Maturity Model (I4RMM) - Round 1

Thank you for participating in this Delphi study. Your input will be highly valuable in developing the new integrated Industry 4.0 Readiness Maturity assessment Model (I4RMM). This new conceptual model will yield better understanding in assessing Industry 4.0 readiness and maturity in businesses. These insights can guide businesses in their I4.0 transformation.

The content of this form will be treated with high confidentiality. For any questions about the procedure, please contact me:

P.W. (Paul) Kaandorp
paul.kaandorp@atos.net (mailto:paul.kaandorp@atos.net)

* Required

Introduction

Before starting the first round, I would like to ask two profiling questions. Note that all your answers will be anonymized.

1. What is your position/function/role within Atos? *

2. Please indicate your working experience in the domain of Industry 4.0. *

- ◯ <2 years
- ◯ 2-4 years
- ◯ 4-8 years
- ◯ >8 years

Round 1: dimensions

In preperation of this project, a Systematic Literature Review (SLR) was conducted to obtain an overview of the available Industry 4.0 (I4.0) readiness and maturity assessment models in the scientific literature. From this overview, results were synthesized to obtain a new integrated model named the Industry 4.0 Readiness Maturity Model (I4RMM). This initial model aims to measure the following dimensions to adequately measure I4.0 readiness and maturity:

1. Technology
2. Operations
3. Strategy and Organization
4. People
5. Products and Services
6. Process
7. Integration
8. Culture
9. Connectivity
10. Collaboration

These 10 dimensions will be discussed in this round of the Delphi technique. Each dimension contains a definition based on the literature. For the new I4RMM model, I will ask you to judge whether these dimensions should stay, change, or can go (be removed). If you choose for the latter two, please provide a motivation.

Finally, this round is explorative in nature. If you can think of new (sub-)dimensions that are not listed here, feel free to share them with me at the end of this survey.

Good luck and thank you again for participating!

3. Technology *

The extent to which I4.0 technologies are implemented and used.

- ◯ Stay
- ◯ Change
- ◯ Can go

4. 'Technology' dimension 'change' motivation *

How exactly would you change this dimension? Would you change/merge the dimension name or definition? Or maybe something else?

5. 'Technology' dimension 'can go' motivation *

Why exactly would you eliminate this dimension?

6. Operations *

The extent to which processes are decentralized and make use of I4.0 paradigms e.g. agile manufacturing systems, and monitoring and decision systems.

- ◯ Stay
- ◯ Change
- ◯ Can go

7. 'Operations' dimension 'change' motivation *

How exactly would you change this dimension? Would you change/merge the dimension name or definition? Or maybe something else?

8. 'Operations' dimension 'can go' motivation *

Why exactly would you eliminate this dimension?

9. Strategy and Organization *

The extent to which the strategy currently adopted by companies is related to I4.0 implementation, including the acknowledgement of an I4.0 roadmap.

- ◯ Stay
- ◯ Change
- ◯ Can go

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10. 'Strategy and Organization' dimension 'change' motivation *

How exactly would you change this dimension? Would you change/merge the dimension name or definition? Or maybe something else?

11. 'Strategy and Organization' dimension 'can go' motivation *

Why exactly would you eliminate this dimension?

12. People *

The extent to which people are competent and open to new I4.0 technologies, and the extent to which HRM practices support I4.0 implementation.

- ◯ Stay
- ◯ Change
- ◯ Can go

13. 'People' dimension 'change' motivation *

How exactly would you change this dimension? Would you change/merge the dimension name or definition? Or maybe something else?

14. 'People' dimension 'can go' motivation *

Why exactly would you eliminate this dimension?

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15. Products and Services *

The extent to which products are individualized and product characteristics are flexible. This also includes product tracking, management of products' lifecycle, and data driven services and product data usage.

- ◯ Stay
- ◯ Change
- ◯ Can go

16. 'Products and Services' dimension 'change' motivation *

How exactly would you change this dimension? Would you change/merge the dimension name or definition? Or maybe something else?

17. 'Products and Services' dimension 'can go' motivation *

Why exactly would you eliminate this dimension?

18. Process *

The extent to which companies support departments collaboration, machine and system integration with the help of I4.0 technologies. This includes self-optimization and self-configuration of processes of production, maintenance, and support processes.

- ◯ Stay
- ◯ Change
- ◯ Can go

19. 'Process' dimension 'change' motivation *

How exactly would you change this dimension? Would you change/merge the dimension name or definition? Or maybe something else?

20. 'Process' dimension 'can go' motivation *

Why exactly would you eliminate this dimension?

21. Integration *

The extent to which vertical and horizontal integration is in place across the value chain.

- ◯ Stay
- ◯ Change
- ◯ Can go

22. 'Integration' dimension 'change' motivation *

How exactly would you change this dimension? Would you change/merge the dimension name or definition? Or maybe something else?

23. 'Integration' dimension 'can go' motivation *

Why exactly would you eliminate this dimension?

24. Culture *

The extent to which the culture is open to innovation enabled by I4.0.

- ◯ Stay
- ◯ Change
- ◯ Can go

25. 'Culture' dimension 'change' motivation *

How exactly would you change this dimension? Would you change/merge the dimension name or definition? Or maybe something else?

26. 'Culture' dimension 'can go' motivation *

Why exactly would you eliminate this dimension?

27. Connectivity *

The availability of infrastructural elements needed for data transmission inside and outside the organization.

- ◯ Stay
- ◯ Change
- ◯ Can go

28. 'Connectivity' dimension 'change' motivation *

How exactly would you change this dimension? Would you change/merge the dimension name or definition? Or maybe something else?

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29. 'Connectivity' dimension 'can go' motivation *

Why exactly would you eliminate this dimension?

30. Collaboration *

The extent to which formal channels are enabled for employees to share information and work together, as well as institutional structures and systems that allow collaborative behavior.

- ◯ Stay
- ◯ Change
- ◯ Can go

31. 'Collaboration' dimension 'change' motivation *

How exactly would you change this dimension? Would you change/merge the dimension name or definition? Or maybe something else?

32. 'Collaboration' dimension 'can go' motivation *

Why exactly would you eliminate this dimension?

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33. Can you think of additional (sub-) dimensions that are not listed here and you would like to mention?

34. Any other remarks or questions?

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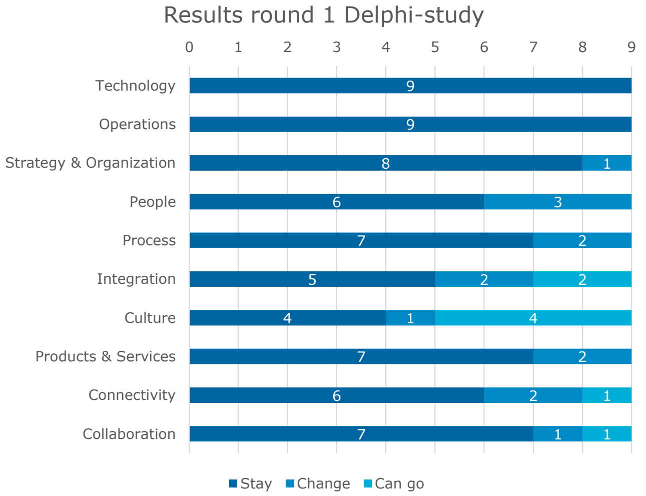
A.3 Result sheet: round 1

I4RMM: Dimensions

Results Delphi study round 1

- Number of participants: 9
- A large majority of the expert panel needs to agree on a model element in order for it to be included (80%, ≥7 'stay')
- In this round, 6/10 dimensions were agreed on.
- Most discussion about the dimensions 'Integration' and 'Culture'.



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What did you think? (1/2)

- **Technology**
- **Operations**
- **Strategy and Organization**
  - The term 'Organization' was perceived to be too generic, such that it will not really influence the I4.0 introduction. Name suggestion: 'Strategy and Vision'.
- **People**
  - 'People' is too generic and vague. 'Competencies' or 'skills' give a better indication of what we currently have and what is targeted.
  - Too much overlap with the 'Culture' dimension.
  - Shift the focus on 'involved process owners' or 'business process stakeholders'.
- **Process**
  - There were some concerns that this is already covered by the 'Operations' dimension.
  - Refine the definition to include the level of standardization and simplicity of the processes.
- **Integration**
  - A distinction needs to be made between 'internal' and 'external' supply chain.
  - Could be combined with 'Connectivity'.
  - The aim should always be an integrated environment; therefore it should be part of other dimensions e.g. 'Technology'.
- **Culture**
  - Already covered by 'Strategy and Organization' and 'People'.
  - Merge it with 'People'.
  - Not applicable in this domain and very difficult to measure.
- **Products & Services**
  - Alter definition: 'product characteristics are ~~flexible~~ customer specific'.
  - Might be covered by the 'Technology' dimension.

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What did you think? (2/2)

- **Connectivity**
  - Could be combined with 'Integration'.
  - Might be a part of the 'Technology' dimension.
  - New name suggestion: 'IT Infrastructure'.
- **Collaboration**
  - Is this not the same as 'Technology'?
  - Not really applicable in this domain.
- **Additional (sub-)dimensions and thoughts**
  - Collaboration could be split up in suppliers and vendors working together for a common solution (product), and those who deliver OT/IT in support of the I4.0 processes and tools.
  - Should we address the dimension of 'Financial Readiness'?
  - Adding the dimension 'Industry' would make it possible to compare companies facing the same circumstances.

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Based on your feedback...

- **Technology**
- **Operations**
- **Strategy and Organization**
  - Changed to 'Strategy and Vision'.
  - Refined the definition.
- **People**
  - Removed and merged with 'Culture' in 'Culture & Skills'.
- **Process**
  - Refined the definition to include the level of standardization and simplicity of the processes.
- **Integration**
  - Removed and merged with 'Connectivity' in 'Connectivity & Integration'.
- **Culture**
  - Merged with 'People' in 'Culture & Skills'.
  - Refined the definition.
- **Products & Services**
  - Refined the definition: product characteristics are ~~flexible~~ customer specific'.
- **Connectivity**
  - Merged with 'Integration' in 'Connectivity & Integration'.
  - Refined the definition so the entities 'vertical' and 'horizontal' integration can be treated separately.
- **Collaboration**

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Dimension	Definition
Technology	The extent to which I4.0 technologies are implemented and used.
Operations	The extent to which processes are decentralized and make use of I4.0 paradigms e.g. agile manufacturing systems, and monitoring and decision systems.
Strategy & Vision	The extent to which the strategy and vision currently adopted by companies is aimed towards I4.0, including the acknowledgement of an I4.0 roadmap.
Culture & Skills	The extent to which people are competent and open to new I4.0 technologies and innovation, and the extent to which HRM practices support I4.0 implementation.
Process	The extent to which companies support departments collaboration, machine and system integration with the help of I4.0 technologies. This includes self-optimization, self-configuration, standardization and simplification of processes of production, maintenance, and support processes.
Connectivity & Integration	The extent to which an IT infrastructure is in place to accommodate vertical or horizontal integration across the value chain.
Products & Services	The extent to which products are individualized and product characteristics are customer specific. This also includes product tracking, management of products' lifecycle, and data driven services and product data usage.
Collaboration	The extent to which formal channels are enabled for employees to share information and work together, as well as institutional structures and systems that allow collaborative behavior.

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Appendix B

Delphi round 2: dimensions

This appendix contains detailed information about the second Delphi round which was confirmative in nature. The goal of this round was to establish the final dimensions of the model and its definitions. Therefore, this round aimed to reach a consensus among the Delphi panel members about these dimensions.

This appendix contains the following:

B.1 I4RMM: round 2
B.2 Microsoft Forms: round 2
B.3 Result sheet: round 2

First, Appendix B.1 presents the model for this round, after improvements based on the previous round (Appendix A.3). Second, Appendix B.2 presents the Microsoft Forms which was used to gather information from the Delphi panel. Finally, Appendix B.3 presents the results of this survey, including the model alterations that were made based on these results.

B.1 I4RMM: round 2

Table B.1: I4RMM: round 2

Index	Dimension code	Description
1	Technology	The extent to which I4.0 technologies are implemented and used.
2	Operations	The extent to which processes are decentralized and make use of I4.0 paradigms e.g. agile manufacturing systems, and monitoring and decision systems.
3	Strategy & Vision	The extent to which the strategy and vision currently adopted by companies is aimed towards I4.0, including the acknowledgment of an I4.0 roadmap.
4	Culture & Skills	The extent to which people are competent and open to new I4.0 technologies and innovation, and the extent to which HRM practices support I4.0 implementation.
5	Process	The extent to which companies support departments collaboration, machine and system integration with the help of I4.0 technologies. This includes self-optimization, self-configuration, standardization and simplification of processes of production, maintenance, and support processes.
6	Connectivity & Integration	The extent to which an IT infrastructure is in place to accommodate vertical or horizontal integration across the value chain.
7	Products & Services	The extent to which products are individualized and product characteristics are customer specific. This also includes product tracking, management of products' life-cycle, and data driven services and product data usage.
8	Collaboration	The extent to which formal channels are enabled for employees to share information and work together, as well as institutional structures and systems that allow collaborative behavior.

Figure B.1: I4RMM: round 2

B.2 Microsoft Forms: round 2

Industry 4.0 Readiness Maturity Model (I4RMM) - Round 2

Thank you for participating in this Delphi study. Your input will be highly valuable in developing the new integrated Industry 4.0 Readiness Maturity assessment Model (I4RMM). This new conceptual model will yield better understanding in assessing Industry 4.0 readiness and maturity in businesses. These insights can guide businesses in their I4.0 transformation.

The content of this form will be treated with high confidentiality. For any questions about the procedure, please contact me:

P.W. (Paul) Kaandorp
paul.kaandorp@atos.net (mailto:paul.kaandorp@atos.net)

* Required

* This form will record your name, please fill your name.

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Round 2: dimensions (re-evaluation)

In the previous round, I asked you to evaluate the dimensions of the initial version of the I4RMM. With your help and input, I managed to evolve the model based on your feedback. Changes were made on a:

- Structural level (e.g. mergers of dimensions)
- Definitional level (refinements of definitions)

A complete overview of all the changes and an overview of the results of the previous round was sent to you by mail or can be found in the Circuit group (Delphi panel I4RMM).

In this second round, the objective is to evaluate the new model, consisting of the following dimensions:

1. Technology
2. Operations
3. Strategy & Vision
4. Culture & Skills
5. Process
6. Connectivity & Integration
7. Products & Services
8. Collaboration

The procedure is the same as the previous round, where I would like you to evaluate these dimensions and judge whether they should stay, change, or can go (be removed). If you choose for the latter two, please provide a motivation.

Good luck and thank you again for participating!

1. Technology *

The extent to which I4.0 technologies are implemented and used.

- ○ Stay
- ○ Change
- ○ Can go

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2. 'Technology' dimension 'change' motivation *

How exactly would you change this dimension? Would you change/merge the dimension name or definition? Or maybe something else?

3. 'Technology' dimension 'can go' motivation *

Why exactly would you eliminate this dimension?

4. Operations *

The extent to which processes are decentralized and make use of I4.0 paradigms e.g. agile manufacturing systems, and monitoring and decision systems.

- ◯ Stay
- ◯ Change
- ◯ Can go

1/27/2021

5. 'Operations' dimension 'change' motivation *

How exactly would you change this dimension? Would you change/merge the dimension name or definition? Or maybe something else?

6. 'Operations' dimension 'can go' motivation *

Why exactly would you eliminate this dimension?

7. Strategy and Vision *

The extent to which the strategy and vision currently adopted by companies is aimed towards I4.0, including the acknowledgement of an I4.0 roadmap.

- ◯ Stay
- ◯ Change
- ◯ Can go

1/27/2021

8. 'Strategy and Vision' dimension 'change' motivation *

How exactly would you change this dimension? Would you change/merge the dimension name or definition? Or maybe something else?

9. 'Strategy and Vision' dimension 'can go' motivation *

Why exactly would you eliminate this dimension?

10. Culture & Skills *

The extent to which people are competent and open to new I4.0 technologies and innovation, and the extent to which HRM practices support I4.0 implementation.

○ Stay

○ Change

○ Can go

1/27/2021

11. 'Culture & Skills' dimension 'change' motivation *

How exactly would you change this dimension? Would you change/merge the dimension name or definition? Or maybe something else?

12. 'Culture & Skills' dimension 'can go' motivation *

Why exactly would you eliminate this dimension?

13. Process *

The extent to which companies support departments collaboration, machine and system integration with the help of I4.0 technologies. This includes self-optimization, self-configuration, standardization and simplification of processes of production, maintenance, and support processes.

○ Stay

○ Change

○ Can go

1/27/2021

14. 'Process' dimension 'change' motivation *

How exactly would you change this dimension? Would you change/merge the dimension name or definition? Or maybe something else?

15. 'Process' dimension 'can go' motivation *

Why exactly would you eliminate this dimension?

16. Connectivity & Integration *

The extent to which an IT infrastructure is in place to accommodate vertical or horizontal integration across the value chain.

- ◯ Stay
- ◯ Change
- ◯ Can go

1/27/2021

17. 'Connectivity & Integration 'change' motivation *

How exactly would you change this dimension? Would you change/merge the dimension name or definition? Or maybe something else?

18. 'Connectivity & Integration' dimension 'can go' motivation *

Why exactly would you eliminate this dimension?

19. Products & Services *

The extent to which products are individualized and product characteristics are customer specific. This also includes product tracking, management of products' lifecycle, and data driven services and product data usage.

- ◯ Stay
- ◯ Change
- ◯ Can go

1/27/2021

20. 'Products & Services' dimension 'change' motivation *

How exactly would you change this dimension? Would you change/merge the dimension name or definition? Or maybe something else?

21. 'Products & Services' dimension 'can go' motivation *

Why exactly would you eliminate this dimension?

22. Collaboration *

The extent to which formal channels are enabled for employees to share information and work together, as well as institutional structures and systems that allow collaborative behavior.

- ◯ Stay
- ◯ Change
- ◯ Can go

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23. 'Collaboration' dimension 'change' motivation *

How exactly would you change this dimension? Would you change/merge the dimension name or definition? Or maybe something else?

24. 'Collaboration' dimension 'can go' motivation *

Why exactly would you eliminate this dimension?

25. Any other remarks or questions?

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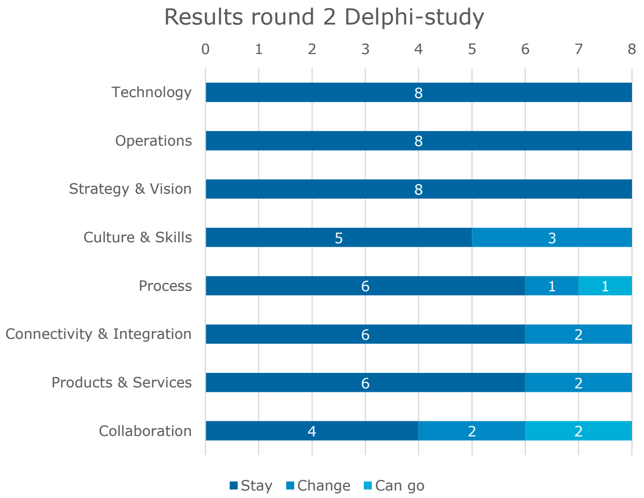
B.3 Result sheet: round 2

I4RMM: Dimensions

Results Delphi study round 2

- Number of participants: 8 (last round: 9)
- A large majority of the expert panel needs to agree on a model element in order for it to be included (80%, ≥6 'stay')
- In this round, 6/8 dimensions were agreed on.
- Most discussion about the dimensions 'Culture & Skills' and 'Collaboration'.
- This round finalizes the dimensions of the I4RMM.



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What did you think?

- **Technology**
- **Operations**
- **Strategy & Vision**
- **Culture & Skills**
  - Rather connect 'Culture' with 'People' than with 'Skills'.
  - Alter definition: merge sentences to make it more cohesive.
  - All departments should be involved instead of 'only' HRM. Maybe include a new recruitment strategy?
- **Process**
  - Merge with 'Operations' as process is an integral part of it.
- **Connectivity & Integration**
  - IT infrastructure may suggest an 'internal' focus, perhaps bring up the word 'cloud' here?
- **Products & Services**
  - Alter definition: include the extent to which the customers acknowledge the need to be able to individualize their products.
- **Collaboration**
  - Not really relevant.
  - Merge with 'Culture & Skills', collaboration is something that can be incorporated as culture.
  - Alter definition: (… *enabled for employees* <u>and collaboration partners</u> *to* …).
- **Additional (sub-)dimensions and thoughts**
  - Include an 'Industry' domain to the dimensions. Different industries cope with different requirements and challenges when engaging or operating in Industry 4.0.

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Based on your feedback…

- **Technology**
- **Operations**
- **Strategy & Vision**
- **~~Culture & Skills~~ → Culture & Competencies**
  - Changed to 'Culture & Competencies'. I feel that 'Skills' are too low-level and don't successfully convey the old dimension: 'People'. Skills are mere abilities, where competencies combine the person's knowledge and behavior (which affects culture).
  - Refined the definition (increased readability and emphasized the importance of organization-wide support).
- **Process**
- **Connectivity & Integration**
  - Refined the definition (added cloud-infrastructure to include virtualization).
- **Products & Services**
  - Refined the definition (including the road towards 'smart products' and 'servitization').
- **Collaboration**
  - Refined the definition (… *enabled for employees and collaboration partners to* …).
- **Additional (sub-)dimensions and thoughts**
  - A comment was made to include an 'Industry' dimension to support the different requirements/challenges that come with different industries within the manufacturing environment. I acknowledge this observation but decided to stick with the generalized focus of the model due to planning and scoping restrictions of this project. Perhaps future specialized adaptions of the model with a specific industry in mind can be generated at a later state.
  - Two comments were made about merging 'Collaboration' with 'Culture and Skills' since 'Collaboration' can be seen as part of culture. I acknowledge this observation. However, I am interested to see how this holds up in round 3 (after evaluating the different levels associated with these dimensions). Therefore, I will re-evaluate this after round 3.

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Final dimensions

- Technology
- Operations
- Strategy & Vision
- Culture & Competencies
- Process
- Connectivity & Integration
- Products & Services
- Collaboration

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Final dimension	Definition
Technology	The extent to which I4.0 technologies are implemented and used.
Operations	The extent to which processes are decentralized and make use of I4.0 paradigms e.g. agile manufacturing systems, and monitoring and decision systems.
Strategy & Vision	The extent to which the strategy and vision currently adopted by companies are aimed towards I4.0, including the acknowledgement of an I4.0 roadmap.
Culture & Competencies	The extent to which all people of all departments are competent (due to adequate training and recruitment of HRM) and support the implementation of I4.0 technologies and innovation.
Process	The extent to which companies support departments collaboration, machine and system integration with the help of I4.0 technologies. This includes self- optimization, self-configuration, standardization and simplification of processes of production, maintenance, and support processes.
Connectivity & Integration	The extent to which an IT/cloud infrastructure is in place to accommodate vertical or horizontal integration across the value chain.
Products & Services	The extent to which products are individualized and product characteristics are customer specific (smart products), and the extent towards offering data-driven services and customer integration (smart services and servitization).
Collaboration	The extent to which formal channels are enabled for employees and collaboration partners to share information and work together, as well as institutional structures and systems that allow collaborative behavior.

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Appendix C

Delphi round 3: levels & labels

This appendix contains detailed information about the third Delphi round which was exploratory in nature. The goal of this round was to evaluate the levels and labels that were created based on the chosen dimensions of the previous rounds. The Delphi panel was introduced to these different level descriptions and were asked to evaluate them. Furthermore, the Delphi panel was asked to comment on the current structure i.e. number of levels and the combination of readiness and maturity levels, to identify possible structural changes.

This appendix contains the following:

C.1 I4RMM: round 3
C.2 Microsoft Forms: round 3
C.3 Result sheet: round 3

First, Appendix C.1 presents the model for this round. The dimensions were improved based on the results of the previous round (Appendix B.3), and unique level descriptions were added based on the found literature. Table C.1 presents an overview of the origin of the adapted level descriptions. Second, Appendix C.2 presents the Microsoft Forms which was used to gather information from the Delphi panel. Finally, Appendix C.3 presents the results of this survey, including the model alterations that were made based on these results.

Table C.1: I4RMM: overview readiness/maturity levels in prior research

Index	Dimension	R0	R1	M0	M1	M2	M3
1	Technology	[1]	[1]	[1]	[1]	[1]	[1]
2	Operations	[2]	[2]	[2]	[2]	[2]	[2]
3	Strategy & Vision	[1,3]	[1,3]	[1,3]	[1,3]	[1,3]	[1,3]
4	Culture & Competencies	[1,4]	[1,4]	[1,4]	[1,4]	[1,4]	[1,4]
5	Process	[3]	[3]	[3]	[3]	[3]	[3]
6	Connectivity & Integration	[1,3]	[1,3]	[1,3]	[1,3]	[1,3]	[1,3]
7	Products & Services	[6,7,5]	[6,7,5]	[6,7,5]	[6,7,5]	[6,7,5]	[6,7,5]
8	Collaboration	[3]	[3]	[3]	[3]	[3]	[3]

[1] Colli et al. (2019)
[2] De Carolis et al. (2017)
[3] Lin et al. (2019)
[4] Sjödin et al. (2018)
[5] Canetta et al. (2018)
[6] Leyh et al. (2017)
[7] Santos and Martinho (2019)

C.1 I4RMM: round 3

Industry 4.0 Readiness Maturity Model

Dimension	Definition	Readiness		Maturity			
		R0 Unprepared	R1 Ready	M0 Incomplete	M1 Performed	M2 Managed	M3 Defined
Technology	The extent to which I4.0 technologies are implemented and used.	No presence of assets that generate digital data.	There are assets available that generate data.	There are interfaces available for those who need it to access data and visualize it.	There are tools available that make it possible to process data correlating and analyzing it, and to communicate results to the user.	There are assets or tools that can act autonomously according to information received after an analytic process.	The assets deployed across the supply chain can interact together and reconfigure themselves to optimize performance.
Operations	The extent to which manufacturing operations (production, storage, quality, test, and maintenance) are formally documented, supported by I4.0 paradigms, and enable continuous improvement and optimization.	Procedures for operations are not documented.	The manufacturing operations are well documented and formally managed.	The manufacturing operations are defined with documented standards and partly supported by software tools.	The manufacturing operations are fully supported by software tools and executed with possibly repeatable results in normal situations.	The manufacturing operations are well defined across all organizational groups, and their executions are repeatable and monitored with software tool supports.	The manufacturing operations are focused on continuous improvement and optimization.
Strategy & Vision	The extent to which the strategy and vision currently adopted by companies are aimed towards I4.0, including the acknowledgement of an I4.0 roadmap.	There is no awareness regarding the digital transformation.	There is a willingness and interest towards the digital transformation from a managerial level.	I4.0 strategy and vision are being developed or have partly been developed.	I4.0 strategy and vision have been formally implemented in at least one functional area.	I4.0 strategy and vision are expanded to include more than one functional area.	I4.0 strategy and vision are refreshed and updated automatically.
Culture & Competencies	The extent to which all people of all departments are competent (due to adequate training and recruitment of HRM) and support the implementation of I4.0 technologies and innovation.	The organizational culture is not open to innovation, nor are there in-house competencies related to data handling.	The organizational culture is open to innovation and there are in-house competencies related to data handling and these can be utilized when needed.	An inclusive culture is (partly) in place by involving workforce in vision development. People are being recruited with digitization competencies.	People are educated to develop the ability to exploit connected data systems. Production staff is revised to proactively coordinate digital insights and knowledge sharing.	Sense-making sessions are in place with suppliers, users, and other stakeholders. Data analysts and data scientists are recruited to optimize production.	A culture of continuous smart factory innovation is in place covering the complete organization. Specialized roles and responsibilities are geared toward predictable production.
Process	The extent to which companies support departments collaboration, machine and system integration with the help of I4.0 technologies. This includes self- optimization, self-configuration, standardization and simplification of processes of production, maintenance, and support processes.	Processes are not explicitly defined.	Processes are defined and executed, with the support of analogue tools.	Defined processes are completed with the support of digital tools.	Digitized processes and systems are securely integrated across all hierarchical levels (machines & workers - boardroom).	Integrated processes and systems are automated, with limited human intervention.	Automated processes and systems are actively analyzing and reacting to data, enabling continuous process improvements.
Connectivity & Integration	The extent to which an IT/cloud infrastructure is in place to accommodate vertical or horizontal integration across the value chain.	There is no IT infrastructure.	The IT infrastructure is developed in separate modules that address different tasks and cannot communicate with each other.	The IT infrastructure is not standardized but all the different modules can communicate with each other.	The IT infrastructure is not fully integrated but is based on a number of recognized standards and when new modules have to be developed, this is done accordingly.	The IT infrastructure is based on a single standard and new modules are developed accordingly enabling interoperability.	The IT infrastructure in the whole supply chain is based on standards that allow plug and play inter-organization real-time communication, enabling interoperability and scalability.
Products & Services	The extent to which products are individualized and product characteristics are customer specific (smart products), and the extent towards offering data-driven services and customer integration (smart services and servitization).	Product development or services are not digitally supported.	Product development or services are partly digitally supported.	Products offer digital features and services are continuously digitally supported.	Products offer connectivity features and little differentiation. Data-driven services offer little customer integration.	Products offer responsive features and can be largely customized. Data-driven services offer customer integration.	Products can be completely customized and feature all smart product functionalities, and many products are being servitized. Data-driven services are fully integrated with the customer.
Collaboration	The extent to which formal channels are enabled for employees and collaboration partners to share information and work together, as well as institutional structures and systems that allow collaborative behavior.	Communication and information sharing across teams happen on an informal basis.	Formal channels are established for communication and information sharing across teams.	Formal channels are established to allow teams to work together on discrete tasks and projects.	"Teams are empowered by the organization to make adjustments that will facilitate cooperation on discrete tasks and projects.	Teams are empowered by the organization to share resources on both discrete and longer-term tasks and projects.	Formal channels are established to enable dynamically-forming teams to work on cross-functional projects with shared goals and resources.

C.2 Microsoft Forms: round 3

Industry 4.0 Readiness Maturity Model (I4RMM) - Round 3

Thank you for participating in this Delphi study. Your input will be highly valuable in developing the new integrated Industry 4.0 Readiness Maturity assessment Model (I4RMM). This new conceptual model will yield better understanding in assessing Industry 4.0 readiness and maturity in businesses. These insights can guide businesses in their I4.0 transformation.

The content of this form will be treated with high confidentiality. For any questions about the procedure, please contact me:

P.W. (Paul) Kaandorp
paul.kaandorp@atos.net (mailto:paul.kaandorp@atos.net)

* Required

* This form will record your name, please fill your name.

1/27/2021

Round 3: levels & labels

In the previous two rounds, we discussed the dimensions of the I4RMM. With your help and input, we managed to finalize these dimensions. A complete overview of all the changes and an overview of the results of the previous round was sent to you by mail or can be found in the Circuit group (Delphi panel I4RMM).

In this round, we shift the focus from dimensions to the associated different levels and labels of the model. The levels are divided in:

- Readiness levels (R0-R1)
- Maturity levels (M0-M3)

The readiness levels try to capture the state of unpreparedness (R0) or readiness (R1) before engaging in the digital transformation. Try to think of these levels as minimum requirements per dimension for successfully starting the digital journey of one of our clients. What is absolutely necessary before adopting I4.0 paradigms/technologies?

The maturity levels try to capture the current state while you are in the digital transformation. These levels follow the structure of the CMMI Capability Levels:

- M0: Incomplete, incomplete approach to meeting the intent of the practice area;
- M1: Initial, initial approach to meeting the intent of the practice area;
- M2: Managed, simple, but complete set of practices that address the full intent of the practice area;
- M3: Defined, uses organizational standards and tailoring to address project and work characteristics.

Each level contains a brief description. These descriptions origin from different I4.0 readiness and I4.0 maturity models from my Systematic Literature Review (this study can be found in the Circuit group). The 'Operations' levels are roughly adapted from the MESA MOM model, based on the ISA-95 standard.

In this round, I will ask you to evaluate these levels and labels. Do you agree with the descriptions? Are there things missing? What do you think of the labels? Do you think definitions of dimensions should be changed according to these presented levels? Feel free to let me know!

Note that at the end of this survey, I will also ask your opinion about its current structure. Do you agree with the number of levels, or would you like to see another approach/structure? The complete model was sent to you by mail in .pdf for reference (it can also be found in the Circuit group).

The survey procedure is the same as the previous rounds, the evaluation take place on your judgement whether a level and label should stay, change, or can go (be removed). If you choose for the latter two, please provide a motivation.

Good luck and thank you again for participating!

<< The model below may not be readable, a scalable .pdf was sent to you by mail and can be found in the Circuit group. However, it is NOT necessary to have the complete model with you when filling in the survey. All the levels and their descriptions are formulated in the questions. >>

1/27/2021

1. Technology *

Definition:
The extent to which I4.0 technologies are implemented and used.

R0 (Unprepared):
No presence of assets that generate digital data.

R1 (Ready):
There are assets available that generate data.

M0 (Incomplete):
There are interfaces available for those who need it to access data and visualize it.

M1 (Performed):
There are tools available that make it possible to process data correlating and analyzing it, and to communicate results to the user.

M2 (Managed):
There are assets or tools that can act autonomously according to information received after an analytic process.

M3 (Defined):
The assets deployed across the supply chain can interact together and reconfigure themselves to optimize performance.

- ○ Stay
- ○ Change
- ○ Can go

2. 'Technology' levels & labels 'change' motivation *

What would you change from these levels and labels? Do you think something is missing or should be excluded from the descriptions? Is it too vague or too precise, or anything else?

3. 'Technology' levels & labels 'can go' motivation *

Why do you think these levels and labels should be removed?

4. Operations *

Definition:
The extent to which manufacturing operations (production, storage, quality test, and maintenance) are formally documented, supported by I4.0 paradigms, and enable continuous improvement and optimization.

R0 (Unprepared):
Procedures for operations are not documented.

R1 (Ready):
The manufacturing operations are well documented and formally managed.

M0 (Incomplete):
The manufacturing operations are defined with documented standards and partly supported by software tools.

M1 (Performed):
The manufacturing operations are fully supported by software tools and executed with possibly repeatable results in normal situations.

M2 (Managed):
The manufacturing operations are well defined across all organizational groups, and their executions are repeatable and monitored with software tool supports.

M3 (Defined):
The manufacturing operations are focused on continuous improvement and optimization.

- ○ Stay
- ○ Change
- ○ Can go

5. 'Operations' levels & labels 'change' motivation *

What would you change from these levels and labels? Do you think something is missing or should be excluded from the descriptions? Is it too vague or too precise, or anything else?

6. 'Operations' levels & labels 'can go' motivation *

Why do you think these levels and labels should be removed?

1/27/2021

7. Strategy & Vision *

Definition:
The extent to which the strategy and vision currently adopted by companies are aimed towards I4.0, including the acknowledgement of an I4.0 roadmap.

R0 (Unprepared):
There is no awareness regarding the digital transformation.

R1 (Ready):
There is a willingness and interest towards the digital transformation from a managerial level.

M0 (Incomplete):
I4.0 strategy and vision are being developed or have partly been developed.

M1 (Performed):
I4.0 strategy and vision have been formally implemented in at least one functional area.

M2 (Managed):
I4.0 strategy and vision are expanded to include more than one functional area.

M3 (Defined):
I4.0 strategy and vision are refreshed and updated automatically.

- Stay
- Change
- Can go

8. 'Strategy & Vision' levels & labels 'change' motivation *

What would you change from these levels and labels? Do you think something is missing or should be excluded from the descriptions? Is it too vague or too precise, or anything else?

1/27/2021

9. 'Strategy & Vision' levels & labels 'can go' motivation *

Why do you think these levels and labels should be removed?

10. Culture & Competencies *

Definition:
The extent to which all people of all departments are competent (due to adequate training and recruitment of HRM) and support the implementation of I4.0 technologies and innovation.

R0 (Unprepared):
The organizational culture is not open to innovation, nor are there in-house competencies related to data handling.

R1 (Ready):
The organizational culture is open to innovation and there are in-house competencies related to data handling and these can be utilized when needed.

M0 (Incomplete):
An inclusive culture is (partly) in place by involving workforce in vision development. People are being recruited with digitization competencies.

M1 (Performed):
People are educated to develop the ability to exploit connected data systems. Production staff is revised to proactively coordinate digital insights and knowledge sharing.

M2 (Managed):
Sense-making sessions are in place with suppliers, users, and other stakeholders. Data analysts and data scientists are recruited to optimize production.

M3 (Defined):
A culture of continuous smart factory innovation is in place covering the complete organization. Specialized roles and responsibilities are geared toward predictable production.

- ◯ Stay
- ◯ Change
- ◯ Can go

1/27/2021

11. 'Culture & Competencies' levels & labels 'change' motivation *

What would you change from these levels and labels? Do you think something is missing or should be excluded from the descriptions? Is it too vague or too precise, or anything else?

12. 'Culture & Competencies' levels & labels 'can go' motivation *

Why do you think these levels and labels should be removed?

1/27/2021

13. Process *

Definition:
The extent to which companies support departments collaboration, machine and system integration with the help of I4.0 technologies. This includes self- optimization, self-configuration, standardization and simplification of processes of production, maintenance, and support processes.

R0 (Unprepared):
Processes are not explicitly defined.

R1 (Ready):
Processes are defined and executed, with the support of analogue tools.

M0 (Incomplete):
Defined processes are completed with the support of digital tools.

M1 (Performed):
Digitized processes and systems are securely integrated across all hierarchical levels (machines & workers - boardroom).

M2 (Managed):
Integrated processes and systems are automated, with limited human intervention.

M3 (Defined):
Automated processes and systems are actively analyzing and reacting to data, enabling continuous process improvements.

- ◯ Stay
- ◯ Change
- ◯ Can go

14. 'Process' levels & labels 'change' motivation *

What would you change from these levels and labels? Do you think something is missing or should be excluded from the descriptions? Is it too vague or too precise, or anything else?

15. 'Process' levels & labels 'can go' motivation *

Why do you think these levels and labels should be removed?

16. Connectivity & Integration *

Definition:
The extent to which an IT/cloud infrastructure is in place to accommodate vertical or horizontal integration across the value chain.

R0 (Unprepared):
There is no IT infrastructure.

R1 (Ready):
The IT infrastructure is developed in separate modules that address different tasks and cannot communicate with each other.

M0 (Incomplete):
The IT infrastructure is not standardized but all the different modules can communicate with each other.

M1 (Performed):
The IT infrastructure is not fully integrated but is based on a number of recognized standards and when new modules have to be developed, this is done accordingly.

M2 (Managed):
The IT infrastructure is based on a single standard and new modules are developed accordingly enabling interoperability.

M3 (Defined):
The IT infrastructure in the whole supply chain is based on standards that allow plug and play inter-organization real-time communication, enabling interoperability and scalability.

- ◯ Stay
- ◯ Change
- ◯ Can go

17. 'Connectivity & Integration' levels & labels 'change' motivation *

What would you change from these levels and labels? Do you think something is missing or should be excluded from the descriptions? Is it too vague or too precise, or anything else?

18. 'Connectivity & Integration' levels & labels 'can go' motivation *

Why do you think these levels and labels should be removed?

19. Products & Services *

Definition:
The extent to which products are individualized and product characteristics are customer specific (smart products), and the extent towards offering data-driven services and customer integration (smart services and servitization).

R0 (Unprepared):
Product development or services are not digitally supported.

R1 (Ready):
Product development or services are partly digitally supported.

M0 (Incomplete):
Products offer digital features and services are continuously digitally supported.

M1 (Performed):
Products offer connectivity features and little differentiation. Data-driven services offer little customer integration.

M2 (Managed):
Products offer responsive features and can be largely customized. Data-driven services offer customer integration.

M3 (Defined):
Products can be completely customized and feature all smart product functionalities, and many products are being servitized. Data-driven services are fully integrated with the customer.

- ○ Stay
- ○ Change
- ○ Can go

20. 'Products & Services' levels & labels 'change' motivation *

What would you change from these levels and labels? Do you think something is missing or should be excluded from the descriptions? Is it too vague or too precise, or anything else?

21. 'Products & Services' levels & labels 'can go' motivation *

Why do you think these levels and labels should be removed?

22. Collaboration *

Definition:
The extent to which formal channels are enabled for employees and collaboration partners to share information and work together, as well as institutional structures and systems that allow collaborative behavior.

R0 (Unprepared):
Communication and information sharing across teams happen on an informal basis.

R1 (Ready):
Formal channels are established for communication and information sharing across teams.

M0 (Incomplete):
Formal channels are established to allow teams to work together on discrete tasks and projects.

M1 (Performed):
Teams are empowered by the organization to make adjustments that will facilitate cooperation on discrete tasks and projects.

M2 (Managed):
Teams are empowered by the organization to share resources on both discrete and longer-term tasks and projects.

M3 (Defined):
Formal channels are established to enable dynamically-forming teams to work on cross-functional projects with shared goals and resources.

- ◯ Stay
- ◯ Change
- ◯ Can go

1/27/2021

23. 'Collaboration' levels & labels 'change' motivation *

What would you change from these levels and labels? Do you think something is missing or should be excluded from the descriptions? Is it too vague or too precise, or anything else?

24. 'Collaboration' levels & labels 'can go' motivation *

Why do you think these levels and labels should be removed?

1/27/2021

25. Technology *

Definition:
The extent to which I4.0 technologies are implemented and used.

R0 (Unprepared):
No presence of assets that generate digital data.

R1 (Ready):
There are assets available that generate data.

M0 (Incomplete):
There are interfaces available for those who need it to access data and visualize it.

M1 (Performed):
There are tools available that make it possible to process data correlating and analyzing it, and to communicate results to the user.

M2 (Managed):
There are assets or tools that can act autonomously according to information received after an analytic process.

M3 (Defined):
The assets deployed across the supply chain can interact together and reconfigure themselves to optimize performance.

- ◯ Stay
- ◯ Change
- ◯ Can go

26. 'Technology' levels & labels 'change' motivation *

What would you change from these levels and labels? Do you think something is missing or should be excluded from the descriptions? Is it too vague or too precise, or anything else?

1/27/2021

27. 'Technology' levels & labels 'can go' motivation *

Why do you think these levels and labels should be removed?

28. Operations *

Definition:
The extent to which manufacturing operations (production, storage, quality test, and maintenance) are formally documented, supported by I4.0 paradigms, and enable continuous improvement and optimization.

R0 (Unprepared):
Procedures for operations are not documented.

R1 (Ready):
The manufacturing operations are well documented and formally managed.

M0 (Incomplete):
The manufacturing operations are defined with documented standards and partly supported by software tools.

M1 (Performed):
The manufacturing operations are fully supported by software tools and executed with possibly repeatable results in normal situations.

M2 (Managed):
The manufacturing operations are well defined across all organizational groups, and their executions are repeatable and monitored with software tool supports.

M3 (Defined):
The manufacturing operations are focused on continuous improvement and optimization.

- ◯ Stay
- ◯ Change
- ◯ Can go

1/27/2021

29. 'Operations' levels & labels 'change' motivation *

What would you change from these levels and labels? Do you think something is missing or should be excluded from the descriptions? Is it too vague or too precise, or anything else?

30. 'Operations' levels & labels 'can go' motivation *

Why do you think these levels and labels should be removed?

1/27/2021

31. Strategy & Vision *

Definition:
The extent to which the strategy and vision currently adopted by companies are aimed towards I4.0, including the acknowledgement of an I4.0 roadmap.

R0 (Unprepared):
There is no awareness regarding the digital transformation.

R1 (Ready):
There is a willingness and interest towards the digital transformation from a managerial level.

M0 (Incomplete):
I4.0 strategy and vision are being developed or have partly been developed.

M1 (Performed):
I4.0 strategy and vision have been formally implemented in at least one functional area.

M2 (Managed):
I4.0 strategy and vision are expanded to include more than one functional area.

M3 (Defined):
I4.0 strategy and vision are refreshed and updated automatically.

- ○ Stay
- ○ Change
- ○ Can go

32. 'Strategy & Vision' levels & labels 'change' motivation *

What would you change from these levels and labels? Do you think something is missing or should be excluded from the descriptions? Is it too vague or too precise, or anything else?

1/27/2021

33. 'Strategy & Vision' levels & labels 'can go' motivation *

Why do you think these levels and labels should be removed?

34. Culture & Competencies *

Definition:
The extent to which all people of all departments are competent (due to adequate training and recruitment of HRM) and support the implementation of I4.0 technologies and innovation.

R0 (Unprepared):
The organizational culture is not open to innovation, nor are there in-house competencies related to data handling.

R1 (Ready):
The organizational culture is open to innovation and there are in-house competencies related to data handling and these can be utilized when needed.

M0 (Incomplete):
An inclusive culture is (partly) in place by involving workforce in vision development. People are being recruited with digitization competencies.

M1 (Performed):
People are educated to develop the ability to exploit connected data systems. Production staff is revised to proactively coordinate digital insights and knowledge sharing.

M2 (Managed):
Sense-making sessions are in place with suppliers, users, and other stakeholders. Data analysts and data scientists are recruited to optimize production.

M3 (Defined):
A culture of continuous smart factory innovation is in place covering the complete organization. Specialized roles and responsibilities are geared toward predictable production.

- ○ Stay
- ○ Change
- ○ Can go

35. 'Culture & Competencies' levels & labels 'change' motivation *

What would you change from these levels and labels? Do you think something is missing or should be excluded from the descriptions? Is it too vague or too precise, or anything else?

36. 'Culture & Competencies' levels & labels 'can go' motivation *

Why do you think these levels and labels should be removed?

37. Process *

Definition:
The extent to which companies support departments collaboration, machine and system integration with the help of I4.0 technologies. This includes self- optimization, self-configuration, standardization and simplification of processes of production, maintenance, and support processes.

R0 (Unprepared):
Processes are not explicitly defined.

R1 (Ready):
Processes are defined and executed, with the support of analogue tools.

M0 (Incomplete):
Defined processes are completed with the support of digital tools.

M1 (Performed):
Digitized processes and systems are securely integrated across all hierarchical levels (machines & workers - boardroom).

M2 (Managed):
Integrated processes and systems are automated, with limited human intervention.

M3 (Defined):
Automated processes and systems are actively analyzing and reacting to data, enabling continuous process improvements.

- ○ Stay
- ○ Change
- ○ Can go

38. 'Process' levels & labels 'change' motivation *

What would you change from these levels and labels? Do you think something is missing or should be excluded from the descriptions? Is it too vague or too precise, or anything else?

1/27/2021

39. 'Process' levels & labels 'can go' motivation *

Why do you think these levels and labels should be removed?

40. Connectivity & Integration *

Definition:
The extent to which an IT/cloud infrastructure is in place to accommodate vertical or horizontal integration across the value chain.

R0 (Unprepared):
There is no IT infrastructure.

R1 (Ready):
The IT infrastructure is developed in separate modules that address different tasks and cannot communicate with each other.

M0 (Incomplete):
The IT infrastructure is not standardized but all the different modules can communicate with each other.

M1 (Performed):
The IT infrastructure is not fully integrated but is based on a number of recognized standards and when new modules have to be developed, this is done accordingly.

M2 (Managed):
The IT infrastructure is based on a single standard and new modules are developed accordingly enabling interoperability.

M3 (Defined):
The IT infrastructure in the whole supply chain is based on standards that allow plug and play inter-organization real-time communication, enabling interoperability and scalability.

- ○ Stay
- ○ Change
- ○ Can go

1/27/2021

41. 'Connectivity & Integration' levels & labels 'change' motivation *

What would you change from these levels and labels? Do you think something is missing or should be excluded from the descriptions? Is it too vague or too precise, or anything else?

42. 'Connectivity & Integration' levels & labels 'can go' motivation *

Why do you think these levels and labels should be removed?

43. Products & Services *

Definition:
The extent to which products are individualized and product characteristics are customer specific (smart products), and the extent towards offering data-driven services and customer integration (smart services and servitization).

R0 (Unprepared):
Product development or services are not digitally supported.

R1 (Ready):
Product development or services are partly digitally supported.

M0 (Incomplete):
Products offer digital features and services are continuously digitally supported.

M1 (Performed):
Products offer connectivity features and little differentiation. Data-driven services offer little customer integration.

M2 (Managed):
Products offer responsive features and can be largely customized. Data-driven services offer customer integration.

M3 (Defined):
Products can be completely customized and feature all smart product functionalities, and many products are being servitized. Data-driven services are fully integrated with the customer.

- Stay
- Change
- Can go

44. 'Products & Services' levels & labels 'change' motivation *

What would you change from these levels and labels? Do you think something is missing or should be excluded from the descriptions? Is it too vague or too precise, or anything else?

45. 'Products & Services' levels & labels 'can go' motivation *

Why do you think these levels and labels should be removed?

46. Collaboration *

Definition:
The extent to which formal channels are enabled for employees and collaboration partners to share information and work together, as well as institutional structures and systems that allow collaborative behavior.

R0 (Unprepared):
Communication and information sharing across teams happen on an informal basis.

R1 (Ready):
Formal channels are established for communication and information sharing across teams.

M0 (Incomplete):
Formal channels are established to allow teams to work together on discrete tasks and projects.

M1 (Performed):
Teams are empowered by the organization to make adjustments that will facilitate cooperation on discrete tasks and projects.

M2 (Managed):
Teams are empowered by the organization to share resources on both discrete and longer-term tasks and projects.

M3 (Defined):
Formal channels are established to enable dynamically-forming teams to work on cross-functional projects with shared goals and resources.

- ◯ Stay
- ◯ Change
- ◯ Can go

47. 'Collaboration' levels & labels 'change' motivation *

What would you change from these levels and labels? Do you think something is missing or should be excluded from the descriptions? Is it too vague or too precise, or anything else?

48. 'Collaboration' levels & labels 'can go' motivation *

Why do you think these levels and labels should be removed?

Round 3: labels & labels (structure)

49. Would you like to see any changes in structure? (optional)

For example: do you agree with the number of levels and overall structure? Or would you propose any other structural changes?

50. Any other remarks or questions?

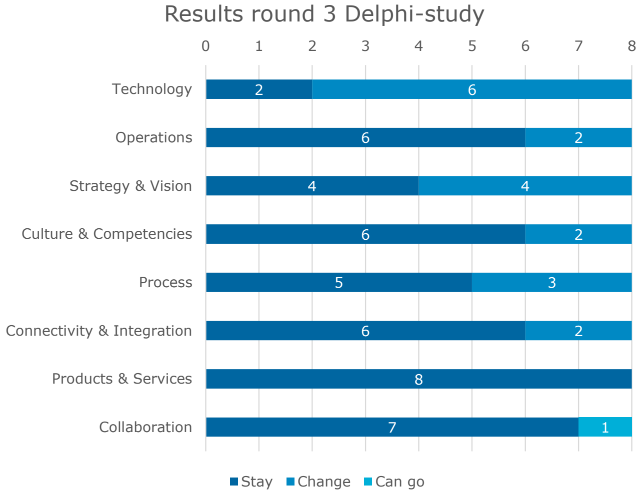
1/27/2021

C.3 Result sheet: round 3

I4RMM: Levels & labels

Results Delphi study round 3

- Number of participants: 8 (last round: 8)
- A large majority of the expert panel needs to agree on a model element in order for it to be included (80%, ≥6 'stay')
- In this round, 5/8 levels & labels were agreed on.
- Most comments about the levels & labels from the 'Technology', 'Strategy & Vision' and 'Process' dimensions.



1 | 16-12-2020 | P.W. (Paul) Kaandorp | © Atos - For internal use

Atos

What did you think? (1/2)

- **Technology**
  - Also consider assets that collect (capture) and transfer data.
  - Add a level between R0-R1 called 'Planned'.
  - M0 is not consistent with M1-M2 (you talk about 'interfaces' instead of 'assets').
  - Maybe add thresholds for R0/R1 e.g. R0 = 0 assets and R1 = ≥ 50 assets.
  - If there are no assets that generate data, maybe it is also interesting to assess how feasible it is for companies to start generating data.
- **Operations**
  - Also include the level of 'deployment' and 'monitoring' of the documentation.
- **Strategy & Vision**
  - The ultimate readiness should be having a clear vision about the adoption of specific I4.0.
  - Add a level between R0-R1 called 'Planned'.
  - IT architecture may visualize the vision and strategy of implementing I4.0.
  - M3 is not very measurable, maybe add a time interval?
- **Culture & Competencies**
  - Include the openness towards collaboration and adoption of external promoted competencies for the readiness check.
  - Change the wording of 'data handling' to digital manufacturing or something similar.

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What did you think? (2/2)

- **Process**
  - What does the support of analogue tools (R1) contribute to the level?
  - Add a level between R0-R1 called 'Planned'.
  - Might include the content of the documented flows, are they required, simple, and standardized?
- **Connectivity & Integration**
  - Include the flexibility of the IT infrastructure in extending towards new I4.0 technology requirements.
  - Every organization has an IT infrastructure nowadays (alter R0).
- **Products & Services**
- **Collaboration**
  - Not sure if this should be part of the I4RMM. Perhaps if it relates to the collaboration between shop-floor and supporting departments?
- **Structure and additional thoughts**
  - The number of topics may reach the limit to confront people within an assessment.
  - Maybe add another readiness level between R0 and R1.
  - There is a certain overlap between the 'Ready' (R1) level and the first maturity level (M0).

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Based on your feedback... (1/2)

- **Technology**
  - Refined the levels to include data collection/capturing capabilities (R0-R2).
  - Added a level 'Planned' (R1).
  - M0-M2: improved description consistency.
- **Operations**
  - Added a level 'Planned' (R1).
  - Refined the levels to include deployment and monitorization of the documentation.
- **Strategy & Vision**
  - Added a level 'Planned' (R1).
  - Re-arranged the descriptions so that 'Ready' (R2) includes a clear I4.0 strategy and vision.
  - M3: quantified the automatic refresh/update by adding a monthly interval.
- **Culture & Competencies**
  - Added a level 'Planned (R1).
  - R0-R2: refined the definitions to also include openness to external competencies to approach I4.0.
  - Refined the levels R0-R2 by changing 'data handling' into 'digital manufacturing'.
- **Process**
  - Added a level 'Planned' (R1).
  - R2: refined the level and omitted the 'support of analogue tools', it does not contribute to the readiness of I4.0 in the process area.
  - M0: included the 'standardization' feature of processes in the definition.

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Based on your feedback… (2/2)

- **Connectivity & Integration**
  - Added a level 'Planned' (R1).
  - R0-R2: refined the definitions to include the level of flexibility in extending the IT infrastructure due to new I4.0 technology requirements, and to include the level of proper documentation and architecting.
- **Products & Services**
  - Added a level 'Planned' (R1).
- **Collaboration**
  - Added a level 'Planned' (R1).
- **Structure and additional thoughts**
  - As stated, I added an additional readiness level called 'Planned' (R1) which entails an intermediate step between 'Unprepared' (R0) and 'Ready' (R2).
  - Following up from the previous round: I decided to keep the 'Collaboration' dimension in the I4RMM due to a majority vote for 'Stay' in this round.
  - There were a few comments this round about making the different levels more quantifiable i.e. more measurable. I think this is an excellent idea. However, I find it difficult to pinpoint exact values due to my lack of experience in the field. If you can think of any specific values next round, please do not hesitate to share them with me.

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Appendix D

Delphi round 4: levels & labels

This appendix contains detailed information about the final Delphi round which was confirmative in nature. The goal of this round was to establish the final levels and labels of the model and their unique descriptions. Therefore, this round aimed to reach a consensus among the Delphi panel members about these levels and labels, to finalize the I4RMM.

This appendix contains the following:

D.1 I4RMM: round 4
D.2 Microsoft Forms: round 4
D.3 Result sheet: round 4

First, Appendix D.1 presents the model for this round, after improvements based on the previous round (Appendix C.3). Second, Appendix D.2 presents the Microsoft Forms which was used to gather information from the Delphi panel. Finally, Appendix D.3 presents the results of this survey, including the model alterations that were made based on these results.

D.1 I4RMM round: 4

Industry 4.0 Readiness Maturity Model - I4RMM

Dimension	Definition	Readiness			Maturity			
		R0 Unprepared	R1 Planned	R2 Ready	M0 Incomplete	M1 Performed	M2 Managed	M3 Defined
Technology	The extent to which I4.0 technologies are implemented and used.	No presence of assets that enable data collection, transfer, and generation.	Planned to buy or upgrade to new technology that enables data collection, transfer and generation.	There are assets available that enable data collection, transfer, and generation.	There are assets available and used for data access and data visualization.	There are assets available and used for data analysis, and communicating the results to the user.	There are assets available that are acting autonomously according to information received after an analytic process.	The assets deployed across the supply chain can interact together and reconfigure themselves to optimize performance.
Operations	The extent to which manufacturing operations (production, storage, quality, test, and maintenance) are formally documented, supported by I4.0 paradigms, and enable continuous improvement and optimization.	No manufacturing operations have been documented	The manufacturing operations are partly documented, and there are plans to finalize the documentation.	All manufacturing operations are well documented, deployed and monitored.	The manufacturing operations are defined, deployed and monitored with documented standards and partly supported by software tools.	The manufacturing operations are defined, deployed and monitored and fully supported by software tools and executed with possibly repeatable results in normal situations.	The manufacturing operations are defined, deployed and monitored across all organizational groups, and their executions are repeatable and monitored with software tool supports.	The manufacturing operations are focused on continuous improvement and optimization.
Strategy & Vision	The extent to which the strategy and vision currently adopted by companies are aimed towards I4.0, including the acknowledgement of an I4.0 roadmap.	There is no awareness regarding the digital transformation, and I4.0 strategy and vision are lacking.	There is a willingness and interest towards the digital transformation. I4.0 strategy and vision are being developed but there is great uncertainty on how to approach I4.0.	There is a clear I4.0 strategy and vision in place.	I4.0 strategy and vision have been formally implemented in at least one functional area.	I4.0 strategy and vision are expanded to include more than one functional area.	I4.0 strategy and vision are expanded to include all functional areas.	I4.0 strategy and vision are refreshed and updated automatically if necessary (monthly).
Culture & Competencies	The extent to which all people of all departments are competent (due to adequate training and recruitment of HRM) and support the implementation of I4.0 technologies and innovation.	The organizational culture is not open to innovation, nor are there in-house or external competencies related to digital manufacturing.	The organizational culture is open to innovation, but there are no in-house or external competencies available to approach digital manufacturing.	The organizational culture is open to innovation and there are in-house or external competencies available related to digital manufacturing, and these can be utilized when needed.	An inclusive culture is (partly) in place by involving workforce in vision development. People are being recruited with digitization competencies.	People are educated to develop the ability to exploit connected data systems. Production staff is revised to proactively coordinate digital insights and knowledge sharing.	Sense-making sessions are in place with suppliers, users, and other stakeholders. Data analysts and data scientists are recruited to optimize production.	A culture of continuous smart factory innovation is in place covering the complete organization. Specialized roles and responsibilities are geared toward predictable production.
Process	The extent to which companies support departments collaboration, machine and system integration with the help of I4.0 technologies. This includes self- optimization, self-configuration, standardization and simplification of processes of production, maintenance, and support processes.	No processes have been explicitly defined.	The processes are partly defined, and there are plans in place to define all processes.	All processes are defined and are being executed.	Defined processes are standardized, and completed with the support of digital tools.	Digitized processes and systems are securely integrated across all hierarchical levels (machines & workers - boardroom).	Integrated processes and systems are automated, with limited human intervention.	Automated processes and systems are actively analyzing and reacting to data, enabling continuous process improvements.
Connectivity & Integration	The extent to which an IT/ cloud infrastructure is in place to accommodate vertical or horizontal integration across the value chain.	The IT infrastructure is poorly documented and designed, and provides no flexibility in extending it.	The IT infrastructure is partly documented and designed, and there are plans in place to increase its flexibility to extend it in the future.	The IT infrastructure is well documented and designed, and provides enough flexibility to extend towards I4.0 technology requirements. In addition, the IT department resources are aligned to support future extensions.	The IT infrastructure is not standardized but all the different modules can communicate with each other.	The IT infrastructure is not fully integrated but is based on a number of recognized standards and when new modules have to be developed, this is done accordingly.	The IT infrastructure is based on a single standard and new modules are developed accordingly enabling interoperability.	The IT infrastructure in the whole supply chain is based on standards that allow plug and play inter-organization real-time communication, enabling interoperability and scalability.
Products & Services	The extent to which products are individualized and product characteristics are customer specific (smart products), and the extent towards offering data-driven services and customer integration (smart services and servitization).	Product development or services are not digitally supported.	There are plans to explore digital support of product development and services, but additional help is required.	Product development or services are partly digitally supported.	Products offer digital features and services are continuously digitally supported.	Products offer connectivity features and little differentiation. Data-driven services offer little customer integration.	Products offer responsive features and can be largely customized. Data-driven services offer customer integration.	Products can be completely customized and feature all smart product functionalities, and many products are being servitized. Data-driven services are fully integrated with the customer.
Collaboration	The extent to which formal channels are enabled for employees and collaboration partners to share information and work together, as well as institutional structures and systems that allow collaborative behavior.	Communication and information sharing across teams happen on an informal basis.	There are plans to formalize the current channels used for communication and information sharing, but additional help is required.	Formal channels are established for communication and information sharing across teams.	Formal channels are established to allow teams to work together on discrete tasks and projects.	Teams are empowered by the organization to make adjustments that will facilitate cooperation on discrete tasks and projects.	Teams are empowered by the organization to share resources on both discrete and longer-term tasks and projects.	Formal channels are established to enable dynamically-forming teams to work on cross-functional projects with shared goals and resources.

D.2 Microsoft Forms: round 4

Industry 4.0 Readiness Maturity Model (I4RMM) - Round 4

Thank you for participating in this Delphi study. Your input will be highly valuable in developing the new integrated Industry 4.0 Readiness Maturity assessment Model (I4RMM). This new conceptual model will yield better understanding in assessing Industry 4.0 readiness and maturity in businesses. These insights can guide businesses in their I4.0 transformation.

The content of this form will be treated with high confidentiality. For any questions about the procedure, please contact me:

P.W. (Paul) Kaandorp
paul.kaandorp@atos.net (mailto:paul.kaandorp@atos.net)

* Required

* This form will record your name, please fill your name.

Round 4: levels & labels (re-evaluation)

In the previous round, I asked you to evaluate the levels & labels of the I4RMM. With your help and input, I managed to evolve the model based on your feedback. Changes were made on a:

- Structural level (the addition of an intermediate readiness level)
- Definitional level (refinements of level descriptions)

A complete overview of all the changes and an overview of the results of the previous round was sent to you by mail or can be found in the Circuit group (Delphi panel I4RMM).

In this round, the objective is to evaluate this new model. The survey procedure is the same as the previous rounds, the evaluation take place on your judgement whether a level and label should stay, change, or can go (be removed). If you choose for the latter two, please provide a motivation.

Good luck and thank you again for participating!

<< The model below may not be readable, a scalable .pdf was sent to you by mail and can be found in the Circuit group. However, it is NOT necessary to have the complete model with you when filling in the survey. All the levels and their descriptions are formulated in the questions. >>

1. Technology *

Definition:
The extent to which I4.0 technologies are implemented and used.

R0 (Unprepared):
No presence of assets that enable data collection, transfer, and generation.

R1 (Planned):
Planned to buy or upgrade to new technology that enables data collection, transfer and generation.

R2 (Ready):
There are assets available that enable data collection, transfer, and generation.

M0 (Incomplete):
There are assets available and used for data access and data visualization.

M1 (Performed):
There are assets available and used for data analysis, and communicating the results to the user.

M2 (Managed):
There are assets available that are acting autonomously according to information received after an analytic process.

M3 (Defined):
The assets deployed across the supply chain can interact together and reconfigure themselves to optimize performance.

- ◯ Stay
- ◯ Change
- ◯ Can go

2. 'Technology' levels & labels 'change' motivation *

What would you change from these levels and labels? Do you think something is missing or should be excluded from the descriptions? Is it too vague or too precise, or anything else?

3. 'Technology' levels & labels 'can go' motivation *

Why do you think these levels and labels should be removed?

1/27/2021

4. Operations *

Definition:
The extent to which manufacturing operations (production, storage, quality test, and maintenance) are formally documented, supported by I4.0 paradigms, and enable continuous improvement and optimization.

R0 (Unprepared):
No manufacturing operations have been documented

R1 (Planned):
The manufacturing operations are partly documented, and there are plans to finalize the documentation.

R2 (Ready):
All manufacturing operations are well documented, deployed and monitored.

M0 (Incomplete):
The manufacturing operations are defined, deployed and monitored with documented standards and partly supported by software tools.

M1 (Performed):
The manufacturing operations are defined, deployed and monitored and fully supported by software tools and executed with possibly repeatable results in normal situations.

M2 (Managed):
The manufacturing operations are defined, deployed and monitored across all organizational groups, and their executions are repeatable and monitored with software tool supports.

M3 (Defined):
The manufacturing operations are focused on continuous improvement and optimization.

- ◯ Stay
- ◯ Change
- ◯ Can go

5. 'Operations' levels & labels 'change' motivation *

What would you change from these levels and labels? Do you think something is missing or should be excluded from the descriptions? Is it too vague or too precise, or anything else?

6. 'Operations' levels & labels 'can go' motivation *

Why do you think these levels and labels should be removed?

1/27/2021

1/27/2021

7. Strategy & Vision *

Definition:
The extent to which the strategy and vision currently adopted by companies are aimed towards I4.0, including the acknowledgement of an I4.0 roadmap.

R0 (Unprepared):
There is no awareness regarding the digital transformation, and I4.0 strategy and vision are lacking.

R1 (Planned):
There is a willingness and interest towards the digital transformation. I4.0 strategy and vision are being developed but there is great uncertainty on how to approach I4.0.

R2 (Ready):
There is a clear I4.0 strategy and vision in place.

M0 (Incomplete):
I4.0 strategy and vision have been formally implemented in at least one functional area.

M1 (Performed):
I4.0 strategy and vision are expanded to include more than one functional area.

M2 (Managed):
I4.0 strategy and vision are expanded to include all functional areas.

M3 (Defined):
I4.0 strategy and vision are refreshed and updated automatically if necessary (monthly).

- ◯ Stay
- ◯ Change
- ◯ Can go

8. 'Strategy & Vision' levels & labels 'change' motivation *

What would you change from these levels and labels? Do you think something is missing or should be excluded from the descriptions? Is it too vague or too precise, or anything else?

9. 'Strategy & Vision' levels & labels 'can go' motivation *

Why do you think these levels and labels should be removed?

10. Culture & Competencies *

Definition:
The extent to which all people of all departments are competent (due to adequate training and recruitment of HRM) and support the implementation of I4.0 technologies and innovation.

R0 (Unprepared):
The organizational culture is not open to innovation, nor are there in-house or external competencies related to digital manufacturing.

R1 (Planned):
The organizational culture is open to innovation, but there are no in-house or external competencies available to approach digital manufacturing.

R2 (Ready):
The organizational culture is open to innovation and there are in-house or external competencies available related to digital manufacturing, and these can be utilized when needed.

M0 (Incomplete):
An inclusive culture is (partly) in place by involving workforce in vision development. People are being recruited with digitization competencies.

M1 (Performed):
People are educated to develop the ability to exploit connected data systems. Production staff is revised to proactively coordinate digital insights and knowledge sharing.

M2 (Managed):
Sense-making sessions are in place with suppliers, users, and other stakeholders. Data analysts and data scientists are recruited to optimize production.

M3 (Defined):
A culture of continuous smart factory innovation is in place covering the complete organization. Specialized roles and responsibilities are geared toward predictable production.

- ◯ Stay
- ◯ Change
- ◯ Can go

11. 'Culture & Competencies' levels & labels 'change' motivation *

What would you change from these levels and labels? Do you think something is missing or should be excluded from the descriptions? Is it too vague or too precise, or anything else?

12. 'Culture & Competencies' levels & labels 'can go' motivation *

Why do you think these levels and labels should be removed?

1/27/2021

1/27/2021

13. Process *

Definition:
The extent to which companies support departments collaboration, machine and system integration with the help of I4.0 technologies. This includes self- optimization, self-configuration, standardization and simplification of processes of production, maintenance, and support processes.

R0 (Unprepared):
No processes have been explicitly defined.

R1 (Planned):
The processes are partly defined, and there are plans in place to define all processes.

R2 (Ready):
All processes are defined and are being executed.

M0 (Incomplete):
Defined processes are standardized, and completed with the support of digital tools.

M1 (Performed):
Digitized processes and systems are securely integrated across all hierarchical levels (machines & workers - boardroom).

M2 (Managed):
Integrated processes and systems are automated, with limited human intervention.

M3 (Defined):
Automated processes and systems are actively analyzing and reacting to data, enabling continuous process improvements.

- ○ Stay
- ○ Change
- ○ Can go

14. 'Process' levels & labels 'change' motivation *

What would you change from these levels and labels? Do you think something is missing or should be excluded from the descriptions? Is it too vague or too precise, or anything else?

15. 'Process' levels & labels 'can go' motivation *

Why do you think these levels and labels should be removed?

16. Connectivity & Integration *

Definition:
The extent to which an IT/cloud infrastructure is in place to accommodate vertical or horizontal integration across the value chain.

R0 (Unprepared):
The IT infrastructure is poorly documented and designed, and provides no flexibility in extending it.

R1 (Planned):
The IT infrastructure is partly documented and designed, and there are plans in place to increase its flexibility to extend it in the future.

R2 (Ready):
The IT infrastructure is well documented and designed, and provides enough flexibility to extend towards I4.0 technology requirements. In addition, the IT department resources are aligned to support future extensions.

M0 (Incomplete):
The IT infrastructure is not standardized but all the different modules can communicate with each other.

M1 (Performed):
The IT infrastructure is not fully integrated but is based on a number of recognized standards and when new modules have to be developed, this is done accordingly.

M2 (Managed):
The IT infrastructure is based on a single standard and new modules are developed accordingly enabling interoperability.

M3 (Defined):
The IT infrastructure in the whole supply chain is based on standards that allow plug and play inter-organization real-time communication, enabling interoperability and scalability.

○ Stay

○ Change

○ Can go

1/27/2021

17. 'Connectivity & Integration' levels & labels 'change' motivation *

What would you change from these levels and labels? Do you think something is missing or should be excluded from the descriptions? Is it too vague or too precise, or anything else?

18. 'Connectivity & Integration' levels & labels 'can go' motivation *

Why do you think these levels and labels should be removed?

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19. Products & Services *

Definition:
The extent to which products are individualized and product characteristics are customer specific (smart products), and the extent towards offering data-driven services and customer integration (smart services and servitization).

R0 (Unprepared):
Product development or services are not digitally supported.

R1 (Planned):
There are plans to explore digital support of product development and services, but additional help is required.

R2 (Ready):
Product development or services are partly digitally supported.

M0 (Incomplete):
Products offer digital features and services are continuously digitally supported.

M1 (Performed):
Products offer connectivity features and little differentiation. Data-driven services offer little customer integration.

M2 (Managed):
Products offer responsive features and can be largely customized. Data-driven services offer customer integration.

M3 (Defined):
Products can be completely customized and feature all smart product functionalities, and many products are being servitized. Data-driven services are fully integrated with the customer.

◯ Stay

◯ Change

◯ Can go

20. 'Products & Services' levels & labels 'change' motivation *

What would you change from these levels and labels? Do you think something is missing or should be excluded from the descriptions? Is it too vague or too precise, or anything else?

21. 'Products & Services' levels & labels 'can go' motivation *

Why do you think these levels and labels should be removed?

22. Collaboration *

Definition:
The extent to which formal channels are enabled for employees and collaboration partners to share information and work together, as well as institutional structures and systems that allow collaborative behavior.

R0 (Unprepared):
Communication and information sharing across teams happen on an informal basis.

R1 (Planned):
There are plans to formalize the current channels used for communication and information sharing, but additional help is required.

R2 (Ready):
Formal channels are established for communication and information sharing across teams.

M0 (Incomplete):
Formal channels are established to allow teams to work together on discrete tasks and projects.

M1 (Performed):
Teams are empowered by the organization to make adjustments that will facilitate cooperation on discrete tasks and projects.

M2 (Managed):
Teams are empowered by the organization to share resources on both discrete and longer-term tasks and projects.

M3 (Defined):
Formal channels are established to enable dynamically-forming teams to work on cross-functional projects with shared goals and resources.

- ◯ Stay
- ◯ Change
- ◯ Can go

23. 'Collaboration' levels & labels 'change' motivation *

What would you change from these levels and labels? Do you think something is missing or should be excluded from the descriptions? Is it too vague or too precise, or anything else?

24. 'Collaboration' levels & labels 'can go' motivation *

Why do you think these levels and labels should be removed?

Round 4: labels & labels (structure)

25. Would you like to see any changes in structure? (optional)

For example: do you agree with the number of levels and overall structure? Or would you propose any other structural changes?

26. Any other remarks or questions? (optional)

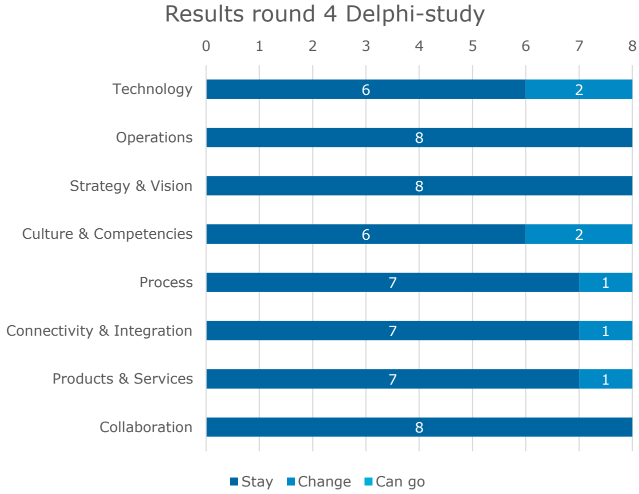
1/27/2021

D.3 Result sheet: round 4

I4RMM: Levels & labels

Results Delphi study round 4

- Number of participants: 8 (last round: 8)
- A large majority of the expert panel needs to agree on a model element in order for it to be included (80%, ≥6 'stay')
- In this round, all levels & labels were agreed on.
- Most comments about the levels & labels from the 'Technology' and 'Culture & Competencies' dimensions.
- This round finalizes the levels & labels of the I4RMM.



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What did you think?

- **Technology**
  - R0: add to the sentence: "without retrofitting".
  - R1: upgrade indicates that assets are already available, which would position them in R2.
- **Operations**
- **Strategy & Vision**
- **Culture & Competencies**
  - M1: elucidate 'revised' production staff.
  - M2: 'sense making' sessions are vague and should be explained, perhaps you should also reflect on some basic KPI's in this level.
- **Process**
  - In addition of processes being defined, the level to which these are simplified and structured should also be addressed.
- **Connectivity & Integration**
  - M2: a 'single' standard is not always the case, perhaps a 'commonly agreed set of standards' is a better alternative.
- **Products & Services**
  - Definition: hedge customer specific product characteristics from 'are' to 'can be'.
- **Collaboration**
- **Structure and additional thoughts**
  - For the maturity levels, maybe add possible improvement opportunities to the different levels.

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Based on your feedback...

- **Technology**
  - R1: removed 'upgrade' to avoid conflicts with R2.
- **Operations**
- **Strategy & Vision**
- **Culture & Competencies**
  - M1: removed 'revised' to make it more concise.
  - M2: replaced 'sense-making' sessions with 'meetings what improve shared group understanding of production processes'.
- **Process**
  - R2: added the degree of 'simplification' and 'standardization' of processes.
  - M0: moved the degree of 'standardization' of processes to R2.
- **Connectivity & Integration**
  - M2: replaced a 'single standard' with a 'commonly agreed set of standards'.
- **Products & Services**
  - Definition: hedged customer specific product characteristics from 'are' to 'can be'.
- **Collaboration**
- **Structure and additional thoughts**
  - I think the addition of improvement opportunities for each level is interesting. However, I find it difficult to include it for each level. Maybe, this could be possible by coupling KPIs to the different levels. Therefore, giving a better overview of potential improvement opportunities based on these KPIs. I will do further research on this and get back to this next round.

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Appendix E

I4RMM

This appendix contains the final I4RMM and is depicted on the next page in full scale.

Industry 4.0 Readiness Maturity Model - I4RMM

Dimension	Definition	Readiness			Maturity			
		R0 Unprepared	R1 Planned	R2 Ready	M0 Incomplete	M1 Performed	M2 Managed	M3 Defined
Technology	The extent to which I4.0 technologies are implemented and used.	No presence of assets that enable data collection, transfer, and generation.	Planned to buy new technology that enables data collection, transfer and generation.	There are assets available that enable data collection, transfer, and generation.	There are assets available and used for data access and data visualization.	There are assets available and used for data analysis, and communicating the results to the user.	There are assets available that are acting autonomously according to information received after an analytic process.	The assets deployed across the supply chain can interact together and reconfigure themselves to optimize performance.
Operations	The extent to which manufacturing operations (production, storage, quality, test, and maintenance) are formally documented, supported by I4.0 paradigms, and enable continuous improvement and optimization.	No manufacturing operations have been documented.	The manufacturing operations are partly documented, and there are plans to finalize the documentation.	All manufacturing operations are well documented, deployed and monitored.	The manufacturing operations are defined, deployed and monitored with documented standards and partly supported by software tools.	The manufacturing operations are defined, deployed and monitored and fully supported by software tools and executed with possibly repeatable results in normal situations.	The manufacturing operations are defined, deployed and monitored across all organizational groups, and their executions are repeatable and monitored with software tool supports.	The manufacturing operations are focused on continuous improvement and optimization.
Strategy & Vision	The extent to which the strategy and vision currently adopted by companies are aimed towards I4.0, including the acknowledgement of an I4.0 roadmap.	There is no awareness regarding the digital transformation, and I4.0 strategy and vision are lacking.	There is a willingness and interest towards the digital transformation. I4.0 strategy and vision are being developed but there is great uncertainty on how to approach I4.0.	There is a clear I4.0 strategy and vision in place.	I4.0 strategy and vision have been formally implemented in at least one functional area.	I4.0 strategy and vision are expanded to include more than one functional area.	I4.0 strategy and vision are expanded to include all functional areas.	I4.0 strategy and vision are refreshed and updated automatically if necessary (monthly).
Culture & Competencies	The extent to which all people of all departments are competent (due to adequate training and recruitment of HRM) and support the implementation of I4.0 technologies and innovation.	The organizational culture is not open to innovation, nor are there in-house or external competences related to digital manufacturing.	The organizational culture is open to innovation, but there are no in-house or external competences available to approach digital manufacturing.	The organizational culture is open to innovation and there are in-house or external competences available related to digital manufacturing, and these can be utilized when needed.	An inclusive culture is (partly) in place by involving workforce in vision development. People are being recruited with digitization competencies.	People are educated to develop the ability to exploit connected data systems. Production staff proactively coordinates digital insights and knowledge sharing.	Suppliers, users, and other stakeholders meet up to improve shared group understanding of production processes. Data analysts and data scientists are recruited to optimize production.	A culture of continuous smart factory innovation is in place covering the complete organization. Specialized roles and responsibilities are geared toward predictable production.
Process	The extent to which companies support departments collaboration, machine and system integration with the help of I4.0 technologies. This includes self- optimization, self-configuration, standardization and simplification of processes of production, maintenance, and support processes.	No processes have been explicitly defined.	The processes are partly defined, and there are plans in place to define all processes.	All processes are defined, simplified, standardized, and are being executed.	Defined processes are completed with the support of digital tools.	Digitized processes and systems are securely integrated across all hierarchical levels (machines & workers - boardroom).	Integrated processes and systems are automated, with limited human intervention.	Automated processes and systems are actively analyzing and reacting to data, enabling continuous process improvements.
Connectivity & Integration	The extent to which an IT/ cloud infrastructure is in place to accommodate vertical or horizontal integration across the value chain.	The IT infrastructure is poorly documented and designed, and provides no flexibility in extending it.	The IT infrastructure is partly documented and designed, and there are plans in place to increase its flexibility to extend it in the future.	The IT infrastructure is well documented and designed, and provides enough flexibility to extend towards I4.0 technology requirements. In addition, the IT department resources are aligned to support future extensions.	The IT infrastructure is not standardized but all the different modules can communicate with each other.	The IT infrastructure is not fully integrated but is based on a number of recognized standards and when new modules have to be developed, this is done accordingly.	The IT infrastructure is based on a commonly agreed set of standards and new modules are developed accordingly, enabling interoperability.	The IT infrastructure in the whole supply chain is based on standards that allow plug and play inter-organization real-time communication, enabling interoperability and scalability.
Products & Services	The extent to which products are individualized and product characteristics can be customer specific (smart products), and the extent towards offering data-driven services and customer integration (smart services and servitization).	Product development or services are not digitally supported.	There are plans to explore digital support of product development and services, but additional help is required.	Product development or services are partly digitally supported.	Products offer digital features and services are continuously digitally supported.	Products offer connectivity features and little differentiation. Data-driven services offer little customer integration.	Products offer responsive features and can be largely customized. Data-driven services offer customer integration.	Products can be completely customized and feature all smart product functionalities, and many products are being servitized. Data-driven services are fully integrated with the customer.
Collaboration	The extent to which formal channels are enabled for employees and collaboration partners to share information and work together, as well as institutional structures and systems that allow collaborative behavior.	Communication and information sharing across teams happen on an informal basis.	There are plans to formalize the current channels used for communication and information sharing, but additional help is required.	Formal channels are established for communication and information sharing across teams.	Formal channels are established to allow teams to work together on discrete tasks and projects.	Teams are empowered by the organization to make adjustments that will facilitate cooperation on discrete tasks and projects.	Teams are empowered by the organization to share resources on both discrete and longer-term tasks and projects.	Formal channels are established to enable dynamically-forming teams to work on cross-functional projects with shared goals and resources.

Appendix F

Evaluation setup

F.1 Case study protocol

The case study protocol aims to keep the researcher targeted on the topic of the case study. In addition, the protocol increases the reliability of the case study and is intended to guide the researcher in consistently carrying out the data collection (Yin, 2017). The protocol consists of the following sections:

A Overview of the case study
B Data collection procedures
C Protocol questions
D Tentative outline for the case study report

A. Overview of the case study

Following the DSR, the mission of the case study is to apply and evaluate the created artifact i.e. the I4RMM, in a real-life business environment. The goal of the case study is to test the model on its completeness, validity, and usability. These constructs will be tested on a high and low level view. The high level view comprises of the complete model, including its structure, the readiness levels, and the maturity levels. The low level view will focus on the individual dimensions, their definitions, and their unique readiness and maturity level descriptions.

The case organization and the participants will be selected based on their industry and experience respectively. During the development of the model, it was hypothesized that different industries would undergo distinct challenges and requirements of I4.0. Therefore, the case study aims to provide new evaluation insights by selecting a case organization with a unique industry (compared to the already conducted case studies). The participants of the case study will be Atos consultants with at least one year experience at this case organization, who can adequately use the model to assess the as-is state of the organization.

B. Data collection procedures

Data will be collected via two procedures. First, data will be gathered by conducting a focus group with 2-3 participants of the case organization. This focus group will be planned as the assessment session in Microsoft Teams with a duration of 1.0-1.5 hours. In this session, the participants will try to use the I4RMM for their organization. During this assessment, the researcher will take an observatory role (Yin, 2017) and take notes of the assessment proceedings. Before the start of this session, the researcher will ask permission to record the meeting. This recording will only be used to aid the researcher in extracting all the feedback for the evaluation. After all comments are successfully extracted, the recording will be deleted. Second, quantitative data will be collected after the assessment session by conducting the developed TAM survey (Appendix F.3). This survey evaluates the I4RMM on the constructs of perceived usefulness, perceived ease-of-use, and intention-to-use. The survey will be sent to the participants after the assessment session by mail, and can be filled in via Microsoft Forms.

C. Protocol questions

As previously mentioned, the I4RMM will be evaluated on the constructs of completeness, validity, and usability. These constructs will be tested on a high and low level view of the I4RMM. The high level view evaluates the complete model by posing the following case study questions during the assessment session:

1. Completeness
   (a) Are all organizational dimensions covered in the I4RMM to adequately assess I4.0 readiness and maturity, or are there any dimensions missing?
2. Validity
   (a) Are the concepts of I4.0 readiness and maturity valid?
3. Usability
   (a) Is the I4RMM comprehensible? Is it clear how to use the model?
   (b) Is the distinction between I4.0 readiness and maturity comprehensible?

The low level view of the I4RMM evaluates the individual dimensions of the model by posing the following case study questions during the assessment session:

1. Completeness
   (a) Is the definition of the dimension complete or are there important aspects missing?
   (b) Do the readiness levels provide a complete spectrum of I4.0 readiness for the manufacturing environment, or are there any levels missing?
   (c) Do the maturity levels provide a complete spectrum of I4.0 maturity for the manufacturing environment, or are there any levels missing?
2. Validity
   (a) Is the definition of the dimension valid?
   (b) Are the descriptions of the readiness levels valid?
   (c) Are the descriptions of the maturity levels valid?
3. Usability
   (a) Is the dimension and its definition comprehensible?
   (b) Are the descriptions of the readiness levels comprehensible?
   (c) Are the descriptions of the maturity levels comprehensible?

D. Tentative outline for the case study report

After 2-3 days of the assessment session, a small report will be generated by the researcher and shared with the case study participants by mail. This report will contain:

- Description of the I4RMM used in the case study.
- Summary of the results/feedback/comments as observed by the researcher during the case study.
- Visualization of the assessment outcome of the case organization.

The researcher will ask the participants to read the report, and encourage them to share additional thoughts or comments if they would arise.

F.2 Microsoft Forms: I4RMM

Industry 4.0 Readiness Maturity Model (I4RMM)

Welcome to the Industry 4.0 Readiness Maturity Model (I4RMM). This model is the final artifact part of a master thesis graduation project from the University of Technology Eindhoven.

The I4RMM was developed to explore the possibilities of integrating I4.0 readiness and maturity assessment models. These readiness and maturity models help organizations to prepare for the challenges and requirements of I4.0, and guide them in reaching higher adoption levels by providing decision-making support during their I4.0 proceedings. Integrating these models provided a comprehensive assessment tool that can be utilized before and during the digital transformation: the I4RMM.

This survey is part of the evaluation study of this new model.

* Required

* This form will record your name, please fill your name.

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Model description

The model assesses 8 dimensions which are deemed to be important to measure I4.0 readiness and maturity. These concepts are defined as:

- I4.0 readiness: the level of preparedness of the conditions, attitudes, and resources, at all levels of an organization, before engaging in I4.0 proceedings.
- I4.0 maturity: the level of maturity of the conditions, attitudes, and resources at all levels of an organization while engaging in I4.0.

For each organizational dimension, the model assesses its I4.0 readiness or I4.0 maturity. These organizational dimensions (total: 8) range from collaboration, culture to process management and technology. These dimensions are assigned to either an I4.0 readiness level or an I4.0 maturity level.

For I4.0 readiness, three levels are used to indicate a progression in readiness:

- R0: Unprepared (the organizational dimension is not prepared i.e. does not have the sufficient conditions, attitudes or resources to successfully engage in its digital transformation).
- R1: Planned (the organizational dimension is not completely prepared but has activities planned to improve their readiness).
- R2: Ready (the organizational dimension is fully ready to start its digital transformation).

For I4.0 maturity, four levels are used to indicate a progression in maturity:

- M0: Incomplete (incomplete approach to meeting the intent of the dimension or minimal effort in I4.0 paradigms).
- M1: Performed (complete set of practices to meet the full intent of the dimension in at least one functional area).
- M2: Managed (complete set of practices that address the full intent of the dimension in all functional areas).
- M3: Defined: (focuses on continuous improvement and optimization).

For the remainder of this survey, you will be asked to assign the adequate levels to each organizational dimension for your organization. Good luck!

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1

Technology *

The extent to which I4.0 technologies are implemented and used.

Readiness			Maturity			
R0 Unprepared	R1 Planned	R2 Ready	M0 Incomplete	M1 Performed	M2 Managed	M3 Defined
No presence of assets that enable data collection, transfer, and generation.	Planned to buy new technology that enables data collection, transfer and generation	There are assets available that enable data collection, transfer, and generation.	There are assets available and used for data access and data visualization.	There are assets available and used for data analysis, and communicating the results to the user.	There are assets available that are acting autonomously according to information received after an analytic process.	The assets deployed across the supply chain can interact together and reconfigure themselves to optimize performance.

- ◯ R0: No presence of assets that enable data collection, transfer, and generation.
- ◯ R1: Planned to buy new technology that enables data collection, transfer and generation.
- ◯ R2: There are assets available that enable data collection, transfer, and generation.
- ◯ M0: There are assets available and used for data access and data visualization.
- ◯ M1: There are assets available and used for data analysis, and communicating the results to the user.
- ◯ M2: There are assets available that are acting autonomously according to information received after an analytic process.
- ◯ M3: The assets deployed across the supply chain can interact together and reconfigure themselves to optimize performance.

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2

Operations *

The extent to which manufacturing operations (production, storage, quality test, and maintenance) are formally documented, supported by I4.0 paradigms, and enable continuous improvement and optimization.

Readiness			Maturity			
R0 Unprepared	R1 Planned	R2 Ready	M0 Incomplete	M1 Performed	M2 Managed	M3 Defined
No manufacturing operations have been documented	The manufacturing operations are partly documented, and there are plans to finalize the documentation.	All manufacturing operations are well documented, deployed and monitored.	The manufacturing operations are defined, deployed and monitored with documented standards and partly supported by software tools.	The manufacturing operations are defined, deployed and monitored and fully supported by software tools and executed with possibly repeatable results in normal situations.	The manufacturing operations are defined, deployed and monitored across all organizational groups, and their executions are repeatable and monitored with software tool supports.	The manufacturing operations are focused on continuous improvement and optimization.

- ◯ R0: No manufacturing operations have been documented.
- ◯ R1: The manufacturing operations are partly documented, and there are plans to finalize the documentation.
- ◯ R2: All manufacturing operations are well documented, deployed and monitored.
- ◯ M0: The manufacturing operations are defined, deployed and monitored with documented standards and partly supported by software tools.
- ◯ M1: The manufacturing operations are defined, deployed and monitored and fully supported by software tools and executed with possibly repeatable results in normal situations.
- ◯ M2: The manufacturing operations are defined, deployed and monitored across all organizational groups, and their executions are repeatable and monitored with software tool supports.
- ◯ M3: The manufacturing operations are focused on continuous improvement and optimization.

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3

Strategy & Vision *

The extent to which the strategy and vision currently adopted by companies are aimed towards I4.0, including the acknowledgement of an I4.0 roadmap.

Readiness			Maturity			
R0 Unprepared	R1 Planned	R2 Ready	M0 Incomplete	M1 Performed	M2 Managed	M3 Defined
There is no awareness regarding the digital transformation, and I4.0 strategy and vision are lacking.	There is a willingness and interest towards the digital transformation. I4.0 strategy and vision are being developed but there is great uncertainty on how to approach I4.0.	There is a clear I4.0 strategy and vision in place.	I4.0 strategy and vision have been formally implemented in at least one functional area.	I4.0 strategy and vision are expanded to include more than one functional area.	I4.0 strategy and vision are expanded to include all functional areas.	I4.0 strategy and vision are refreshed and updated automatically if necessary (monthly).

- ◯ R0: There is no awareness regarding the digital transformation, and I4.0 strategy and vision are lacking.
- ◯ R1: There is a willingness and interest towards the digital transformation. I4.0 strategy and vision are being developed but there is great uncertainty on how to approach I4.0.
- ◯ R2: There is a clear I4.0 strategy and vision in place.
- ◯ M0: I4.0 strategy and vision have been formally implemented in at least one functional area.
- ◯ M1: I4.0 strategy and vision are expanded to include more than one functional area.
- ◯ M2: I4.0 strategy and vision are expanded to include all functional areas.
- ◯ M3: I4.0 strategy and vision are refreshed and updated automatically if necessary (monthly).

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4

Culture & Competencies *

The extent to which all people of all departments are competent (due to adequate training and recruitment of HRM) and support the implementation of I4.0 technologies and innovation.

Readiness			Maturity			
R0 Unprepared	R1 Planned	R2 Ready	M0 Incomplete	M1 Performed	M2 Managed	M3 Defined
The organizational culture is not open to innovation, nor are there in-house or external competencies related to digital manufacturing.	The organizational culture is open to innovation, but there are no in-house or external competencies available to approach digital manufacturing.	The organizational culture is open to innovation and there are in-house or external competencies available related to digital manufacturing, and these can be utilized when needed.	An inclusive culture is (partly) in place by involving workforce in vision development. People are being recruited with digitization competencies.	People are educated to develop the ability to exploit connected data systems. Production staff proactively coordinates digital insights and knowledge sharing.	Suppliers, users, and other stakeholders meet up to improve shared group understanding of production processes. Data analysts and data scientists are recruited to optimize production.	A culture of continuous smart factory innovation is in place covering the complete organization. Specialized roles and responsibilities are geared toward predictable production.

- ◯ R0: The organizational culture is not open to innovation, nor are there in-house or external competencies related to digital manufacturing.
- ◯ R1: The organizational culture is open to innovation, but there are no in-house or external competencies available to approach digital manufacturing.
- ◯ R2: The organizational culture is open to innovation and there are in-house or external competencies available related to digital manufacturing, and these can be utilized when needed.
- ◯ M0: An inclusive culture is (partly) in place by involving workforce in vision development. People are being recruited with digitization competencies.
- ◯ M1: People are educated to develop the ability to exploit connected data systems. Production staff proactively coordinates digital insights and knowledge sharing.
- ◯ M2: Suppliers, users, and other stakeholders meet up to improve shared group understanding of production processes. Data analysts and data scientists are recruited to optimize production.
- ◯ M3: A culture of continuous smart factory innovation is in place covering the complete organization. Specialized roles and responsibilities are geared toward predictable production.

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5

Process *

The extent to which companies support departments collaboration, machine and system integration with the help of I4.0 technologies. This includes self- optimization, self-configuration, standardization and simplification of processes of production, maintenance, and support processes.

Readiness			Maturity			
R0 Unprepared	R1 Planned	R2 Ready	M0 Incomplete	M1 Performed	M2 Managed	M3 Defined
No processes have been explicitly defined.	The processes are partly defined, and there are plans in place to define all processes.	All processes are defined, simplified, standardized, and are being executed.	Defined processes are completed with the support of digital tools.	Digitized processes and systems are securely integrated across all hierarchical levels (machines & workers - boardroom).	Integrated processes and systems are automated, with limited human intervention.	Automated processes and systems are actively analyzing and reacting to data, enabling continuous process improvements.

- R0: No processes have been explicitly defined.
- R1: The processes are partly defined, and there are plans in place to define all processes.
- R2: All processes are defined, simplified, standardized, and are being executed.
- M0: Defined processes are completed with the support of digital tools.
- M1: Digitized processes and systems are securely integrated across all hierarchical levels (machines & workers - boardroom).
- M2: Integrated processes and systems are automated, with limited human intervention.
- M3: Automated processes and systems are actively analyzing and reacting to data, enabling continuous process improvements.

6

Connectivity & Integration *

The extent to which an IT/cloud infrastructure is in place to accommodate vertical or horizontal integration across the value chain.

Readiness			Maturity			
R0 Unprepared	R1 Planned	R2 Ready	M0 Incomplete	M1 Performed	M2 Managed	M3 Defined
The IT infrastructure is poorly documented and designed, and provides no flexibility in extending it.	The IT infrastructure is partly documented and designed, and there are plans in place to increase its flexibility to extend it in the future.	The IT infrastructure is well documented and designed, and provides enough flexibility to extend towards I4.0 technology requirements. In addition, the IT department resources are aligned to support future extensions.	The IT infrastructure is not standardized but all the different modules can communicate with each other.	The IT infrastructure is not fully integrated but is based on a number of recognized standards and when new modules have to be developed, this is done accordingly.	The IT infrastructure is based on a commonly agreed set of standards and new modules are developed accordingly, enabling interoperability.	The IT infrastructure in the whole supply chain is based on standards that allow plug and play inter-organization real-time communication, enabling interoperability and scalability.

- R0: The IT infrastructure is poorly documented and designed, and provides no flexibility in extending it.
- R1: The IT infrastructure is partly documented and designed, and there are plans in place to increase its flexibility to extend it in the future.
- R2: The IT infrastructure is well documented and designed, and provides enough flexibility to extend towards I4.0 technology requirements. In addition, the IT department resources are aligned to support future extensions.
- M0: The IT infrastructure is not standardized but all the different modules can communicate with each other.
- M1: The IT infrastructure is not fully integrated but is based on a number of recognized standards and when new modules have to be developed, this is done accordingly.
- M2: The IT infrastructure is based on a commonly agreed set of standards and new modules are developed accordingly, enabling interoperability.
- M3: The IT infrastructure in the whole supply chain is based on standards that allow plug and play inter-organization real-time communication, enabling interoperability and scalability.

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7

Products & Services *

The extent to which products are individualized and product characteristics can be customer specific (smart products), and the extent towards offering data-driven services and customer integration (smart services and servitization).

Readiness			Maturity			
R0 Unprepared	R1 Planned	R2 Ready	M0 Incomplete	M1 Performed	M2 Managed	M3 Defined
Product development or services are not digitally supported.	There are plans to explore digital support of product development and services, but additional help is required.	Product development or services are partly digitally supported.	Products offer digital features and services are continuously digitally supported.	Products offer connectivity features and little differentiation. Data-driven services offer little customer integration.	Products offer responsive features and can be largely customized. Data-driven services offer customer integration.	Products can be completely customized and feature all smart product functionalities, and many products are being servitized. Data-driven services are fully integrated with the customer.

- ◯ R0: Product development or services are not digitally supported.
- ◯ R1: There are plans to explore digital support of product development and services, but additional help is required.
- ◯ R2: Product development or services are partly digitally supported.
- ◯ M0: Products offer digital features and services are continuously digitally supported.
- ◯ M1: Products offer connectivity features and little differentiation. Data-driven services offer little customer integration.
- ◯ M2: Products offer responsive features and can be largely customized. Data-driven services offer customer integration.
- ◯ M3: Products can be completely customized and feature all smart product functionalities, and many products are being servitized. Data-driven services are fully integrated with the customer.

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8

Collaboration *

The extent to which formal channels are enabled for employees and collaboration partners to share information and work together, as well as institutional structures and systems that allow collaborative behavior.

Readiness			Maturity			
R0 Unprepared	R1 Planned	R2 Ready	M0 Incomplete	M1 Performed	M2 Managed	M3 Defined
Communication and information sharing across teams happen on an informal basis.	There are plans to formalize the current channels used for communication and information sharing, but additional help is required.	Formal channels are established for communication and information sharing across teams.	Formal channels are established to allow teams to work together on discrete tasks and projects.	Teams are empowered by the organization to make adjustments that will facilitate cooperation on discrete tasks and projects.	Teams are empowered by the organization to share resources on both discrete and longer-term tasks and projects.	Formal channels are established to enable dynamically-forming teams to work on cross-functional projects with shared goals and resources.

- ◯ R0: Communication and information sharing across teams happen on an informal basis.
- ◯ R1: There are plans to formalize the current channels used for communication and information sharing, but additional help is required.
- ◯ R2: Formal channels are established for communication and information sharing across teams.
- ◯ M0: Formal channels are established to allow teams to work together on discrete tasks and projects.
- ◯ M1: Teams are empowered by the organization to make adjustments that will facilitate cooperation on discrete tasks and projects.
- ◯ M2: Teams are empowered by the organization to share resources on both discrete and longer-term tasks and projects.
- ◯ M3: Formal channels are established to enable dynamically-forming teams to work on cross-functional projects with shared goals and resources.

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F.3 TAM survey

Technology Acceptance Model (TAM) survey I4RMM

Thank you for participating in this short questionnaire related to the case study of the I4RMM. You will be asked 10 questions to assess the perceived usefulness, ease of use, and intention to use of the I4RMM, and will take approximately 10 minutes.

* Required

* This form will record your name, please fill your name.

1. Perceived Usefulness *

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
I think the I4RMM provides an effective solution to the problem of assessing Industry 4.0 in organizations.	○	○	○	○	○
Readiness and maturity represented in this way would be difficult for users and stakeholders to understand.	○	○	○	○	○
Overall, I found the I4RMM in this experiment to be useful.	○	○	○	○	○
Using the I4RMM would make it difficult to communicate readiness/maturity of Industry 4.0 to users and other stakeholders.	○	○	○	○	○

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2. Perceived Ease of Use *

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Learning to use the I4RMM to assess Industry 4.0 would be easy for me.	○	○	○	○	○
I found the way readiness/maturity is represented as unclear and difficult to understand.	○	○	○	○	○
It would be easy for me to become skillful at using the I4RMM to assess Industry 4.0.	○	○	○	○	○
Overall, I found the I4RMM for assessing Industry 4.0 difficult to use.	○	○	○	○	○

3. Intention to Use *

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
I would prefer to use the I4RMM to assess Industry 4.0 in the future.	○	○	○	○	○
I would definitely not use the I4RMM to assess Industry 4.0.	○	○	○	○	○

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F.4 Report: results case study company A

This report was compiled after the assessment session of case organization A and consists of:

- Description of the I4RMM used in the case study.
- Summary of the results/feedback/comments as observed by the researcher during the case study.
- Visualization of the assessment outcome of the case organization.

The report was shared with the participants 2-3 days after the assessment session by mail. In addition, the researcher asked the participants to read the report, and encourage them to share additional thoughts or comments if they would arise. The report can be found on the next page.

Case study

Industry 4.0 Readiness Maturity Model
I4RMM

Case study (company A) to evaluate the I4RMM on completeness, validity, and usability.

Trusted partner for your **Digital Journey**

Atos

Case study

Model description & setup

The I4RMM was developed following the Design Science Research paradigm, combining scientific knowledge and practical insights to assure relevance and rigor. This case study was performed to assess the I4RMM on its completeness, validity, and usability when applying it as-if we are applying it for our customers.

The Industry 4.0 Readiness Maturity Model (I4RMM) was developed to explore the possibilities of integrating I4.0 readiness and maturity assessment models. These readiness and maturity models help organizations to prepare for the challenges and requirements of I4.0. Therefore, guiding them in reaching higher adoption levels by providing decision-making support during their I4.0 proceedings. Integrating these models provided a comprehensive assessment tool that can be utilized before and during the digital transformation: the I4RMM.

The model assesses the following dimensions on I4.0 readiness and maturity:

1. Technology
2. Operations
3. Strategy & Vision
4. Culture & Competencies
5. Process
6. Connectivity & Integration
7. Products & Services
8. Collaboration

During the assessment session, the participants attempted to assign readiness (R0-R2) or maturity levels (M0-M3) to these dimensions of the organization in question.

The researcher guided the assessment procedure in an observative stance, and provided explanation if this was needed. Furthermore, the researcher collected feedback about the model concerning its usability, and overall ease-of-use.

After the assessment session, the researcher asked the participants to fill in a brief questionnaire that assessed the constructs of perceived usefulness, ease-of-use, and intention-to-use.

Industry 4.0 Readiness Maturity Model - I4RMM

Dimension	Definition	Readiness			Maturity			
		R0 Unprepared	R1 Planned	R2 Ready	M0 Incomplete	M1 Performed	M2 Managed	M3 Defined
Technology	The extent to which I4.0 technologies are implemented and used.	No presence of assets that enable data collection, transfer, and generation.	Planned to buy new technology that enables data collection, transfer and generation.	There are assets available that enable data collection, transfer, and generation.	There are assets available and used for data access and data visualization.	There are assets available and used for data analysis, and communicating the results to the user.	There are assets available that are acting autonomously according to information received after an analytic process.	The assets deployed across the supply chain can interact together and reconfigure themselves to optimize performance.
Operations	The extent to which manufacturing operations (production, storage, quality, test, and maintenance) are formally documented, supported by I4.0 paradigms, and enable continuous improvement and optimization.	No manufacturing operations have been documented.	The manufacturing operations are partly documented, and there are plans to finalize the documentation.	All manufacturing operations are well documented, deployed and monitored.	The manufacturing operations are defined, deployed and monitored with documented standards and partly supported by software tools.	The manufacturing operations are defined, deployed and monitored and fully supported by software tools and executed with possibly repeatable results in normal situations.	The manufacturing operations are defined, deployed and monitored across all organizational groups, and their executions are repeatable and monitored with software tool supports.	The manufacturing operations are focused on continuous improvement and optimization.
Strategy & Vision	The extent to which the strategy and vision currently adopted by companies are aimed towards I4.0, including the acknowledgement of an I4.0 roadmap.	There is no awareness regarding the digital transformation, and I4.0 strategy and vision are lacking.	There is a willingness and interest towards the digital transformation. I4.0 strategy and vision are being developed but there is great uncertainty on how to approach I4.0.	There is a clear I4.0 strategy and vision in place.	I4.0 strategy and vision have been formally implemented in at least one functional area.	I4.0 strategy and vision are expanded to include more than one functional area.	I4.0 strategy and vision are expanded to include all functional areas.	I4.0 strategy and vision are refreshed and updated automatically if necessary (monthly).
Culture & Competencies	The extent to which all people of all departments are competent (due to adequate training and recruitment of HRM) and support the implementation of I4.0 technologies and innovation.	The organizational culture is not open to innovation, nor are there in-house or external competencies related to digital manufacturing.	The organizational culture is open to innovation, but there are no in-house or external competencies available to approach digital manufacturing.	The organizational culture is open to innovation and there are in-house or external competencies available related to digital manufacturing, and these can be utilized when needed.	An inclusive culture is (partly) in place by involving workforce in vision development. People are being recruited with digitization competencies.	People are educated to develop the ability to exploit connected data systems. Production staff proactively coordinates digital insights and knowledge sharing.	Suppliers, users, and other stakeholders meet up to improve shared group understanding of production processes. Data analysts and data scientists are recruited to optimize production.	A culture of continuous smart factory innovation is in place covering the complete organization. Specialized roles and responsibilities are geared toward predictable production.
Process	The extent to which companies support departments collaboration, machine and system integration with the help of I4.0 technologies. This includes self- optimization, self-configuration, standardization and simplification of processes of production, maintenance, and support processes.	No processes have been explicitly defined.	The processes are partly defined, and there are plans in place to define all processes.	All processes are defined, simplified, standardized, and are being executed.	Defined processes are completed with the support of digital tools.	Digitized processes and systems are securely integrated across all hierarchical levels (machines & workers - boardroom).	Integrated processes and systems are automated, with limited human intervention.	Automated processes and systems are actively analyzing and reacting to data, enabling continuous process improvements.
Connectivity & Integration	The extent to which an IT/ cloud infrastructure is in place to accommodate vertical or horizontal integration across the value chain.	The IT infrastructure is poorly documented and designed, and provides no flexibility in extending it.	The IT infrastructure is partly documented and designed, and there are plans in place to increase its flexibility to extend it in the future.	The IT infrastructure is well documented and designed, and provides enough flexibility to extend towards I4.0 technology requirements. In addition, the IT department resources are aligned to support future extensions.	The IT infrastructure is not standardized but all the different modules can communicate with each other.	The IT infrastructure is not fully integrated but is based on a number of recognized standards and when new modules have to be developed, this is done accordingly.	The IT infrastructure is based on a commonly agreed set of standards and new modules are developed accordingly, enabling interoperability.	The IT infrastructure in the whole supply chain is based on standards that allow plug and play inter-organization real-time communication, enabling interoperability and scalability.
Products & Services	The extent to which products are individualized and product characteristics can be customer specific (smart products), and the extent towards offering data-driven services and customer integration (smart services and servitization).	Product development or services are not digitally supported.	There are plans to explore digital support of product development and services, but additional help is required.	Product development or services are partly digitally supported.	Products offer digital features and services are continuously digitally supported.	Products offer connectivity features and little differentiation. Data-driven services offer little customer integration.	Products offer responsive features and can be largely customized. Data-driven services offer customer integration.	Products can be completely customized and feature all smart product functionalities, and many products are being servitized. Data-driven services are fully integrated with the customer.
Collaboration	The extent to which formal channels are enabled for employees and collaboration partners to share information and work together, as well as institutional structures and systems that allow collaborative behavior.	Communication and information sharing across teams happen on an informal basis.	There are plans to formalize the current channels used for communication and information sharing, but additional help is required.	Formal channels are established for communication and information sharing across teams.	Formal channels are established to allow teams to work together on discrete tasks and projects.	Teams are empowered by the organization to make adjustments that will facilitate cooperation on discrete tasks and projects.	Teams are empowered by the organization to share resources on both discrete and longer-term tasks and projects.	Formal channels are established to enable dynamically-forming teams to work on cross-functional projects with shared goals and resources.

Case study
Results

During the assessment, the researcher asked the participants to provide feedback about the structure of the model, the unique level descriptions, and if they were able to assign a level to the case study organization.

Structural comments
A few comments were made with regards to the structure of the model:

- The difference on how to use the model with regards to the concepts of readiness and maturity is unclear. Are both entities assessed, or only one?
- The continuation from level R2 to level M0 seems unnatural, due to number suffix.
- Perhaps the model could be altered to streamline level R2 under the maturity levels, so that it becomes clear you are always in level R2 when you assign a dimension to one of the maturity levels.
- A glossary of terminology used in the model could be very useful, to increase consistency and understandability.

Technology
No specific comments were made about the technology dimension.

- The level **M2** was assigned.

Operations
A few comments were made:

- The level **M1** was assigned.
- The starting sentence of M0-M3 is very repetitive, changing the word order would improve readability.
- The difference between the different levels should be more distinct in an eye-sight. Perhaps work with bullet points or with keywords? For example: keep the top sentence and describe the qualifications under it.

Strategy & Vision
No specific comments were made about the strategy & vision dimension:

- The level **M1** was assigned.

Culture & Competencies
A few comments were made:

- The level **M2** was assigned.
- Culture & Competencies seems like a misfit, perhaps replace 'Competencies' with 'People'? 'Competencies' do not have much in common with 'Culture'.
- The definition of this dimension is too focused on 'Competencies', maybe add the effect of cultural influence or cultural behavior to the definition and its levels?
- Readiness level descriptions (R0-R2) are focused on culture and maturity level descriptions (M0-M3) are focused on competencies. However, these constructs should both be assessed on readiness and maturity.
- How do you cope with the challenges that come from working in an international environment?
- Perhaps add business change management to the readiness and maturity levels i.e. the flexibility of people to change and adopt new technologies?

Process
A few comments were made:

- The level **R1** was assigned.
- Remove the "machines & workers - boardroom" description in maturity level M1, it is unclear and redundant.

Connectivity & Integration
No specific comments were made about the connectivity & integration dimension.

- The level **M2** was assigned.

Products & Services
A few comments were made:

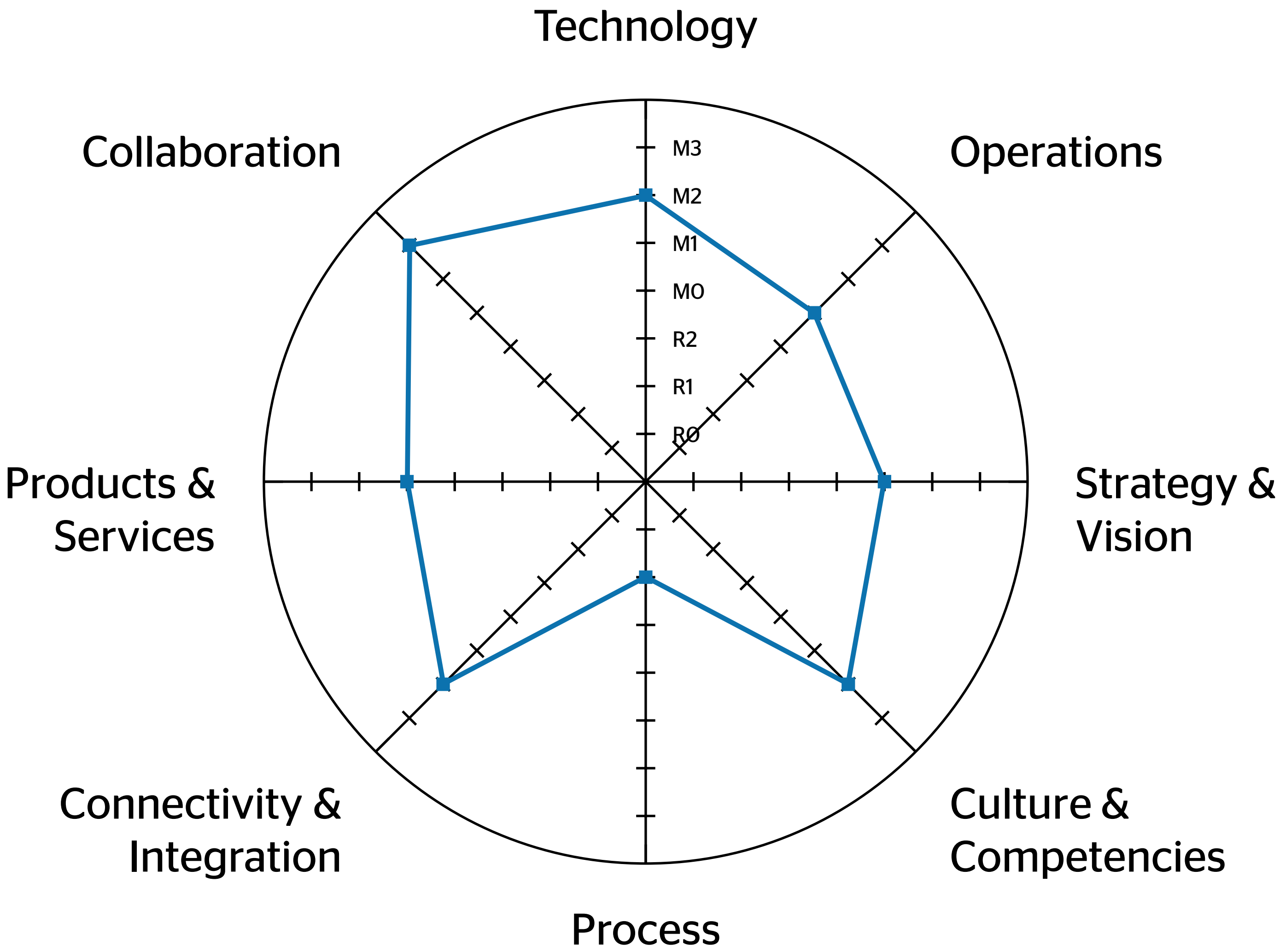
- The level **M1** was assigned.
- Products & Services should be two separate dimensions.
- In the current form, it is near impossible to assign a level e.g. if smart products are developed but servitization is not being applied.

Collaboration
A few comments were made:

- The level **M3** was assigned.
- Security & compliance rules could be a nice addition to these levels.
- "Institutional structures" in the definition is too vague.
- Perhaps change the labels to appropriately reflect the different dimension stages?

Final comments
Final comments including comments with regards to deployment:

- The I4RMM could be very useful for small-medium companies that want to enter their digital transformation. However, the readiness levels could be less interesting to bigger companies who are already far developed in their digital transformation.
- The distinction between readiness and maturity must be made more explicit in the model.
- The difference between R2 and M0 is very subtle, an important distinction must be made.
- The I4RMM could both be used for the as-is scenario and the to-be scenario. In addition, the difference between these two assessments could initiate discussion and perhaps provide an improvement path.
- It is important that the assessors provide consistency i.e. Atos consultants in collaboration with clients.
- Benchmarking opportunities should be explored.
- Only utilize the model with our clients when the follow-up steps i.e. improvement opportunities are absolutely clear.


Technology
Operations
Strategy & Vision
Culture & Competencies
Process
Connectivity & Integration
Products & Services
Collaboration
M3
M2
M1
M0
R2
R1
R0

F.5 Report: results case study company B

This report was compiled after the assessment session of case organization B and consists of:

- Description of the I4RMM used in the case study.
- Summary of the results/feedback/comments as observed by the researcher during the case study.
- Visualization of the assessment outcome of the case organization.

The report was shared with the participants 2-3 days after the assessment session by mail. In addition, the researcher asked the participants to read the report, and encourage them to share additional thoughts or comments if they would arise. The report can be found on the next page.

Case study

Industry 4.0 Readiness Maturity Model

I4RMM

Case study (company B) to evaluate the I4RMM on completeness, validity, and usability.

Trusted partner for your **Digital Journey**

Case study

Model description & setup

The I4RMM was developed following the Design Science Research paradigm, combining scientific knowledge and practical insights to assure relevance and rigor. This case study was performed to assess the I4RMM on its completeness, validity, and usability when applying it as-if we are applying it for our customers.

The Industry 4.0 Readiness Maturity Model (I4RMM) was developed to explore the possibilities of integrating I4.0 readiness and maturity assessment models. These readiness and maturity models help organizations to prepare for the challenges and requirements of I4.0. Therefore, guiding them in reaching higher adoption levels by providing decision-making support during their I4.0 proceedings. Integrating these models provided a comprehensive assessment tool that can be utilized before and during the digital transformation: the I4RMM.

The model assesses the following dimensions on I4.0 readiness and maturity:

1. Technology
2. Operations
3. Strategy & Vision
4. Culture & Competencies
5. Process
6. Connectivity & Integration
7. Products & Services
8. Collaboration

During the assessment session, the participants attempted to assign readiness (R0-R2) or maturity levels (M0-M3) to these dimensions of the organization in question.

The researcher guided the assessment procedure in an observative stance, and provided explanation if this was needed. Furthermore, the researcher collected feedback about the model concerning its usability, and overall ease-of-use.

After the assessment session, the researcher asked the participants to fill in a brief questionnaire that assessed the constructs of perceived usefulness, ease-of-use, and intention-to-use.

Industry 4.0 Readiness Maturity Model - I4RMM

Dimension	Definition	Readiness			Maturity			
		R0 Unprepared	R1 Planned	R2 Ready	M0 Incomplete	M1 Performed	M2 Managed	M3 Defined
Technology	The extent to which I4.0 technologies are implemented and used.	No presence of assets that enable data collection, transfer, and generation.	Planned to buy new technology that enables data collection, transfer and generation.	There are assets available that enable data collection, transfer, and generation.	There are assets available and used for data access and data visualization.	There are assets available and used for data analysis, and communicating the results to the user.	There are assets available that are acting autonomously according to information received after an analytic process.	The assets deployed across the supply chain can interact together and reconfigure themselves to optimize performance.
Operations	The extent to which manufacturing operations (production, storage, quality, test, and maintenance) are formally documented, supported by I4.0 paradigms, and enable continuous improvement and optimization.	No manufacturing operations have been documented.	The manufacturing operations are partly documented, and there are plans to finalize the documentation.	All manufacturing operations are well documented, deployed and monitored.	The manufacturing operations are defined, deployed and monitored with documented standards and partly supported by software tools.	The manufacturing operations are defined, deployed and monitored and fully supported by software tools and executed with possibly repeatable results in normal situations.	The manufacturing operations are defined, deployed and monitored across all organizational groups, and their executions are repeatable and monitored with software tool supports.	The manufacturing operations are focused on continuous improvement and optimization.
Strategy & Vision	The extent to which the strategy and vision currently adopted by companies are aimed towards I4.0, including the acknowledgement of an I4.0 roadmap.	There is no awareness regarding the digital transformation, and I4.0 strategy and vision are lacking.	There is a willingness and interest towards the digital transformation. I4.0 strategy and vision are being developed but there is great uncertainty on how to approach I4.0.	There is a clear I4.0 strategy and vision in place.	I4.0 strategy and vision have been formally implemented in at least one functional area.	I4.0 strategy and vision are expanded to include more than one functional area.	I4.0 strategy and vision are expanded to include all functional areas.	I4.0 strategy and vision are refreshed and updated automatically if necessary (monthly).
Culture & Competencies	The extent to which all people of all departments are competent (due to adequate training and recruitment of HRM) and support the implementation of I4.0 technologies and innovation.	The organizational culture is not open to innovation, nor are there in-house or external competencies related to digital manufacturing.	The organizational culture is open to innovation, but there are no in-house or external competencies available to approach digital manufacturing.	The organizational culture is open to innovation and there are in-house or external competencies available related to digital manufacturing, and these can be utilized when needed.	An inclusive culture is (partly) in place by involving workforce in vision development. People are being recruited with digitization competencies.	People are educated to develop the ability to exploit connected data systems. Production staff proactively coordinates digital insights and knowledge sharing.	Suppliers, users, and other stakeholders meet up to improve shared group understanding of production processes. Data analysts and data scientists are recruited to optimize production.	A culture of continuous smart factory innovation is in place covering the complete organization. Specialized roles and responsibilities are geared toward predictable production.
Process	The extent to which companies support departments collaboration, machine and system integration with the help of I4.0 technologies. This includes self- optimization, self-configuration, standardization and simplification of processes of production, maintenance, and support processes.	No processes have been explicitly defined.	The processes are partly defined, and there are plans in place to define all processes.	All processes are defined, simplified, standardized, and are being executed.	Defined processes are completed with the support of digital tools.	Digitized processes and systems are securely integrated across all hierarchical levels (machines & workers - boardroom).	Integrated processes and systems are automated, with limited human intervention.	Automated processes and systems are actively analyzing and reacting to data, enabling continuous process improvements.
Connectivity & Integration	The extent to which an IT/ cloud infrastructure is in place to accommodate vertical or horizontal integration across the value chain.	The IT infrastructure is poorly documented and designed, and provides no flexibility in extending it.	The IT infrastructure is partly documented and designed, and there are plans in place to increase its flexibility to extend it in the future.	The IT infrastructure is well documented and designed, and provides enough flexibility to extend towards I4.0 technology requirements. In addition, the IT department resources are aligned to support future extensions.	The IT infrastructure is not standardized but all the different modules can communicate with each other.	The IT infrastructure is not fully integrated but is based on a number of recognized standards and when new modules have to be developed, this is done accordingly.	The IT infrastructure is based on a commonly agreed set of standards and new modules are developed accordingly, enabling interoperability.	The IT infrastructure in the whole supply chain is based on standards that allow plug and play inter-organization real-time communication, enabling interoperability and scalability.
Products & Services	The extent to which products are individualized and product characteristics can be customer specific (smart products), and the extent towards offering data-driven services and customer integration (smart services and servitization).	Product development or services are not digitally supported.	There are plans to explore digital support of product development and services, but additional help is required.	Product development or services are partly digitally supported.	Products offer digital features and services are continuously digitally supported.	Products offer connectivity features and little differentiation. Data-driven services offer little customer integration.	Products offer responsive features and can be largely customized. Data-driven services offer customer integration.	Products can be completely customized and feature all smart product functionalities, and many products are being servitized. Data-driven services are fully integrated with the customer.
Collaboration	The extent to which formal channels are enabled for employees and collaboration partners to share information and work together, as well as institutional structures and systems that allow collaborative behavior.	Communication and information sharing across teams happen on an informal basis.	There are plans to formalize the current channels used for communication and information sharing, but additional help is required.	Formal channels are established for communication and information sharing across teams.	Formal channels are established to allow teams to work together on discrete tasks and projects.	Teams are empowered by the organization to make adjustments that will facilitate cooperation on discrete tasks and projects.	Teams are empowered by the organization to share resources on both discrete and longer-term tasks and projects.	Formal channels are established to enable dynamically-forming teams to work on cross-functional projects with shared goals and resources.

Case study
Results

During the assessment, the researcher asked the participants to provide feedback about the structure of the model, the unique level descriptions, and if they were able to assign a level to the case study organization.

Structural comments
A few comments were made with regards to the structure of the model:

- The two different perspectives IT/OT or IT/Business are not always synchronized in an organization. Therefore, it is important to make a decision from which perspective you are assessing the dimensions of the I4RMM, since they can lead to different results.
- It was suggested to include a glossary, to increase understandability and consistency of terminology used in the model.
- Each industry introduces its own challenges and requirements that occur before or during the digital transformation of an organization. Therefore, some dimensions may be irrelevant in assessing I4.0 proceedings. Hence, the dimensions' relevance of different industries should be explored and made explicit.

Technology
A few comments were made:

- The level **M1** was assigned.
- It is unclear from which perspective this dimension should be assessed (IT/OT).
- The definition of "I4.0 technologies" should be clarified, what are examples of these technologies?

Operations
No specific comments were made about the operations dimension.

- The level **M1** was assigned.

Strategy & Vision
No specific comments were made about the strategy & vision dimension:

- The level **R0** was assigned.

Culture & Competencies
A few comments were made:

- The level **R2** was assigned.
- The description of level R0 should be hedged: "organizational culture is **not** open to innovation" does not apply to any organization (of any size). It could be hedged in: "organizational culture is **poorly** open to innovation".
- Elements of the maturity levels are not necessarily evolutionary items of each other i.e. they could be treated independently. These descriptions should be further refined.

Process
A few comments were made:

- The level **R2** was assigned. However, level M0 would be preferred if the description would be altered: "... **partially** supported of digital tools".
- The current description of level M0 is too 'mature'. Its maturity should be toned down to adequately represent its level.

Connectivity & Integration
No specific comments were made about the connectivity & integration dimension.

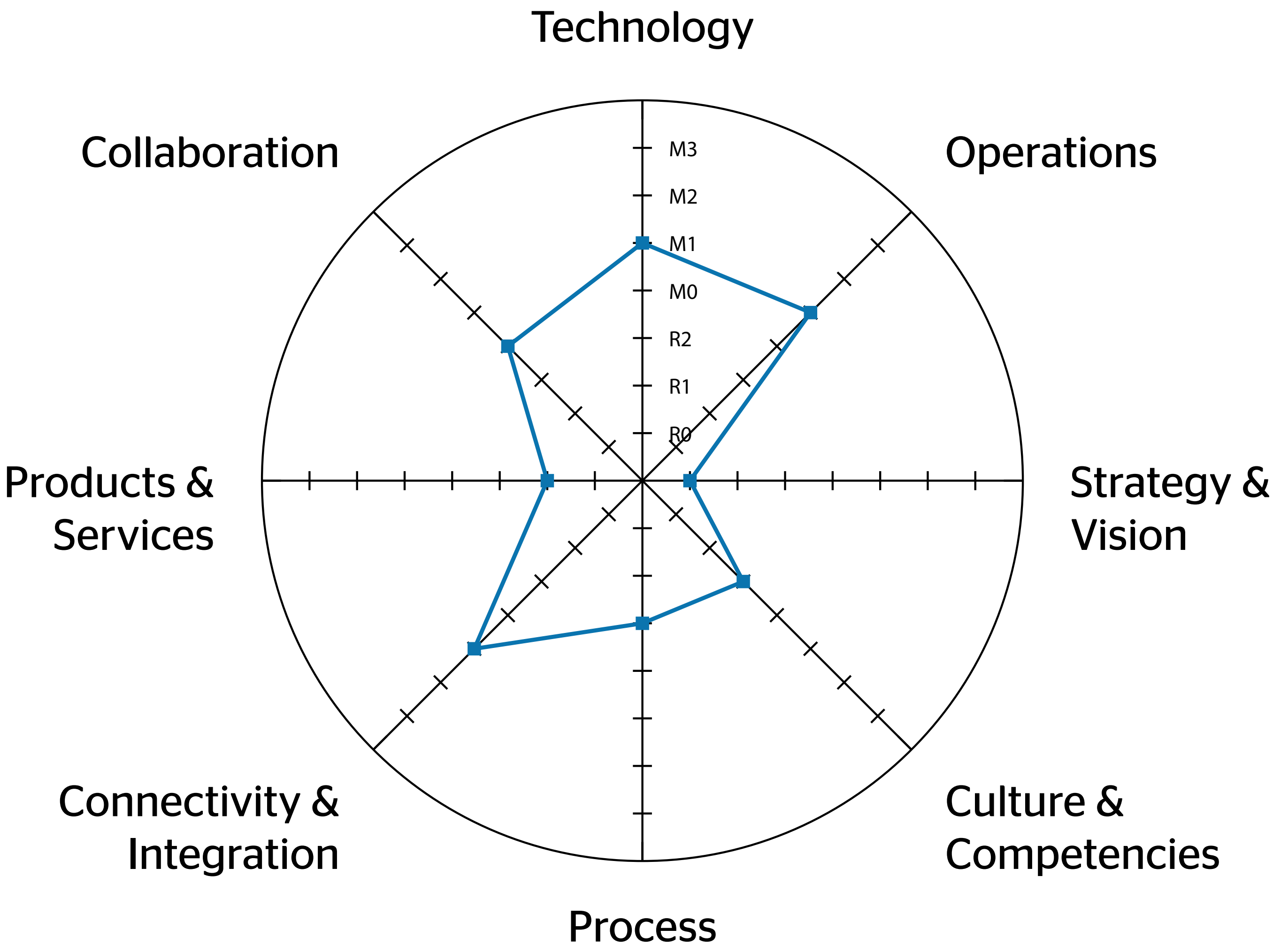
- The level **M1** was assigned.

Products & Services
A few comments were made:

- The level **R1** was assigned.
- This dimension is not relevant for this case organization and industry. There is a great amount of strict regulations in the pharmaceutical industry. Therefore, it is near impossible to offer 'customer specific' products.
- In addition, there is no market-pull for 'customer specific' products, making this dimension irrelevant to assess for this organization.

Collaboration
A few comments were made:

- The level **M0** was assigned.
- What does 'team empowerment' mean in this context? For example, there is a difference when 'team empowerment' entails that teams can bring up new initiatives or that teams can also (independently) execute these new initiatives. In the pharmaceutical industry, the latter would likely be impossible due to strict regulations and laws. Therefore, making 'team empowerment' irrelevant to assess in the current form of the I4RMM.


Technology
Operations
Strategy &
Vision
Culture &
Competencies
Process
Connectivity &
Integration
Products &
Services
Collaboration
M3
M2
M1
M0
R2
R1
R0

F.6 Report: results case study company C

This report was compiled after the assessment session of case organization C and consists of:

- Description of the I4RMM used in the case study.
- Summary of the results/feedback/comments as observed by the researcher during the case study.
- Visualization of the assessment outcome of the case organization.

The report was shared with the participants 2-3 days after the assessment session by mail. In addition, the researcher asked the participants to read the report, and encourage them to share additional thoughts or comments if they would arise. The report can be found on the next page.

Case study

Industry 4.0 Readiness Maturity Model

I4RMM

Case study (company C) to evaluate the I4RMM on completeness, validity, and usability.

Trusted partner for your Digital Journey

Case study

Model description & setup

The I4RMM was developed following the Design Science Research paradigm, combining scientific knowledge and practical insights to assure relevance and rigor. This case study was performed to assess the I4RMM on its completeness, validity, and usability when applying it as-if we are applying it for our customers.

The Industry 4.0 Readiness Maturity Model (I4RMM) was developed to explore the possibilities of integrating I4.0 readiness and maturity assessment models. These readiness and maturity models help organizations to prepare for the challenges and requirements of I4.0. Therefore, guiding them in reaching higher adoption levels by providing decision-making support during their I4.0 proceedings. Integrating these models provided a comprehensive assessment tool that can be utilized before and during the digital transformation: the I4RMM.

The model assesses the following dimensions on I4.0 readiness and maturity:

1. Technology
2. Operations
3. Strategy & Vision
4. Culture & Competencies
5. Process
6. Connectivity & Integration
7. Products & Services
8. Collaboration

During the assessment session, the participants attempted to assign readiness (R0-R2) or maturity levels (M0-M3) to these dimensions of the organization in question.

The researcher guided the assessment procedure in an observative stance, and provided explanation if this was needed. Furthermore, the researcher collected feedback about the model concerning its usability, and overall ease-of-use.

After the assessment session, the researcher asked the participants to fill in a brief questionnaire that assessed the constructs of perceived usefulness, ease-of-use, and intention-to-use.

Industry 4.0 Readiness Maturity Model - I4RMM

Dimension	Definition	Readiness			Maturity			
		R0 Unprepared	R1 Planned	R2 Ready	M0 Incomplete	M1 Performed	M2 Managed	M3 Defined
Technology	The extent to which I4.0 technologies are implemented and used.	No presence of assets that enable data collection, transfer, and generation.	Planned to buy new technology that enables data collection, transfer and generation.	There are assets available that enable data collection, transfer, and generation.	There are assets available and used for data access and data visualization.	There are assets available and used for data analysis, and communicating the results to the user.	There are assets available that are acting autonomously according to information received after an analytic process.	The assets deployed across the supply chain can interact together and reconfigure themselves to optimize performance.
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Strategy & Vision	The extent to which the strategy and vision currently adopted by companies are aimed towards I4.0, including the acknowledgement of an I4.0 roadmap.	There is no awareness regarding the digital transformation, and I4.0 strategy and vision are lacking.	There is a willingness and interest towards the digital transformation. I4.0 strategy and vision are being developed but there is great uncertainty on how to approach I4.0.	There is a clear I4.0 strategy and vision in place.	I4.0 strategy and vision have been formally implemented in at least one functional area.	I4.0 strategy and vision are expanded to include more than one functional area.	I4.0 strategy and vision are expanded to include all functional areas.	I4.0 strategy and vision are refreshed and updated automatically if necessary (monthly).
Culture & Competencies	The extent to which all people of all departments are competent (due to adequate training and recruitment of HRM) and support the implementation of I4.0 technologies and innovation.	The organizational culture is not open to innovation, nor are there in-house or external competencies related to digital manufacturing.	The organizational culture is open to innovation, but there are no in-house or external competencies available to approach digital manufacturing.	The organizational culture is open to innovation and there are in-house or external competencies available related to digital manufacturing, and these can be utilized when needed.	An inclusive culture is (partly) in place by involving workforce in vision development. People are being recruited with digitization competencies.	People are educated to develop the ability to exploit connected data systems. Production staff proactively coordinates digital insights and knowledge sharing.	Suppliers, users, and other stakeholders meet up to improve shared group understanding of production processes. Data analysts and data scientists are recruited to optimize production.	A culture of continuous smart factory innovation is in place covering the complete organization. Specialized roles and responsibilities are geared toward predictable production.
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Connectivity & Integration	The extent to which an IT/ cloud infrastructure is in place to accommodate vertical or horizontal integration across the value chain.	The IT infrastructure is poorly documented and designed, and provides no flexibility in extending it.	The IT infrastructure is partly documented and designed, and there are plans in place to increase its flexibility to extend it in the future.	The IT infrastructure is well documented and designed, and provides enough flexibility to extend towards I4.0 technology requirements. In addition, the IT department resources are aligned to support future extensions.	The IT infrastructure is not standardized but all the different modules can communicate with each other.	The IT infrastructure is not fully integrated but is based on a number of recognized standards and when new modules have to be developed, this is done accordingly.	The IT infrastructure is based on a commonly agreed set of standards and new modules are developed accordingly, enabling interoperability.	The IT infrastructure in the whole supply chain is based on standards that allow plug and play inter-organization real-time communication, enabling interoperability and scalability.
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Collaboration	The extent to which formal channels are enabled for employees and collaboration partners to share information and work together, as well as institutional structures and systems that allow collaborative behavior.	Communication and information sharing across teams happen on an informal basis.	There are plans to formalize the current channels used for communication and information sharing, but additional help is required.	Formal channels are established for communication and information sharing across teams.	Formal channels are established to allow teams to work together on discrete tasks and projects.	Teams are empowered by the organization to make adjustments that will facilitate cooperation on discrete tasks and projects.	Teams are empowered by the organization to share resources on both discrete and longer-term tasks and projects.	Formal channels are established to enable dynamically-forming teams to work on cross-functional projects with shared goals and resources.

Case study
Results

During the assessment, the researcher asked the participants to provide feedback about the structure of the model, the unique level descriptions, and if they were able to assign a level to the case study organization.

Technology
A few comments were made:

- The level **M1** was assigned.
- The results of this assessment are heavily dependent on the focused department. Some departments may be further developed than others. Examples of these departments are work scheduling, preparation, and production.
- The term 'supply chain' in level M3 should be refined, as it may exclude production processes in its current formulation.

Operations
A few comments were made:

- The level **M3** was assigned.
- Different factories or departments may lead to different assessment outcomes.
- The maturity levels should be expanded, either by introducing new (higher) maturity levels, or by altering the level descriptions.

Strategy & Vision
No specific comments were made about the strategy & vision dimension:

- The level **R1** was assigned.

Culture & Competencies
No specific comments were made about the culture & competencies dimension:

- The level **M1** was assigned.

Process
A few comments were made:

- The level **R1** was assigned.
- The definition of the dimension should be refined i.e. "... departments collaboration" is unclear. In addition, the flow of the sentence could be improved to enhance readability.

Connectivity & Integration
A few comments were made:

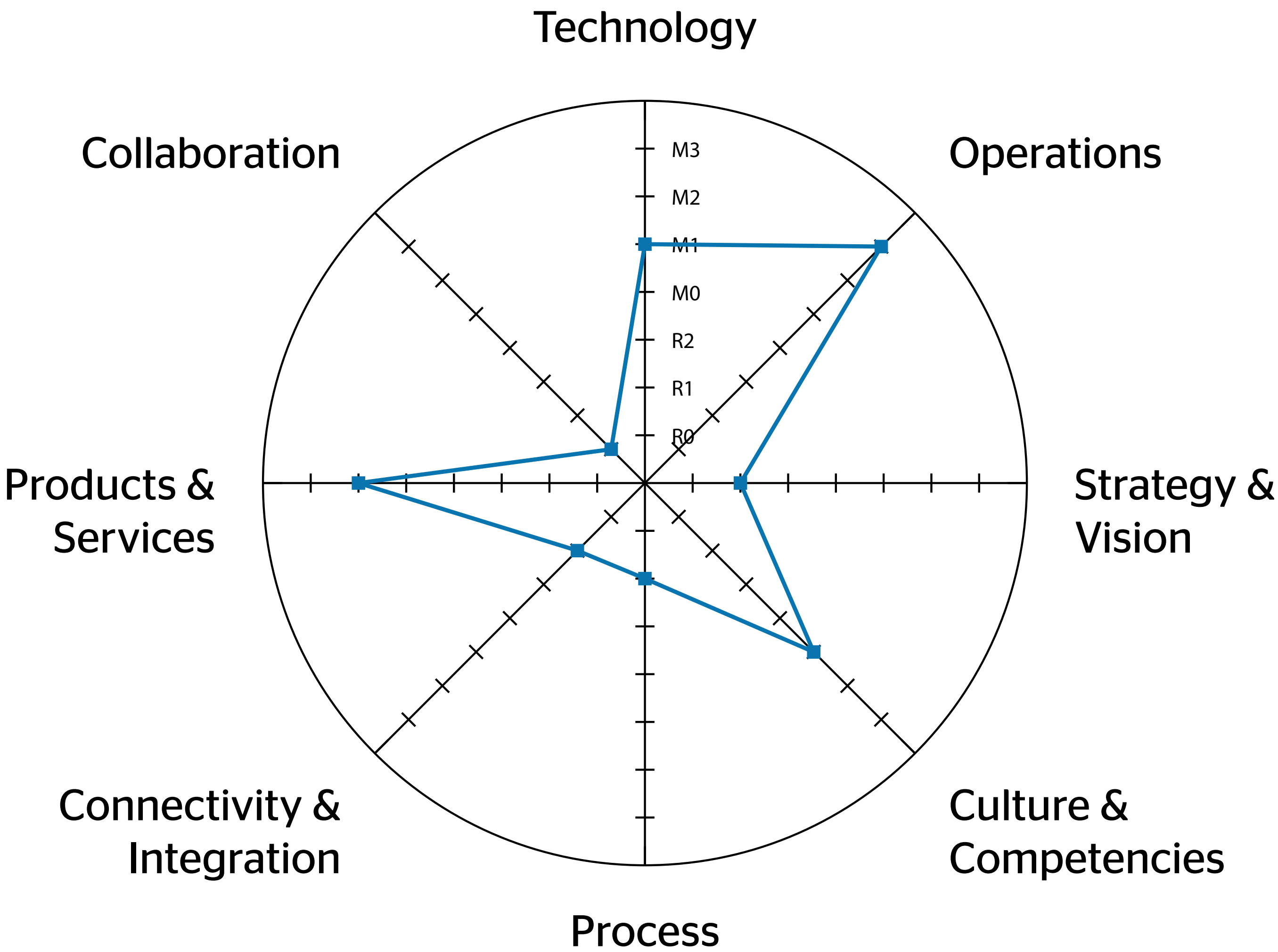
- The level **R1** was assigned.
- The term 'supply chain' is too broad. The model could be improved by specifying sub-areas of the supply chain. For example, multiple IT/cloud infrastructures could be utilized in these different sub-areas. Therefore, it is unwise to aggregate them and attempt to select a general readiness/ maturity level.
- In addition, the client could be interested in I4.0 proceedings for one specific sub-area. Therefore, the model would benefit from more specific applications.

Products & Services
A few comments were made:

- The level **M2** was assigned.
- Products and services should be split up in two dimensions as they are two different (independent) entities.

Collaboration
A few comments were made:

- The level **R0** was assigned.
- The extent to which collaboration could be acknowledged under I4.0 is unclear. Examples or use-cases could be used to better explain how I4.0 can improve collaboration e.g. co-engineering.


Technology
Operations
Strategy &
Vision
Culture &
Competencies
Process
Connectivity &
Integration
Products &
Services
Collaboration
M3
M2
M1
M0
R2
R1
R0

Appendix G

Systematic Literature Review

This appendix contains the complete Systematic Literature Review conducted in August 2020, in preparation of this master thesis project.

Department of Industrial Engineering & Innovation Sciences
Information Systems Research Group

Towards standardizing I4.0 readiness, maturity, and adoption assessment models

Literature study

P.W. (Paul) Kaandorp

Supervisors:
dr.ir. I.T.P. (Irene) Vanderfeesten, TU/e
ir. J.L.M. (Hans) Kwaspen, Atos
ir. G.J. (Guido) van der Sluis, Atos

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Contents

Chapter 1

Introduction

In 2011, the concept of Industry 4.0 (I4.0) was introduced during the Hannover Fair by professor Wolfgang Wahlster. He suggested that firms must be in shape for the fourth Industrial Revolution that is being driven by the internet. One of the applications of I4.0 that follows this driver is the Internet of Things (IoT). This phenomenon is a technological revolution that represents the future of computing and communications (Tan and Wang, 2010). IoT is considered to be a network of smart devices that are connected to sense, monitor, and interact both within a company and between the company and its supply chain (Ehie and Chilton, 2020). Applications of IoT in the manufacturing environment is also referred to as Industrial Internet of Things (IIoT). While this technology might yield many benefits for organizations (Brous et al., 2020), most manufacturing companies have limited understanding of IIoT or how it might be applied in their business processes (Brandt. J, 2015). In addition, manufacturers lack a concrete methodology to choose and prioritize emerging technologies that aid in the roadmap to I4.0 (Jung et al., 2016).

This absence of a standardized methodology to assess the applicability of I4.0 driven technologies in organizations, is most noticeable in the literature. At the time of writing, a considerable number of scientific articles have been published on I4.0 readiness, maturity, and adoption. According to Schmitt et al. (2020), these keywords are often used to categorize publications related to proceedings of I4.0 projects. Each publication proposes a new or modified model assessing the mentioned characteristics. However, some models treat readiness and maturity as synonyms, leaving the difference between the degree of maturity and the degree of readiness undefined (Schumacher et al., 2016). For example, the publication of Rajnai and Kocsis (2018) present and evaluate two I4.0 readiness assessments, while simultaneously referring to them as maturity assessments. On the contrary, Pacchini et al. (2019) propose a model to measure the degree of readiness with regard to the implementation of I4.0 while actively distinguishing it from the degree of maturity. These inconsistencies combined with the novelty of I4.0 lead to the challenge of standardizing I4.0 terminology and assessment methodologies. Standardizing these I4.0 assessments streamline the overpopulated landscape of existing tools, and help companies in their I4.0 decision making.

In an effort to address this challenge, the goal of this literature study is to provide an extensive overview of the different I4.0 readiness, maturity, and adoption assessment models proposed in scientific publications. In addition, these models will be analyzed on structure, measurement dimensions, similarities, and differences. Finally, these findings will be integrated to obtain a more cohesive lexicon, providing the theoretical basis of future standardized I4.0 assessment methodologies.

The rest of the paper is structured as follows: the research questions are given in chapter 2. Second, the research methodology is presented in chapter 3. Next, chapter 4 provides an in-depth review of the different assessments models, and chapter 5 synthesizes the findings in conclusions.

Chapter 2

Research aim

According to Randolph (2009), the goal of many literature studies is to integrate and generalize findings across units, treatments, outcomes, and settings. To successfully achieve this goal, it is important to identify the research goal, the scope, and the research questions. These aspects will guide and help structure the research, and are discussed respectively in this chapter.

2.1 Research objective

As stated in chapter 1, the research objective can be defined as:

> *To provide an extensive overview of the different I4.0 readiness, maturity, and adoption assessment models proposed in scientific publications.*

2.2 Scope

According to Hofmann and Rüsch (2017), I4.0 still *"lacks a precise, generally accepted definition"*. Moreover, Culot et al. (2020) states that I4.0 is an *"umbrella concept for a broad range of technologies and applications"*. Therefore, it is most important to scope the literature study to avoid vague research questions, and narrow the search field. Hence, in constructing the research questions, the following constraints are taken into account:

- The I4.0 assessment models are applicable in the manufacturing industry.
- The I4.0 assessment models mention IoT in the assessment procedure as an I4.0 enabler.

2.3 Research questions

Specifying the research questions is the most important part of any systematic review (Keele et al., 2007). These questions will help to structure the search protocol and to aid in achieving the research goal:

RQ1 What are readiness, maturity, and adoption models to assess I4.0?
RQ2 Which dimensions are measured in readiness, maturity, and adoption models for I4.0?
RQ3 What are shortcomings or weaknesses of readiness, maturity, and adoption models for I4.0?
RQ4 What are advantages or strengths of readiness, maturity, and adoption models for I4.0?
RQ5 How are the dimensions measured in readiness, maturity, and adoption models for I4.0?

Chapter 3

Research methodology

This chapter provides information on the research methodology. First, the adapted Systematic Literature Review method is introduced, followed by the literature collection strategy. This strategy elaborates on the used search engines, used search terms, and the procedure required to obtain the long-list. Subsequently, the literature selection strategy describes the screening procedure, used exclusion criteria, and presents the short-list procedure. Next, the results of the search protocol are presented and discussed. Finally, the data extraction and data synthesis is elaborated.

3.1 Systematic Literature Review

This literature study follows the guidelines and activities from the Systematic Literature Review (SLR) as defined by Keele et al. (2007) and Okoli (2015). These guidelines are aimed for conducting SLRs in software engineering, making it a good fit with the topic of I4.0 readiness, maturity, and adoption. According to Keele et al. (2007), there are many reasons for undertaking a SLR. In this literature study, the main reason is *"to summarise the existing evidence concerning a treatment or technology"*.

To ensure that this SLR can be reproduced as accurate as possible, it is important to specify the steps of the methodology. The complete SLR as defined by Keele et al. (2007) and Okoli (2015) is too extensive for the specified duration of this study (140 hours). Therefore, an adapted structure will be used. First, literature will be collected by using a literature collection strategy. This strategy introduces and motivates the chosen search engines and search terms, leading to a long-list of 75-150 publications. Second, the long-list will be reduced to a short-list by using the literature selection strategy. This strategy elaborates on the exclusion criteria which are used to reduce the long-list to a short-list of 17-23 publications. Finally, these publications are thoroughly analyzed in chapter 4, and the SLR is concluded in chapter 5.

3.2 Literature collection strategy

3.2.1 Search engines

The goal of this literature study is to provide an extensive overview of the different I4.0 readiness, maturity, and adoption assessment models. To achieve this, multiple (complementary) search engines are used. These search engines were found by using the database list of the university. This list was filtered on the research areas of computer sciences and industrial engineering and management sciences. In addition, a combination of search engines were used to include both journal articles and conference proceedings. Table 3.1 presents the selected search engines. The combination of these databases should give a reasonably complete overview of the topic at hand.

Table 3.1: Selected search engines

Search engine	Knowledge domain	Description
ScienceDirect	All	According to Elsevier (2020), ScienceDirect is *"built on the widest range of trusted, high-quality, interdisciplinary research"*. ScienceDirect has approximately 2,500 journals with 16 million articles, and 39,000 e-books.
Web of Science	All	According to Clarivate (2020), Web of Science *"provides data, analytics and insights, as well as workflow tools and bespoke professional services to researchers and the entire research community that underpins research - universities and research institutions, national and local governments, private and public research funding organizations, publishers and research intensive corporations, across the world"*. Web of Science has approximately 34,000 journals with 161 million records.
IEEE Xplore	Electrical engineering, computer science, and electronics	According to IEEE (2020), IEEE Xplore *"provides web access to more than five-million full-text documents from some of the world's most highly-cited publications in electrical engineering, computer science, and electronics"*. IEEE Xplore has approximately 195+ journals, 9,000+ technical standards, and 2,400 books.

3.2.2 Search terms

The search terms are derived from the research questions to find the most relevant publications. Table 3.2 presents these derived keywords with synonyms and variants. These synonyms could help to reveal more interesting publications. This is most certainly relevant to this research area, where there is no clear standardized terminology concerning the landscape of I4.0 (Hofmann and Rüsch, 2017). Some synonyms were found by using the online American dictionary of Merriam-Webster (Merrian-Webster, 2020), while others were determined by using field terminology/knowledge. For example, 'IoT' would not yield any results on the online dictionary but in the industry it is often associated with 'Industry 4.0' or 'Smart Manufacturing'.

These search terms are then constructed in a search query (SQ), using `AND` and `OR` operators. First, the title, abstract, and keywords (*TITLE-ABS-KEY*) of publications are searched for the right context i.e. row 4 of Table 3.2. Second, the title (*TITLE*) is exclusively searched for the assessment type (rows 1-3) and model type (row 5). Therefore, the outcome will be a list of publications merely focusing in-depth on the different assessment models. Finally, the search terms from row 6-8 are not included in the search query considering that they can most likely be found in the discussion or implication section of a publication. To summarize, the following search queries were used to find publications about readiness, maturity, and adoption assessments respectively:

SQ1 *TITLE-ABS-KEY(iot* `OR` *iiot* `OR` *"internet of things"* `OR` *"industry 4.0"* `OR` *"smart manufacturing"* `OR` *"smart factory") * `AND` *TITLE(readiness* `AND` *(model* `OR` *assessment* `OR` *framework* `OR` *evaluation))*

SQ2 *TITLE-ABS-KEY(iot* `OR` *iiot* `OR` *"internet of things"* `OR` *"industry 4.0"* `OR` *"smart manufacturing"* `OR` *"smart factory")* `AND` *TITLE(maturity* `AND` *(model* `OR` *assessment* `OR` *framework* `OR` *evaluation))*

SQ3 *TITLE-ABS-KEY(iot* `OR` *iiot* `OR` *"internet of things"* `OR` *"industry 4.0"* `OR` *"smart manufacturing"* `OR` *"smart factory")* `AND` *TITLE(adoption* `AND` *(model* `OR` *assessment* `OR` *framework* `OR` *evaluation))*

Table 3.2: List of search terms and corresponding synonyms and variants

Index	Keyword	Synonyms and variants
1	Readiness	-
2	Maturity	-
3	Adoption	-
4	IoT	IIoT, Internet of Things, Industry 4.0, Smart Manufacturing, Smart Factory
5	Model	Assessment, Framework, Evaluation
6	Dimensions	Measurements
7	Shortcomings	Weaknesses
8	Advantages	Strengths

3.2.3 Long-list

Table 3.3 presents the results of collecting literature using ScienceDirect and Web of Science. The first row present the assessment type, the second row the search query as defined in the previous section. Next, the third and fourth row represent the used filters: range of publication years and language respectively. Finally, results are presented in the fifth row, and total results per search engine in the sixth row. Respectively, Table 3.4 presents the results of IEEE Xplore search engine. Note that the publication years were set from 2011, when the concept of I4.0 was first introduced in Hannover. In conclusion, the combination of these engines form a list of 195 publications. After removing the duplicates, the long-list consists of 140 publications and can be found in Appendix A.

Table 3.3: Results of collecting literature using ScienceDirect and Web of Science

Search engines	ScienceDirect			Web of Science		
Assessment type	Readiness	Maturity	Adoption	Readiness	Maturity	Adoption
Search query	SQ1	SQ2	SQ3	SQ1	SQ2	SQ3
Publication years	2011-2020	2011-2020	2011-2020	2011-2020	2011-2020	2011-2020
Language filter	English	English	English	English	English	English
Results	4	10	8	28	45	94
Total results	22			167		

Table 3.4: Results of collecting literature using IEEE Xplore

Search engines	IEEE Xplore		
Assessment type	Readiness	Maturity	Adoption
Search query	SQ1	SQ2	SQ3
Publication years	2011-2020	2011-2020	2011-2020
Language filter	English	English	English
Results	1	4	1
Total results	6		

3.3 Literature selection strategy

3.3.1 Screening procedure

To find the most relevant publications, the long-list will be screened on several exclusion criteria. These criteria are discussed in the next section. After applying the exclusion criteria on the long-list, the output will be a short-list of 17-23 publications. These publications will be used for the analysis of this SLR.

3.3.2 Exclusion criteria

According to Keele et al. (2007), selection criteria are intended to identify those primary studies that provide direct evidence about the research question. Therefore, exclusion criteria (EC) should remove publications that are irrelevant in answering the research questions. The following criteria will be discussed in order of weightiness. First, the articles should be accessible through the university, and second, written in English or Dutch. Without accessibility, no analysis can take place. Third, the publications must contain a description of a readiness, maturity, or adoption model, framework, assessment, or evaluation. Fourth, these models must be applicable in a manufacturing environment. Fifth, publications are excluded if they focus on a too specific case study. Table 3.5 presents the five exclusion criteria.

Table 3.5: Exclusion criteria (EC)

Index	Description
EC1	Full text not accessible.
EC2	Not written in English or Dutch.
EC3	Does not present a model (or framework, assessment, evaluation) to represent (or explain, assess, evaluate) readiness, maturity, or adoption of I4.0 technologies.
EC4	Does not present a model that is applicable in a manufacturing environment.
EC5	Does not present a model that is built upon a too specific case study and cannot be generalized.

3.3.3 Short-list

After applying the exclusion criteria, the long-list is reduced from 140 publications to 24 publications. From this reduction: 8 publications were excluded due to EC1, 1 publication due to EC2, 62 publications due to EC3, 40 publications due to EC4, and 5 publications due to EC5. An overview of this distribution is presented in Table 3.6. In addition, the applied exclusion criteria per publication can also be found in Appendix A.

Table 3.6: Distribution of the excluded publications per exclusion criteria

Index	Number of publications excluded
EC1	8
EC2	1
EC3	62
EC4	40
EC5	5

As noted in section 3.1, the time to perform this SLR is limited to 140 hours. Therefore, additional publications need to be excluded in order to reach a short-list of 17-23 publications. Hence, the Journal Impact Factor (JIF) of the journals of the scientific articles were assessed. From the 24 publications, 12 were published in scientific journals and the other 12 were published in conference proceeding papers. The JIF of the 12 scientific articles were assessed using Web of Science and ranged from 0.160 till 5.105, with an average of 3.064. A complete overview of this assessment is documented in Appendix B. In conclusion, three articles were deducted from the short-list with journals of a JIF below 1.0. Therefore, the final short-list contains 21 publications. Table 3.7 presents the final short-list. The first column presents the assessment type that is being reviewed in the publication, the second column the index, and the third column the title and author(s) of the publication.

3.4 Discussion

After applying the search queries and exclusion criteria, an interesting observation can be made with regards to the number of publications per assessment type. As presented in Table 3.7, three, fifteen, and three publications were found with a focus on readiness, maturity, and adoption models respectively. This skewed distribution could be explained by the fact that the terms 'readiness' and 'maturity' are often used interchangeably by academic authors, this observation will be further explored in the next chapters. In addition, the low number of publications focused on adoption could be explained by the novelty of I4.0 technologies. The fourth Industrial Revolution is just gaining momentum. Therefore, it could be assumed that academics are yet unable to fully focus on acceptance or adoption theories of the new technologies of this age.

3.5 Data extraction

According to Keele et al. (2007), the objective of the data extraction stage is *"to design data extraction forms to accurately record the information researchers obtain from the primary studies"*. These forms must be designed to collect all the information needed to answer the review questions. In general, this data extraction should be performed independently by two or more researchers. Furthermore, data should be compared and disagreements resolved. However, this SLR is conducted by one person. Therefore, in order to check data extraction consistency, a test-retest process could be used where the researcher performs a second extraction from a random selection of primary studies. To conclude, the complete set of data extraction forms can be found in Appendix C.

3.6 Data synthesis

Data synthesis involves collating and summarising the results of the included primary studies (Keele et al., 2007). The synthesis of this SLR is descriptive (non-quantitative). For example, one part of the synthesis is identifying returning themes of the measured dimensions (RQ2). Here, inductive coding is applied as described by Chandra et al. (2019). Inductive coding refers to *"a data analysis process whereby the researcher reads and interprets raw textual data to develop concepts, themes, or a process model though interpretations based on data"*. This method seems highly applicable to this SLR research goal. The authors propose six steps of coding:

1. Read raw data
2. Identify key text segments that highlight theory
3. Label segments of text with code
4. Review first-level codes
5. Aggregate first-level codes into higher-level codes by combining similar codes into broader categories
6. Create a data structure to summarize data-aggregation process

This procedure will be used in chapter 5 to conclude this literature study.

Table 3.7: Final short-list

Assessment type	Index	Title, author
Readiness	1	An overview of a smart manufacturing system readiness assessment (Jung et al., 2016)
	2	The degree of readiness for the implementation of Industry 4.0 (Pacchini et al., 2019)
	3	Assessing industry 4.0 readiness of enterprises (Rajnai and Kocsis, 2018)
Maturity	4	Development of a Digitalization Maturity Model for the Manufacturing Sector (Canetta et al., 2018)
	5	A maturity assessment approach for conceiving context-specific roadmaps in the Industry 4.0 era (Colli et al., 2019)
	6	Contextualizing the outcome of a maturity assessment for Industry 4.0 (Colli et al., 2018)
	7	Maturity Models and tools for enabling smart manufacturing systems: Comparison and reflections for future developments (De Carolis et al., 2017)
	8	Assessing the IT and software landscapes of industry 4.0-enterprises: The maturity model SIMMI 4.0 (Leyh et al., 2017)
	9	Application of SIRI for Industry 4.0 Maturity Assessment and Analysis (Lin et al., 2019)
	10	A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs) (Mittal et al., 2018a)
	11	Towards a smart manufacturing maturity model for SMEs (SM3E) (Mittal et al., 2018b)
	12	A maturity level-based assessment tool to enhance the implementation of industry 4.0 in small and medium-sized enterprises (Rauch et al., 2020)
	13	An Industry 4.0 maturity model proposal (Santos and Martinho, 2019)
	14	A Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises (Schumacher et al., 2016)
	15	Roadmapping towards industrial digitalization based on an Industry 4.0 maturity model for manufacturing enterprises (Schumacher et al., 2019)
	16	Smart Factory Implementation and Process Innovation (Sjödin et al., 2018)
	17	Assessing Industry 4.0 Maturity: An Essential Scale for SMEs (Trotta and Garengo, 2019)
	18	Development of maturity model for assessing the implementation of Industry 4.0: learning from theory and practice (Wagire et al., 2020)
Adoption	19	A smart manufacturing adoption framework for SMEs (Mittal et al., 2020)
	20	Understanding the influence of IT/OT Convergence on the adoption of Internet of Things (IoT) in manufacturing organizations: An empirical investigation (Ehie and Chilton, 2020)
	21	System Dynamics perspective for Adoption of Internet of Things: A Conceptual Framework (Tripathi, 2019)

Chapter 4

Literature review

This chapter presents the data extraction as proposed by Keele et al. (2007) and Okoli (2015). The content is based on the data extraction forms, as documented in Appendix C. At the start of this chapter, a number of definitions are presented based on the analyzed literature. These definitions will be used throughout this chapter, and chapter 5. First, the concept of Industry 4.0 (I4.0) and its lack of consensus on a standardized definition is discussed. Second, the Internet of Things (IoT) is defined and its relation to I4.0. Third, the three different I4.0 assessment types are defined and discussed. Finally, the chapter concludes by answering the research questions and by providing an extensive overview of I4.0 readiness, maturity, and adoption models as found in the scientific literature.

4.1 Industry 4.0

The manufacturing industry is a experiencing a significant change labelled as 'the fourth industrial revolution'. This change is also known as Industry 4.0, and is triggered by an exponential growth in new digital technologies (Colli et al., 2018). In this literature study, the term Industry 4.0 (I4.0) will be used. According to Mittal et al. (2020), I4.0 is also known as 'Smart Manufacturing' in the United States, 'Smart Factory' in Asia (most noticeably: South-Korea), and 'Industrie 4.0' in Germany. The lack of a universally accepted label translates well to its definition, as a universal definition for the term I4.0 does not exist (Leyh et al., 2017; Trotta and Garengo, 2019; Wagire et al., 2020).

However, current endeavours in reaching a consensual definition do share a number of similarities. For example, according to Trotta and Garengo (2019), *"Industry 4.0 is a new organizational model based on the implementation of several* ***technologies*** *(i.e. Cloud, Additive Manufacturing, Cyber Security, Big Data Analytics, Simulation, Augmented Reality, Horizontal and Vertical Integration) that work together for the* ***improvement*** *of organisational* ***performance****"*. Pacchini et al. (2019) state that *"I4.0 is an* ***integrated*** *set of intelligent production systems and advanced information* ***technologies*** *that are based on sets of* ***integrated*** *software systems"*. Finally, Li et al. (2017) claim that *"I4.0 is a set of* ***technologies*** *based on the digitization and* ***interconnection*** *of all production units present within an economic system"*.

There is a vast amount of definitions on I4.0 proposed in the scientific literature. However, based on these three definitions, the following recurring themes can already be easily identified:

- Technologies
- Improvement
- Integration

Using these themes, I4.0 could be initially explained as the phenomenon of using **technologies** to improve the **integration** of people, objects, and systems into the value chain (Rajnai and Kocsis, 2018) with the objective to improve organizational **performance**. However, this initial interpretation of I4.0 is relatively vague and is in need of some refinements.

Technology is a broad term. According to Merrian-Webster (2020), technology can be defined as: *"a manner of accomplishing a task especially using technical processes, methods, or knowledge"*. In Industry 4.0, these technical methods differ from previous industrial revolutions. Moreover, one could argue these methods define I4.0. According to Pacchini et al. (2019); Santos and Martinho (2019), the adoption of I4.0 is enabled by I4.0 enabling technologies i.e. Internet of Things (IoT), Big Data, Cloud Computing, Cyber Physical System (CPS), Autonomous Robot, Additive Manufacturing, Augmented Reality (Pacchini et al., 2019; Santos and Martinho, 2019; Trotta and Garengo, 2019). In addition, Santos and Martinho (2019) argue that the attributes related to these technologies are intrinsically linked to CPS and IoT, and can be summarized in digitalization, connectivity, interoperability, adaptability, scalability, efficiency, predictive capability, reconfigurability. Note that some of these attributes can be linked to the integration theme of the initial interpretation of I4.0.

Integration is one of most important characteristics of I4.0. According to Leyh et al. (2017), horizontal and vertical integration across the entire value chain is vital in adopting the concept of I4.0. Complementing the technological attributes of Santos and Martinho (2019), Leyh et al. (2017) introduce the concept of connecting the physical world to the virtual world. In this integration, the authors claim that all process steps of the engineering, are digitized and interconnected, to share and distribute information along the vertical and the horizontal value chains.

This extensive integration leads to organizational improvements. According to Rajnai and Kocsis (2018), this new level of organization and control forms a real-time optimized, self-organizing system. In addition, Santos and Martinho (2019) state that completely new solutions and services will emerge because of this integration, generating new business opportunities. For example, emerging concepts such as mass customization and business servitization can make great use of I4.0 technologies. Moreover, Pacchini et al. (2019) argue that I4.0 is on a path with no return and will become a competitive challenge for companies interested in long-term survival with adequate performance. In conclusion, the use of I4.0 technologies can enable horizontal and vertical integration across the entire value chain, leading to an increase of organizational performance. Based on the discussed literature, the following definition of I4.0 will be used throughout this literature study:

Definition 4.1.1. *I4.0 Industry 4.0 (I4.0) is a new organizational model based on the implementation of I4.0 technologies that enable horizontal and vertical integration across the entire value chain, leading to the improvement of organizational performance.*

4.2 Internet of Things

As stated in the previous section, the Internet of Things (IoT) is one of the I4.0 enabling technologies. In contrast to I4.0, there is more consensual understanding about IoT. However, the definition of IoT varies in comprehensibility. For example, Hofmann and Rüsch (2017) explain IoT as a world where all (physical) things can turn into so-called 'smart things' by featuring small computers that are connected to the internet. In addition, Tripathi (2019) introduces IoT as a system where the items from the physical world and sensors will be connected either by a wireless or wired connection. Ehie and Chilton (2020) define IoT as a network of smart devices that are connected to sense, monitor and interact both within a company and between the company and its supply chain. The latter definition introduces the concept of IoT-devices interacting with each other. According to Lee and Lee (2015), the true value of IoT can be fully realized when connected devices are able to communicate with each others. Integration with inventory systems, customer support systems, business intelligence applications, and business analytics can provide a great number of organizational performance improvements. Note the recurring integration aspect as part of the proposed definition of I4.0. Therefore, one could argue IoT to be a vital (technical) enabler of I4.0, as proposed by Santos and Martinho (2019). In order for IoT to successfully enable I4.0, it must be comprised of four layers (Ehie and Chilton, 2020):

1. Data collection
2. Transmission
3. Service
4. Interface

The data collection layer (1) often uses Radio Frequency IDentification (RFID), which allows automatic identification and data capture using radio waves, a tag, and a reader (Lee and Lee, 2015). This is also known as the 'sensor' of the IoT-device. Transmission (2) is achieved using either a wired or wireless connection. Services (3) provide monitor and control functions, also known as the 'actuator' of the IoT-device. Finally, the interface (4) enables connection with other IoT-devices and systems. Note that this literature study will not extensively explain all the technical details. However, this brief explanation should provide a general understanding of IoT.

In conclusion, IoT can be viewed as one of the technical enablers of I4.0. In addition, it can be described as a network of IoT-devices attached to physical items that are connected to the internet either wireless or wired. These devices collect real-time data, and communicate with each other to enable business decisions. Based on the discussed literature, the following definition of IoT will be used throughout this literature study:

Definition 4.2.1. *IoT Internet of Things (IoT) is a network of devices attached to physical items while being connected to the internet: collecting real-time data, and transmitting the data between devices to improve business decision making.*

As an important enabler of I4.0, IoT can yield many benefits to organizations. However, most firms lack insight in the activities and capabilities required to successfully implement IoT (Sjödin et al., 2018). In addition, Colli et al. (2019) state that there is a need for methods to support companies in the operationalization of this transformation. Furthermore, most companies have limited understanding of IoT adoption, or how it might be applied in their business processes (Brandt. J, 2015). In order to address these challenges; readiness, maturity, and adoption assessment models can be used respectively.

4.3 Assessment types

In the literature, a great number of studies have proposed different I4.0 assessment models over the years. These assessments can be categorized as:

- Readiness assessments
- Maturity assessments
- Adoption assessments

Readiness and maturity assessments have been proposed to guide organizations through their maturing process or transformation phases in a more effective and efficient way (Wagire et al., 2020). However, the difference between the terms 'readiness' and 'maturity' is discussed by many researchers. For example, the publication of Mittal et al. (2018a) refer to readiness models as maturity models. In contrast, Pacchini et al. (2019); Schumacher et al. (2016) claim that readiness is different from maturity, and that these terms cannot be used as synonyms. Pacchini et al. (2019) propose readiness as the state in which the organization is ready to accomplish a task, and maturity as the level of evolution that an organization has accomplished with respect to that task. Schumacher et al. (2016) claim that the difference between readiness and maturity is that *"readiness assessments takes place **before** engaging in the maturing process whereas maturity assessment aims for capturing the **as-it-is** state whilst the maturing process"*. Therefore, underlining the difference in timing. The confusion between these terms and their assessments may be explained due to their relation to each other (De Carolis et al., 2017). For example, the results of a readiness assessment could be used as a baseline for a maturity assessment. Therefore, it is important to provide a definition of both readiness and maturity assessments, since the understanding of these terms and models may vary within the same field of expertise.

According to Benedict et al. (2017), a readiness assessment can evaluate the preparedness of capabilities towards a goal. In addition, a more comprehensive definition is given by Mittal et al. (2018a), who define readiness assessments as *"evaluation tools to analyze and determine the level of preparedness of the conditions, attitudes, and resources, at all levels of a system, needed for achieving its goal(s)"*. Moreover, De Carolis et al. (2017) define readiness assessments as tools to measure the capability of a manufacturing firm to deploy I4.0 enablers.

Maturity models are defined by Santos and Martinho (2019) as conceptual structures that define the maturity of a determined interest area of study. Mittal et al. (2018a) state that maturity models should help individuals or entities to reach a more sophisticated maturity level in people/culture, process/structures and/or objects/technologies following a step-by-step continuous improvement process. Finally, De Carolis et al. (2017) define maturity models as how well a manufacturing firm has employed I4.0 enablers.

In order to provide clarity and consensus about the terms 'readiness' and 'maturity' in this literature study. Two adapted definitions of I4.0 readiness and maturity assessments are presented based on the definitions of De Carolis et al. (2017); Mittal et al. (2018a):

Definition 4.3.1. *I4.0 readiness assessment Evaluation tool to determine the level of preparedness of the conditions, attitudes, and resources, at all levels of a system, needed to deploy I4.0 enablers.*

Definition 4.3.2. *I4.0 maturity assessment Evaluation tool to determine the level of maturity of an employed I4.0 enabler, and to provide guidance in reaching a more sophisticated maturity level of that I4.0 enabler.*

Note that the definition of the maturity assessment also includes helping the firm to provide guidance in reaching higher maturity levels. In the literature, this is referred to the prescriptive purpose of the maturity model. According to de Bruin et al. (2005), a maturity model can have three different purposes:

- Descriptive
- Prescriptive
- Comparative

Descriptive maturity models only present the current maturity state, whereas prescriptive models also indicate how to approach maturity improvement. In addition, comparative maturity models are descriptive in nature. However, these models are able to compare similar practices across organizations, to benchmark maturity within industries. Therefore, comparative maturity models are also referred to as benchmarking models. Finally, these different purposes will be acknowledged in the next sections, and can also be assigned to readiness and adoption assessment models.

Adoption is *"the process through which an individual (or other decision unit) passes from first knowledge of an innovation to forming an attitude toward the innovation, to a decision to adopt or reject, to implementation of the new idea and to confirmation of this decision"* (Rogers, 1995). According to this definition, adoption models should assess the complete life-cycle of an I4.0 enabler in a firm. In contrast, readiness and maturity assessments are time specific in nature. Therefore, adoption assessment models may differ in structure, and focus more on identifying factors that positively or negatively influence the adoption of I4.0 enablers (Ehie and Chilton, 2020). Hence, the following definition describes I4.0 adoption assessments:

Definition 4.3.3. *I4.0 adoption assessment Evaluation tool to identify determinants to successfully adopt an I4.0 enabler, and to provide a roadmap to aid in this adoption.*

4.4 I4.0 readiness assessment models

Table 4.1 presents an overview of the extracted I4.0 readiness, maturity, and adoption assessment models. The first section is dedicated to the readiness models. In the table, the first column presents the index, the second column the name of the model, the third column the author(s) or institution, the fourth column the purpose of the model, the fifth column the number of measured dimensions, the sixth column the number of possible readiness levels, and the final column states the used methods to measure the dimensions. Note that some models are not explicitly named. Therefore, these are labeled as 'I4.0 readiness model' in the overview.

Jung et al. (2016) propose a method for assessing a factory for its readiness to implement I4.0 technologies by calculating the Smart Manufacturing System Readiness Level (SMSRL). This index is calculated by measuring the dimensions: organizational maturity, IT maturity, performance management maturity, and information connectivity maturity. These measurements are conducted by counting measures, using activity maturity scoring schemes, and incidence scoring schemes. Since the SMSRL is quantifiable, the model is both descriptive and comparative in nature. Moreover, the SMSRL provides an indication of the current state with respect to a reference model. This reference model can easily evolve as new technologies merge and become available. Therefore, making this method highly future proof.

Pacchini et al. (2019) developed a model that determines the degree of readiness of a company of the implementation of I4.0. In this model, the focus lies on the enabling technologies. Therefore, eight technologies are measured on adoption i.e. IoT, Big Data, Cloud Computing, Cyber Physical System, Autonomous Robot, Additive Manufacturing, Augmented Reality, and Artificial Intelligence. These technologies are scored on four readiness levels (L0-L3) by semi-structured interviews. The final degree of readiness is calculated by taking the average of the sum of degrees of adoptions of the enabled technologies. This mathematical approach is perceived user-friendly and easy-to-use. However, the model does not include interrelationships between the enabling technologies, nor does it include different weights for each technology. Hence, the authors argue that future work is required to address these implications.

Rajnai and Kocsis (2018) reviewed the I4.0 readiness model of the IMPULS foundation of VDMA (association for mechanical engineering, plant engineering, and information technology). This model measures six dimensions, decomposed into 18 fields. These dimensions are: strategy and organization, smart factory, smart operations, smart products, data-driven services, and employees. Each dimension is measured by a questionnaire. Based on this score, the dimension receives a readiness level. There are six readiness levels: outsider (L0), beginner (L1), intermediate (L2), experienced (L3), expert (L4), and top performer (L5). The final readiness score is calculated as a weighted average of the readiness scores of the six dimensions.

De Carolis et al. (2017) presented the Digital Readiness Assessment MaturitY (DREAMY) tool. Note that the model name includes both terms readiness and maturity. However, this model measures the I4.0 readiness by measuring four dimensions with a focus on their respective business processes. These dimensions are: process, monitoring and control, technology, and organization. Each dimension is assessed by interviews and case studies. DREAMY has a descriptive and prescriptive purpose and identifies the following five readiness levels after measurements: initial (L1), managed (L2), defined (L3), integrated and interoperable (L4), and digital oriented (L5). Finally, because of the modular structure of the model, other process areas can be easily included.

Lin et al. (2019) developed the Smart Industry Readiness Index (SIRI) to assess I4.0 readiness. This method measures ten dimensions on I4.0 readiness: vertical integration, horizontal integration, integrated product life cycle, automation, connectivity, intelligence, workforce learning and development, leadership competency, inter- and intra-company collaboration, and strategy and governance. These dimensions are scored on six readiness levels (L0-L5), each with a comprehensive description. Data is gathered by interviews, questionnaires, and focus groups. Finally, the model draws on the Reference Architectural Model for Industry 4.0 (RAMI 4.0). Therefore, providing the same benefits as the SMSRL model proposed by Jung et al. (2016).

Mittal et al. (2018a) reviewed the I4.0 readiness model by Akdil et al. (2018). This descriptive model assesses I4.0 readiness by measuring the following three dimensions using questionnaires: smart products and services, smart business processes, and strategy and organization. These dimensions are scored on four readiness levels: absence (L0), existence (L1), survived (L2), and maturity (L3).

4.5 I4.0 maturity assessment models

The second part of Table 4.1 is dedicated to the I4.0 maturity models. Note that some models are not explicitly named. Therefore, these are labeled as 'I4.0 maturity model' in the overview.

Rajnai and Kocsis (2018) reviewed the maturity model from the firm PricewaterhouseCoopers (PwC). This descriptive maturity model assesses I4.0 maturity by measuring seven dimensions: business, products and services, integration of value chain, data analytics, agile IT architecture, compliance and security, and organization and culture. These dimensions are scored on four maturity levels: digital novice (L1), vertical integrator (L2), horizontal collaborator (L3), and digital champion (L4).

In addition, Rajnai and Kocsis (2018) reviewed the maturity model from acatech (German Academy of Science and Engineering). This descriptive model measures four the following four dimensions by using questionnaires aimed at functional areas of the enterprise: organizational structure, resources, information systems, and culture. These dimensions are scored on six maturity levels: computerization (L1), connectivity (L2), visibility (L3), transparency (L4), predictive capacity (L5), and adaptability (L6).

Finally, Rajnai and Kocsis (2018) reviewed the Forrester Digital Maturity Model 4.0. This descriptive model also measures four dimensions by using questionnaires. These dimensions are: culture, technology, organization, and insights. After measurements, the dimensions are scored on four maturity levels: skeptics (L1), adopters (L2), collaborators (L3), and differentiators (L4).

Canetta et al. (2018) proposed the Digitalization Maturity Model to assess the state of a company journey towards Industry 4.0. This descriptive and prescriptive model measures the following five dimensions using questionnaires (36 questions): strategy, processes, technologies, products and services, people. These dimensions are scored on four maturtiy levels: absence (L1), novice (L2), intermediate (L3), and expert (L4). In addition, an Overall Maturity Level (OML) is calculated by summing the results of each maturity dimension. Therefore, allowing the model to be used for benchmarking purposes.

Colli et al. (2019) developed an adapted version of the acatech maturity model, named the 360 Digital Maturity Assessment (360DMA). This descriptive model measures five dimensions by using workshops and questionnaires (25 questions). These dimensions are: governance, technology, connectivity, value creation, and competencies. In addition, they are scored on six maturity levels: none (L0), basic (L1), transparent (L2), aware (L3), autonomous (L4), and integrated (L5). The 360DMA relies significantly on qualitative analysis: a large team of experts is required to successfully perform the assessment process. Hence, this method may not be affordable to smaller companies with limited resources.

De Carolis et al. (2017) argue that the maturity of a firms manufacturing system is a key indicator for success in adopting I4.0 technologies. Therefore, the authors reviewed the Manufacturing Operations Management (MOM) capability maturity model. This descriptive and comparative model measures eight dimensions using comprehensive questionnaires of 832 questions. These dimensions are: scheduling, dispatching, execution management, resource management, definition management, data collection, tracking, and performance analysis. MOM scores these mentioned dimensions on six maturity levels (L0-L5). Due to its comprehensive questionnaire (832 questions), the authors question its usability for smaller firms with limited resources.

Leyh et al. (2017) developed a model that enables a company to classify its IT system landscape with focus on I4.0 requirements. This descriptive and prescriptive model is called the System Integration Maturity Model Industry 4.0 (SIMMI). SIMMI measures the following four dimensions using interviews: vertical integration, horizontal integration, digital product development, cross-sectional technology criteria. These dimensions are scored on five maturity levels: basic digitalization level (L1), cross-departmental digitization (L2), horizontal and vertical digitization (L3), full digitization (L4), and optimized full digitization (L5). The authors recognize the implication that the model has not yet been evaluated or properly tested. Leyh et al. (2017) claim to address this issue in future research.

Mittal et al. (2018a) reviewed four maturity models from Ganzarain and Errasti (2016); Gökalp et al. (2017); Lee et al. (2017); Scremin et al. (2018) respectively, and one maturity model from the company Rockwell Automation. Rockwell Automation Inc. is an American provider of industrial automation and information technology. The firm suggested a Connected Enterprise Maturity Model with technology as its key enabler. This descriptive and prescriptive model measures four dimensions: information infrastructure, controls and devices, networks, and security policies.

Ganzarain and Errasti (2016) proposed a three-stage maturity model towards I4.0. These stages can be interpreted as dimensions and are: envision, enable, and enact. These dimensions are scored on five maturity levels: initial (L1), managed (L2), defined (L3), transform (L4), and detailed business model (L5). This method provides guidelines to firms to identify their current stage.

Gökalp et al. (2017) developed the I4.0 maturity model. This descriptive model measures five dimensions: asset management, data governance, application management, process transformation, and organization alignment. These dimensions are scored on six maturity levels: incomplete (L0), performed (L1), managed (L2), established (L3), predictable (L4), and optimizing (L5).

Lee et al. (2017) presented the Smartness Assessment framework. This descriptive model measures four dimensions: leadership, process, system and automation, and performance. These dimensions are scored on five maturity levels: checking (L1), monitoring (L2), control (L3), optimization (L4), and autonomy (L5).

Scremin et al. (2018) developed the assessment framework named the Adoption Maturity Model (AMM). The objective of this descriptive model was to evaluate the maturity of a firm that has already started its journey towards I4.0. AMM measures 30 maturity items by interviews, divided along three dimensions: strategy, maturity, and adoption.

Mittal et al. (2018b) proposed a new Smart Manufacturing Maturity Model for small and Medium-sized Enterprises (SM^{3}E). This maturity model supports companies during their digital transformation journey and shift towards I4.0. SM^{3}E measures five dimensions: finance, people, strategy, process, and product. These dimensions are scored on five maturity levels: novice (L1), beginner (L2), learner (L3), intermediate (L4), and expert (L5).

Rauch et al. (2020) developed a maturity level-based assessment tool of I4.0 for small and medium sized enterprises (SMEs). This descriptive and prescriptive model assesses maturity on four dimensions: operations, organization, socio-culture, and technology. These dimensions are scored on five maturity levels (L1-L5). This maturity model includes weights to each different dimension, and visualizes gaps with radar diagrams. Hence, this model is perceived to be easy-to-use and to understand. However, during validation, users claimed that the model requires a great amount of time and resources to use. In addition, the model uses a static collection of I4.0 concepts. Therefore, new technologies must be added manually, and the authors argue that this might become quite cumbersome. These observations are identified as implications of the model, especially for the target group: SMEs with restricted resources.

Santos and Martinho (2019) proposed an I4.0 maturity model to plan and monitor the transformation actions towards I4.0. The proposed descriptive model has 41 variables considering five dimensions: organizational strategy, structure, and culture, workforce, smart factories, smart processes, smart products and services. These dimensions are scored by questionnaires on six levels (L0-L5).

Schumacher et al. (2016) introduced an empirically grounded maturity model to assess the I4.0 maturity of industrial enterprises in the domain of discrete manufacturing. This descriptive model was perceived easy-to-use during the validation, and is an extension of existing models and tools through its strong focus on organizational aspects. In this model, 62 items were assigned to the following nine dimensions: products, customers, operations, technology, strategy, leadership, governance, culture, and people. These dimensions were measured by questionnaires and scored on five maturity levels (L1-L5).

Schumacher et al. (2019) developed a holistic procedure model that guides manufacturing companies in their journey towards I4.0. This model is an adapted version of the model of Schumacher et al. (2016). The authors extend the model by adding a prescriptive purpose which includes elements of strategic guidance and road mapping. The industry 4.0 realization model measures eight dimensions: technology, products, customers and partners, value creation processes, data and information, corporate standards, employees, and strategy and leadership. These dimensions are scored by questionnaires on four maturity levels (L1-L4).

Sjödin et al. (2018) proposed a smart factory maturity model that measures the following three dimensions: people, process, and technology. These dimensions are scored on four maturity levels: connected technologies (L1), structured data gathering and sharing (L2), real-time process analytics and optimization (L3), and smart, predictable manufacturing (L4).

Trotta and Garengo (2019) provided a new maturity model aimed at SMEs and put a focus on human resource management (HRM). According to the authors, when 'people' or 'culture' appear in the maturity scales, they are briefly and only superficially analyzed. Therefore, not resulting in a good comprehension of the I4.0 phenomenon and its effect on employees. This model addresses this issue by measuring five dimensions using questionnaires: strategy, technology, production, products, and people. These dimensions are scored on five maturity levels (L1-L5).

Wagire et al. (2020) proposed an unique I4.0 maturity model as it empirically assesses organizational awareness. This descriptive and prescriptive model comprises of 38 maturity items, distributed over seven dimensions: people and culture, industry 4.0 awareness, organizational strategy, value chain and processes, smart manufacturing technology, products and services-oriented technology, and industry 4.0 base technology. These dimensions are measured by an extensive questionnaire, and scored on four maturity levels: outsider (L1), digital novice (L2), experienced (L3), and expert (L4). Every maturity item has different priority weights or significance levels while assessing the final maturity level.

4.6 I4.0 adoption assessment models

As mentioned in section 4.3, adoption assessment models are different in structure and purpose compared to readiness and maturity models. These assessment tools do not typically measure dimensions and assign current (adoption) levels. However, the models do provide insight in factors that influence the successful adoption of I4.0 and its enablers. The final section of Table 4.1 document the three adoption models found in the literature search.

Mittal et al. (2020) developed and evaluated a smart manufacturing (SM) adoption framework. This framework consists of four steps: identify manufacturing data available within the SME (1), readiness assessment of the SME data-hierarchy steps (2), developing SM awareness of SME leadership and staff (3), develop a SM tailored vision for the SMEs (4), and identify appropriate SM tools and practices necessary to realise the tailored SM vision (5). These steps were defined with the help of a multiple case study research approach, and should help SMEs in developing a SM adoption roadmap.

Ehie and Chilton (2020) built and tested a framework with a focus on the integration of information technology (IT) and operational technology (OT). IT/OT convergence refers to the extent to which information and operations technology are coming together to share components, functions, and staff. According to Ehie and Chilton (2020), achieving IT/OT alignment at the technical and process level is the first step towards an effective digital I4.0 business strategy. The authors concluded that IoT enablers in the form of IT infrastructure, IT governance, interoperability, and to a lesser extent, staff collaboration, positively impact IT/OT convergence, which in turn positively influences IoT adoption in manufacturing organizations.

Tripathi (2019) developed a model basted on system dynamics (SD). SD is a mathematical modelling technique to frame, understand, and discuss complex issues related to systems. This technique was used to identify factors that influence IoT adoption. The five factors communication, control and automation, efficient business processes, self-configuration, and cost savings positevely affect IoT adoption. In contrast, the following six factors: privacy risks and security risks, interoperability, reliability, poor infrastructure, and less skilled IT professionals negatively affect IoT adoption. In conclusion, the publication gives a good overview of technical, personal, and organizational factors of IoT adoption.

4.7 Conclusion

This section concludes the literature review. In total, 26 models from 21 scientific publications were analyzed. From these models, 6 models were focused on I4.0 readiness, and 20 models on I4.0 maturity. In addition, three publications introduced I4.0 adoption models. These models are different in structure, and mainly identify factors that positively and negatively influence the adoption of I4.0 technologies. In conclusion, from the generated overview of Table 4.1, the research questions can be answered as followed:

> *RQ1 What are readiness, maturity, and adoption models to assess I4.0?*

- According to Definition 4.3.1, I4.0 readiness models are evaluation tools to determine the level of preparedness of the conditions, attitudes, and resources, at all levels of a system, needed to deploy I4.0 enablers.
- According to Definition 4.3.2, I4.0 maturity models are evaluation tools to determine the level of maturity of an employed I4.0 enabler, and to provide guidance in reaching a more sophisticated maturity level of that I4.0 enabler.
- According to Definition 4.3.3, I4.0 adoption models are evaluation tools to identify determinants to successfully adopt an I4.0 enabler, and to provide a roadmap to aid in this adoption.

An overview of the reviewed I4.0 assessment models is presented in Table 4.1.

> *RQ2 Which dimensions are measured in readiness, maturity, and adoption models for I4.0?*

In total, 134 dimensions were identified from the analyzed models. These dimensions can be found in Appendix D. In the next chapter, these dimensions are further investigated and categorized.

> *RQ3 What are shortcomings or weaknesses of readiness, maturity, and adoption models for I4.0?*

Three types of recurring shortcomings were identified from the models. First, Pacchini et al. (2019); Trotta and Garengo (2019) argue that many models focus too heavily on technology. Although I4.0 is driven by new technology, it is important to realise non-technology factors are just as important, or even more crucial. Second, during the evaluation of the models of Colli et al. (2018); De Carolis et al. (2017); Rauch et al. (2020), companies claim that the assessment models are too resource-intensive. There is a challenging trade-off between the size of the measurement tool e.g. number of questions, and the associated accuracy of the model. Finally, due to the novelty of the models of Colli et al. (2018); Rauch et al. (2020); Santos and Martinho (2019); Schumacher et al. (2019); Trotta and Garengo (2019); Wagire et al. (2020), the authors claim that the models need more evaluation and case-studies to assure validity.

RQ4 What are advantages or strengths of readiness, maturity, and adoption models for I4.0?

The main strength of the assessment models lies in their purpose. It helps companies in their decision making during their I4.0 transformation. However, a few models stand out with two distinctive properties. First, the models of Jung et al. (2016); Lin et al. (2019) make use of reference frameworks. These reference models are allowed to evolve as new technologies emerge and become available. Because of this, the assessment piece of the method, by design, is kept independent of the reference model. Therefore, making the assessment tool future proof. Second, the models of Canetta et al. (2018); Rajnai and Kocsis (2018); Rauch et al. (2020); Wagire et al. (2020) make use of a weighted average score. Using this mechanism allows to prioritize dimensions based on determined weights. This could lead to more accurate results, and more valid prescriptive suggestions. However, the determination of the weights is under discussion and vastly differs between company sizes, and industries.

RQ5 How are the dimensions measured in readiness, maturity, and adoption models for I4.0?

Table 4.1 presents the used measurement method(s) for each analyzed model. In conclusion, the following measurement methods were used (ranked on frequency):

- Questionnaires
- Interviews
- Focus groups
- Workshops
- Counting measures, activity maturity scoring schemes, incidence scoring schemes

Questionnaires were used the most due to their self-assessment capability. They are relatively easy to understand and to use. The main challenge lies in determining the size of the questionnaires (as previously mentioned), and determining who fills in the questionnaire. The second measurement method is interviews. During these interviews, experts of companies are asked about different dimensions to determine a readiness or maturity level in collaboration with the interviewee. Focus groups and workshops were used by Colli et al. (2018); Lin et al. (2019) respectively, but only for complementing interviews and questionnaires. Finally, Jung et al. (2016) made use of counting measures, activity maturity scoring schemes, and incidence scoring schemes to determine an I4.0 readiness score.

Table 4.1: Overview extracted I4.0 readiness, maturity, and adoption assessment models

	Index	Model name	Author(s)/institution	Model purpose	# Dimensions	# Levels	Measurement method
Readiness	1	SMSRL	Jung et al. (2016)	Descriptive, comparative	4	n.a.	Counting measures, activity maturity scoring schemes, incidence scoring schemes
	2	I4.0 readiness model	Pacchini et al. (2019)	Descriptive, comparative	8	4 (L0-L3)	Interviews
	3	IMPULS	IMPULS Foundation	Descriptive	6	6 (L0-L5)	Questionnaires
	4	DREAMY	De Carolis et al. (2017)	Descriptive, prescriptive	4	5 (L1-L5)	Interviews
	5	SIRI	Lin et al. (2019)	Descriptive	10	6 (L0-L5)	Interviews, questionnaires, focus groups
	6	I4.0 readiness model	Akdil et al. (2018)	Descriptive	3	4 (L0-L3)	Questionnaires
Maturity	1	PwC I4.0 maturity model	PwC	Descriptive	7	4 (L1-L4)	n.a.
	2	Acatech I4.0 maturity model	acatech	Descriptive	4	6 (L1-L6)	Questionnaires
	3	Digital Maturity Model 4.0	Forrester	Descriptive	4	4 (L1-L4)	Questionnaires
	4	Digitalization Maturity Model	Canetta et al. (2018)	Descriptive, comparative	5	4 (L1-L4)	Questionnaires
	5	360DMA	Colli et al. (2019)	Descriptive	5	6 (L0-L5)	Questionnaires, workshops
	6	MOM	De Carolis et al. (2017)	Descriptive, comparative	8	6 (L0-L5)	Questionnaires
	7	SIMMI	Leyh et al. (2017)	Descriptive, prescriptive	4	5 (L1-L5)	Interviews
	8	Connected Enterprise Maturity	Rockwell Automation	Descriptive, prescriptive	4	n.a.	n.a.
	9	Three-stage maturity model	Ganzarain and Errasti (2016)	Descriptive	3	5 (L1-L5)	n.a.
	10	Smartness Assessment Framework	Lee et al. (2017)	Descriptive	4	5 (L1-L5)	n.a.
	11	I4.0 maturity model	Gökalp et al. (2017)	Descriptive	5	6 (L0-L5)	n.a.
	12	AMM	Scremin et al. (2018)	Descriptive	3	n.a.	Interviews
	13	SM^3E	Mittal et al. (2018b)	Descriptive	5	5 (L1-L5)	n.a.
	14	I4.0 maturity model	Rauch et al. (2020)	Descriptive, prescriptive	4	5 (L1-L5)	Questionnaires
	15	I4.0 maturity model	Santos and Martinho (2019)	Descriptive	5	6 (L0-L5)	Questionnaires
	16	I4.0 maturity model	Schumacher et al. (2016)	Descriptive	9	5 (L1-L5)	Questionnaires
	17	I4.0 realization model	Schumacher et al. (2019)	Descriptive, prescriptive	8	4 (L1-L4)	Questionnaires
	18	I4.0 maturity model	Sjödin et al. (2018)	Descriptive	3	4 (L1-L4)	n.a.
	19	I4.0 maturity model	Trotta and Garengo (2019)	Descriptive	5	5 (L1-L5)	Questionnaires
	20	I4.0 maturity model	Wagire et al. (2020)	Descriptive, prescriptive	7	4 (L1-L4)	Questionnaires
Adoption	1	SM adoption framework	Mittal et al. (2020)	Prescriptive	5	n.a.	n.a.
	2	IT/OT convergence model	Ehie and Chilton (2020)	Descriptive	5	n.a.	n.a.
	3	IoT adoption model	Tripathi (2019)	Descriptive	11	n.a.	n.a.

Chapter 5

Synthesis

This chapter concludes the literature study by providing data synthesis. First, the coupling of readiness and maturity assessments is discussed, followed by a new proposed structural framework to assess these aspects respectively. This proposal includes a motivation of the model its purpose, the measured dimensions, scoring mechanism, and the measurement tools. Finally, the objective of this new proposed framework is to successfully integrate the found models in a first iteration towards a standardized I4.0 assessment tool.

5.1 Discussion of coupling readiness and maturity

In section 4.3, the similarities and differences between the terms 'readiness' and 'maturity' are discussed. To summarize that discussion: readiness and maturity are relative and related (De Carolis et al., 2017), but different (Pacchini et al., 2019). This perceived difference leads to a segmentation of assessment tools in 'readiness assessment models', and 'maturity assessment models'. Hence, leading to a vast variety of different tools. However, when briefly analyzing the measured dimensions of these tools, it becomes clear that the models do not assess entirely different aspects. For example, the readiness models of Akdil et al. (2018); De Carolis et al. (2017); Jung et al. (2016); Rajnai and Kocsis (2018) and maturity models of Gökalp et al. (2017); Rauch et al. (2020); Santos and Martinho (2019); Wagire et al. (2020) all measure organizational, and technology dimensions. In addition, all mentioned models have a scoring mechanism, ranging from either level 0 or level 1 (L0, L1 respectively) to level 5 (L5). Mittal et al. (2018a) complements this observation by identifying the research gap of the disconnection between maturity models and self-assessment readiness-tools. The authors claim that there is a current disconnection, where some maturity models do not include a readiness assessment. Moreover, De Carolis et al. (2017) acknowledge that some assessment methodologies are merging. However, the authors state that there is no established approach or framework to combine these assessment tools. Furthermore, Mittal et al. (2018a) argue that a unique method is needed that allows integrating self-assessing approaches for evaluating the current level of I4.0 readiness and maturity. Therefore, this literature study aims to provide the theoretical basis of a first attempt of integrating these assessment models. The next section proposes this integrated framework, its purpose, its measured dimensions, and its general structure based on the studied literature.

5.2 Proposed I4.0 readiness/maturity assessment model

This first attempt to integrate I4.0 readiness and maturity assessment tools is based on the collected data from chapter 4. This initial proposal discusses the following aspects of the framework: its purpose, the measured dimensions, the scoring mechanism, and the measurement methods.

Therefore, it follows the same structure of Table 4.1. Finally, Table 5.3 presents an overview of this initial framework, summarizing all its discussed aspects.

5.2.1 Purpose

All the readiness and maturity models of Table 4.1 are descriptive in nature. In addition, some models are comparative, providing benchmarking capabilities. According to De Carolis et al. (2017), benchmarking can also aid in understanding where to make improvements. Hence, giving a prescriptive purpose to the model. The proposed model aims to fulfill all three purposes to make it as versatile and comprehensive as possible.

5.2.2 Dimensions

From the analyzed studies (Table 3.7), a total of 35 and 99 dimensions were identified from readiness and maturity assessment models respectively (total of *n=134*). Figure 5.1 presents a world-cloud of these dimensions. This figure was generated using open source software from KNIME (KNIME, 2020).

Figure 5.1: Word cloud of measured dimensions, *n=134*

Note that 'Technology' seems to be the most frequent recurring dimension. However, to find a more reliable pattern in the dimensions, the 134 entries must be labelled accordingly first i.e. stemming and coding. In order to integrate these dimensions, a qualitative synthesis was conducted. This integration was realized by inductive coding as proposed by Chandra et al. (2019). The first step was done by carefully reading the publications. Second, the dimensions as proposed in these publications were documented in Appendix C. Third, these dimensions were aggregated and labeled with a code. For example, the dimensions *"smart manufacturing technology"*, *"IoT"*, and *"cyber physical system"* were labeled with 'Technology', to cover all dimensions as accurate as possible on a first-level. The method of Chandra et al. (2019) continues with reviewing these first-level codes and aggregate them into even higher-level codes by combining similar codes into broader categories. However, in this dataset, the dimensions are already on a relatively high level. Therefore, no further aggregation has been conducted. This method also complements the general approach from Rajnai and Kocsis (2018), to bundle indicators into thematic groups (dimensions). The final collection of integrated dimensions with their frequency and description is presented in Table 5.1. Finally, a complete overview of the 134 dimensions and their coding is documented in Appendix D.

Table 5.1: Results of coded dimensions in order of frequency, *n=134*

Index	Dimension code	#	Description
1	Technology	32	The extent to which I4.0 technologies are implemented and used (Canetta et al., 2018; Mittal et al., 2020; Schumacher et al., 2019; Trotta and Garengo, 2019).
2	Operations	23	The extent to which processes are decentralized and make use of I4.0 paradigms e.g. agile manufacturing systems, and monitoring and decision systems (Rauch et al., 2020; Schumacher et al., 2016).
3	Strategy and Organization	23	The extent to which the strategy currently adopted by companies is related to I4.0 implementation, including the acknowledgement of an I4.0 roadmap (Schumacher et al., 2016, 2019; Trotta and Garengo, 2019; Wagire et al., 2020).
4	People	15	The extent to which people are competent and open to new I4.0 technologies, and the extent to which HRM practices support I4.0 implementation (Rauch et al., 2020; Schumacher et al., 2016; Sjödin et al., 2018; Trotta and Garengo, 2019).
5	Products and Services	14	The extent to which products are individualized and product characteristics are flexible. This also includes product tracking, management of products' lifecycle, and data driven services and product data usage (Canetta et al., 2018; Leyh et al., 2017; Mittal et al., 2018a; Schumacher et al., 2016, 2019; Trotta and Garengo, 2019).
6	Process	12	The extent to which companies support departments collaboration, machine and system integration with the help of I4.0 technologies. This includes self-optimization and self-configuration of processes of production, maintenance, and support processes (Canetta et al., 2018; Santos and Martinho, 2019; Schumacher et al., 2019; Sjödin et al., 2018; Wagire et al., 2020).
7	Integration	6	The extent to which vertical and horizontal integration is in place across the value chain (Leyh et al., 2017; Lin et al., 2019; Rajnai and Kocsis, 2018).
8	Culture	5	The extent to which the culture is open to innovation enabled by I4.0 (Santos and Martinho, 2019; Schumacher et al., 2016; Wagire et al., 2020).
9	Connectivity	3	The availability of infrastructural elements needed for data transmission inside and outside the organization (Colli et al., 2019, 2018; Lin et al., 2019).
10	Collaboration	1	The extent to which formal channels are enabled for employees to share information and work together, as well as institutional structures and systems that allow collaborative behavior (Lin et al., 2019).

In total, ten dimension codes were assigned to the identified dimensions from the literature. However, it could be quite resource-intensive to measure all these dimensions. Furthermore, dimension codes 7-10 (Table 5.1) have a relatively low frequency. Therefore, these codes may not be most suitable to include in this new standardized I4.0 assessment framework. In addition, the average number of measured dimensions from the studied I4.0 readiness and maturity models is 5.269. Moreover, Figure 5.2 depicts the frequency of models with a specific number of dimensions.

From this figure, it can be concluded that most models in the literature measure four, five, and three dimensions (from respectively eight, six, and four assessed models out of a total of 26 models). To conclude, this literature study proposes to measure five dimensions for a new I4.0 readiness/maturity assessment model. This number of dimensions is based on the average number of measured dimensions in the literature, the frequency of the number of models that assess five

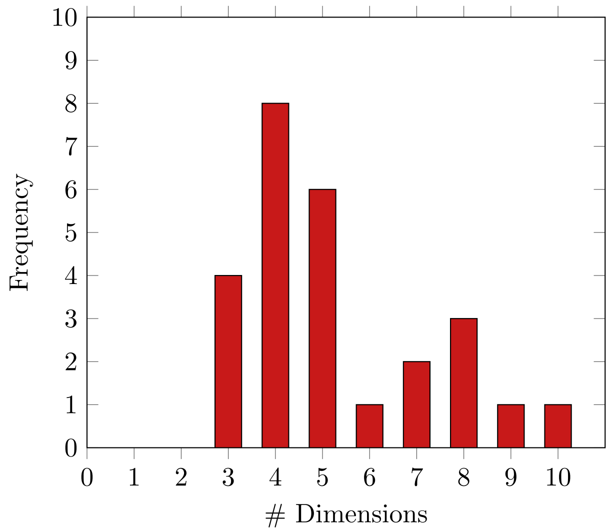

Figure 5.2: Frequency diagram of the number of identified dimensions per model

dimensions, and to limit resource intensity by restraining the number of dimensions. In addition, the type of dimensions are determined by selecting the most frequent dimensions according to the coding scheme of Table 5.1. To summarize, the proposed dimensions are:

1. Technology
2. Operations
3. Strategy and Organization
4. People
5. Products and Services

5.2.3 Scoring mechanism

In the literature, the dimensions are measured and assigned to a readiness/maturity level. These levels range from level 0 (L0) or level 1 (L1) to a maximum of level 6 (L6). In addition, the levels are often labelled with relatable names. For example, the proposed maturity model of Mittal et al. (2018b) introduces the levels novice (L1), beginner (L2), learner (L3), intermediate (L4), and expert (L5). According to this example, these levels indicate a kind of progression: where a higher level stands for a higher maturity. Note that this specific model starts from L1, and not from L0. There is an interesting observation to be made about this starting point of readiness and maturity models. Only four models of the extracted maturity models (n=20) include a L0. In contrast to the readiness models, where four out of six models include a L0. Therefore, one could argue that the L0 might be more important in readiness models. This level could roughly be translated to a zero percentage in progress towards I4.0 i.e. the enterprise is completely unprepared for their transition towards I4.0. In addition, one could argue that most maturity models already imply that the firm is already involved in some degree in I4.0. Therefore, by coupling the readiness and maturity models, this study proposes to include L0 (with focus on the readiness assessment), and L1-L5 (with focus on the maturity assessment). In this proposal, L6 is excluded since only the model of acatech includes this level. In addition, maturity scales provided by consultancy firms do not provide any details about the way the scales were created (Trotta and Garengo, 2019). Therefore, it was not possible to evaluate this level on validity.

As mentioned before, these scales provide relatable names. An overview of these names from the literature is presented in Table 5.2. The first column states the index, the second column the model name, and the following columns the different level names for L0-L6 (note that 'x' stands for an unlabeled level name). Furthermore, this table follows the same order of Table 4.1. However, the column with the author(s)/institution is excluded in this table due to limited space. After analyzing these level names, it is difficult or nearly impossible to find recurring themes or names. Moreover, in the literature, it is unclear how these names were declared. Therefore, a small research gap could be proposed to investigate these level names, and identify the best names with respect to relatability, and understandability. Hence, this proposed model is limited to labeling the levels: L1-L5.

The final aspect of the scoring mechanism is the inclusion of weights. Weights can prioritize certain dimensions to be measured. The models from Canetta et al. (2018); Rajnai and Kocsis (2018); Rauch et al. (2020); Wagire et al. (2020) all include weighting factors. However, the authors do not specify these weight factors and leave them open for interpretation. This provides a small research gap, to investigate the weighting ratios of the just proposed five dimensions. Hence, this proposed model is limited to only include weighting factors in the framework. Finally, using the weighting factors and the measurements of the dimensions, the final readiness or maturity level can be mathematically calculated for benchmarking purposes, as proposed by Canetta et al. (2018); Rajnai and Kocsis (2018); Rauch et al. (2020); Wagire et al. (2020). This final readiness/maturity score can be determined by taking the sum of the products of the weighting factors and their respective dimension scores. These dimensions scores are measured with one measurement method.

Table 5.2: Overview extracted level names I4.0 readiness and maturity assessment models

	Index	Model name	L0	L1	L2	L3	L4	L5	L6
Readiness	1	SMSRL							
	2	I4.0 readiness model	x	x	x	x			
	3	IMPULS	Intermediate	Experienced	Expert	Top performer			
	4	DREAMY		Initial	Managed	Defined	Integrated and interoperable	Digital-oriented	
	5	SIRI	x	x	x	x	x	x	
	6	I4.0 readiness model	Absence	Existence	Survived	Maturity			
Maturity	1	PwC I4.0 maturity model		Digital novice	Vertical integrator	Horizontal collaborator	Digital champion		
	2	Acatech I4.0 maturity model		Computerization	Connectivity	Visibility	Transparency	Predictive capability	Adaptability
	3	Digital Maturity Model 4.0		Skeptics	Adopters	Collaborators	Differentiators		
	4	Digitalization Maturity Model		Absence	Novice	Intermediate	Expert		
	5	360DMA	None	Basic	Transparent	Aware	Autonomous		
	6	MOM	x	x	x	x	x	x	
	7	SIMMI		Basic digitization level	Cross-departmental digitization	Horizontal and vertical digitization	Full digitization	Optimized full digitization	
	8	Connected Enterprise Maturity							
	9	Three-stage maturity model		Initial	Managed	Defined	Transform	Digital business model	
	10	Smartness Assessment Framework		Checking	Monitoring	Control	Optimization	Autonomy	
	11	I4.0 maturity model	Incomplete	Performed	Managed	Established	Predictable	Optimizing	
	12	AMM							
	13	SM^3E		Novice	Beginner	Learner	Intermediate	Expert	
	14	I4.0 maturity model		x	x	x	x	x	
	15	I4.0 maturity model	x	x	x	x	x	x	
	16	I4.0 maturity model		x	x	x	x	x	
	17	I4.0 realization model			x	x	x	x	
	18	I4.0 maturity model		Connected technologies	Structured data gathering and sharing	Real-time process analytics and optimization	Smart, predictable manufacturing		
	19	I4.0 maturity model		x	x	x	x	x	
	20	I4.0 maturity model	Outsider	Digital novice	Experienced	Expert			

5.2.4 Measurement method

In the literature, the majority of measurements are conducted by questionnaires (as can be observed from Table 4.1). These questionnaires use Likert scale questions and are perceived with good understanding of the industry (Rauch et al., 2020; Schumacher et al., 2016; Trotta and Garengo, 2019; Wagire et al., 2020). Therefore, this proposed model adopts the use of Likert scale questionnaires for the proposed dimensions. However, during the evaluation stages, the models from Colli et al. (2019); De Carolis et al. (2017); Rauch et al. (2020) are perceived as too resource-intensive. For example, the questionnaire used by De Carolis et al. (2017) contains 832 questions. However, the authors are unable to specify a number or a range of questions that fulfill the model its objective, while conforming to the available resources of a company. It can be assumed that the available resources can vary immensely between different companies. Nevertheless, when proceeding towards standardizing I4.0 assessment models, it could prove to be valuable to get a better understanding of the acceptable number of questions of these questionnaires for different company sizes. Future research is needed to address this question. This concludes the measurement method proposal of the new I4.0 readiness/maturity assessment framework. As previously mentioned, a summary of the framework is presented in Table 5.3.

Table 5.3: Proposed I4.0 readiness/maturity assessment model

Model aspect	Description
Purpose	Descriptive, prescriptive, comparative
Dimensions	1. Technology 2. Operations 3. Strategy and Organization 4. People 5. Products and Services
Measurement method	Questionnaires using Likert scale questions are used to measure the five dimensions.
Scoring mechanism	Dimensions are assigned to one of six levels (L0-L5). The final readiness/maturity score is determined by taking the weighted average of the five dimensions.

5.3 Discussion I4.0 adoption

The presented I4.0 adoption assessment models are different compared to the readiness and maturity models in structure and purpose. In this literature search, no adoption model was found that could easily be used by companies. Nevertheless, the research from Ehie and Chilton (2020); Mittal et al. (2020); Tripathi (2019) do provide insight in factors that positively and negatively affect the adoption of I4.0 technologies. Therefore, these insights could prove to be valuable during the development of the just proposed I4.0 readiness/maturity assessment tool. Specifically, the questions of the surveys could be created by assessing these important factors. In conclusion, it seems that there is no clear I4.0 adoption model in the current literature (based on this search). This could provide an interesting research gap. However, it should be noted that an actual need or desire of the industry should be identified first, before endeavouring in developing I4.0 assessment models.

5.4 Conclusion

This section concludes the Systematic Literature Review. In this study, 21 publications presenting I4.0 readiness, maturity, and adoption assessment models were thoroughly studied, compared, and reviewed in chapter 4. Subsequently, chapter 5 synthesized current assessment models to form a new framework proposal towards the standardization of these assessment models.

In this proposal, the coupling of I4.0 readiness and maturity assessments was discussed. This led to a new framework with both a descriptive, prescriptive, and comparative purpose. This framework assesses I4.0 readiness and maturity by using questionnaires measuring the dimensions: technology, operations, strategy and organization, people, and products and services. Furthermore, these dimensions are assigned to one of six levels (L0-L5), and the final readiness/maturity score is determined by taking the weighted average of the five dimensions. This framework should guide future research in creating an integrated I4.0 readiness/maturity model, providing the first steps towards a standardized I4.0 assessment model in an overpopulated landscape of different assessment tools. This model should aid companies in successfully adopting the many benefits that I4.0 may provide.

I4.0 adoption was also discussed. In this literature study, no clear and validated I4.0 adoption assessment models could be found. However, the study introduces factors that positively affect the adoption of I4.0 technologies. These insights are crucial for the development of this new proposed I4.0 readiness/maturity model.

In conclusion, this literature study proposes a blueprint for a new standardized assessment model to measure both I4.0 readiness and maturity. This blueprint is based on a careful selection of related studies, and therefore holds certain scientific validity. However, it is a mere beginning towards reaching a standardized I4.0 assessment tool. In order to successfully develop the proposed model, more research is required to obtain essential details embodying the model. Therefore, the following research gaps have been identified:

- This study provides a blueprint for a new standardized assessment tool that measures I4.0 readiness, and maturity. Future research should use this blueprint to develop such a model.
  - Naming the dimensions of I4.0 assessment models seems arbitrary. More research is required to identify labels that companies in the manufacturing industry find most relatable and understandable.
  - Different dimensions can be prioritized by using weighting factors. However, future research is needed to fully understand the distribution of weights, used in I4.0 assessment models.
  - Most I4.0 assessment models use extensive questionnaires to measure the respective dimensions. These questionnaires are perceived to be too extensive and resource-intensive during model validations. Hence, more research is required to get a better understanding of the acceptable number of questions of these questionnaires for different company sizes in the manufacturing industry.
- Future research should test, and evaluate the proposed I4.0 readiness/maturity assessment model on usability, and validity.
- In contrast to the great number of I4.0 readiness and I4.0 maturity models in the current literature, no clear I4.0 adoption models have been developed. This could provide an interesting research gap for future research.

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Appendix A

Long-list

This appendix presents the long-list as generated by the method described in chapter 3. Table A.1 contains three columns. The first column states the index (ID), the second column states the publication, and the third column states which exclusion criterion was applied.

Table A.1: Long-list with applied exclusion criteria

ID	Publication	EC
1	Agostini, L., & Nosella, A. (2019). The adoption of Industry 4.0 technologies in SMEs: results of an international study. Management Decision, 58(4), 625–643. https://doi.org/10.1108/MD-09-2018-0973	3
2	Ahmed, W., Hizam, S. M., Sentosa, I., Akter, H., Yafi, E., & Ali, J. (2020). Predicting IoT service adoption towards smart mobility in Malaysia: SEM-neural hybrid pilot study. International Journal of Advanced Computer Science and Applications, 11(1), 524–535. https://doi.org/10.14569/ijacsa.2020.0110165	4
3	AlHogail, A. (2018). Improving IoT Technology Adoption through Improving Consumer Trust. Technologies, 6(3), 64. https://doi.org/10.3390/technologies6030064	3
4	AlHogail, A., & AlShahrani, M. (2019). Building consumer trust to improve Internet of Things (IoT) technology adoption. In A. H. and M. L (Ed.), Advances in Intelligent Systems and Computing (Vol. 775, pp. 325–334). GEWERBESTRASSE 11, CHAM, CH-6330, SWITZERLAND: SPRINGER INTERNATIONAL PUBLISHING AG. https://doi.org/10.1007/978-3-319-94866-9_33	3
5	Aljowder, T., Ali, M., & Kurnia, S. (2019). Systematic literature review of the smart city maturity model. In 2019 International Conference on Innovation and Intelligence for Informatics, Computing, and Technologies, 3ICT 2019. 345 E 47TH ST, NEW YORK, NY 10017 USA: IEEE. https://doi.org/10.1109/3ICT.2019.8910321	4
6	Ammirato, S., Sofo, F., Felicetti, A. M., & Raso, C. (2019). A methodology to support the adoption of IoT innovation and its application to the Italian bank branch security context. European Journal of Innovation Management, 22(1), 146–174. https://doi.org/10.1108/EJIM-03-2018-0058	4
7	Anggrahini, D., Kurniati, N., Karningsih, P. D., Parenreng, S. M., & Syahroni, N. (2018). Readiness Assessment Towards Smart Manufacturing System for Tuna Processing Industry in Indonesia. In Kurniati, N and Dewi, RS and Dewi, DS and Hartanto, D and Arvitrida, NI and Karningsih, PD (Ed.), IOP Conference Series: Materials Science and Engineering (Vol. 337). DIRAC HOUSE, TEMPLE BACK, BRISTOL BS1 6BE, ENGLAND: IOP PUBLISHING LTD. https://doi.org/10.1088/1757-899X/337/1/012060	5
8	Arnold, C., & Voigt, K. I. (2019). Determinants of Industrial Internet of Things Adoption in German Manufacturing Companies. International Journal of Innovation and Technology Management, 16(6). https://doi.org/10.1142/S021987701950038X	-

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Table A.1 – continued from previous page

ID	Publication	EC
9	Arthanat, S., Chang, H., & Wilcox, J. (2020). Determinants of information communication and smart home automation technology adoption for aging-in-place. Journal of Enabling Technologies. https://doi.org/10.1108/JET-11-2019-0050	4
10	Asdecker, B., & Felch, V. (2018). Development of an Industry 4.0 maturity model for the delivery process in supply chains. Journal of Modelling in Management, 13(4), 840–883. https://doi.org/10.1108/JM2-03-2018-0042	4
11	Atayero, A. A., Oluwatobi, S. O., & Alege, P. O. (2015). An assessment of the Internet of Things (IoT) adoption readiness of Sub-Saharan Africa. In S. KS (Ed.), Proceedings of the 26th International Business Information Management Association Conference - Innovation Management and Sustainable Economic Competitive Advantage: From Regional Development to Global Growth, IBIMA 2015 (pp. 4238–4250). 34 E GERMANTOWN PIKE, NO. 327, NORRISTOWN, PA 19401 USA: INT BUSINESS INFORMATION MANAGEMENT ASSOC-IBIMA. https://doi.org/10.5171/2016.321563	3
12	Balsamo, D., Magno, M., Kubara, K., Lazarescu, B., & Merrett, G. V. (2019). Energy harvesting meets iot: Fuelling adoption of transient computing in embedded systems. In IEEE 5th World Forum on Internet of Things, WF-IoT 2019 - Conference Proceedings (pp. 413–417). 345 E 47TH ST, NEW YORK, NY 10017 USA: IEEE. https://doi.org/10.1109/WF-IoT.2019.8767302	4
13	Bandara, O. K. K., Tharaka, V. K., & Wickramarachchi, A. P. R. (2019). Industry 4.0 maturity assessment of the Banking Sector of Sri Lanka. In Proceedings - IEEE International Research Conference on Smart Computing and Systems Engineering, SCSE 2019 (pp. 190–195). Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.23919/SCSE.2019.8842818	4
14	Basl, J., & Doucek, P. (2018). Metamodel of indexes and maturity models for industry 4.0 readiness in enterprises. In Doucek, P and Chroust, G and Oskrdal, V (Ed.), IDIMT 2018: Strategic Modeling in Management, Economy and Society - 26th Interdisciplinary Information Management Talks (Vol. 47, pp. 33–40). KOGLSTR 14, 4020 LINZ, AUSTRIA: TRAUNER VERLAG.	3
15	Basl, J., & Doucek, P. (2019). A metamodel for evaluating enterprise readiness in the context of industry 4.0. Information (Switzerland), 10(3). https://doi.org/10.3390/info10030089	3
16	Bertolini, M., Esposito, G., Neroni, M., & Romagnoli, G. (2019). Maturity models in industrial internet: A review. Procedia Manufacturing, 39, 1854–1863. https://doi.org/10.1016/j.promfg.2020.01.253	3
17	Bibby, L., & Dehe, B. (2018). Defining and assessing industry 4.0 maturity levels–case of the defence sector. Production Planning and Control, 29(12), 1030–1043. https://doi.org/10.1080/09537287.2018.1503355	4
18	Botha, A. P. (2018). Rapidly arriving futures: Future readiness for industry 4.0. South African Journal of Industrial Engineering, 29(3 Special Edition), 148–160. https://doi.org/10.7166/29-3-2056	-
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101	Rajnai, Z., & Kocsis, I. (2018). Assessing industry 4.0 readiness of enterprises. In SAMI 2018 - IEEE 16th World Symposium on Applied Machine Intelligence and Informatics Dedicated to the Memory of Pioneer of Robotics Antal (Tony) K. Bejczy, Proceedings (Vol. 2018-February, pp. 225–230). 345 E 47TH ST, NEW YORK, NY 10017 USA: IEEE. https://doi.org/10.1109/SAMI.2018.8324844	-
102	Ramezani, J., & Nasrollahi, M. (2020). A Model to Evaluate the Organizational Readiness for Big Data Adoption. International Journal of Computers Communications & Control, 15(3). https://doi.org/10.15837/ijccc.2020.3.3874	3
103	Rampasso, I. S., Mello, S. L. M., Walker, R., Simão, V. G., Araújo, R., Chagas, J., . . . Anholon, R. (2020). An investigation of research gaps in reported skills required for Industry 4.0 readiness of Brazilian undergraduate students. Higher Education, Skills and Work-Based Learning. https://doi.org/10.1108/HESWBL-10-2019-0131	3

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Table A.1 – continued from previous page

ID	Publication	EC
104	Rauch, E., Unterhofer, M., Rojas, R. A., Gualtieri, L., Woschank, M., & Matt, D. T. (2020). A maturity level-based assessment tool to enhance the implementation of industry 4.0 in small and medium-sized enterprises. Sustainability (Switzerland), 12(9). https://doi.org/10.3390/SU12093559	-
105	Roy, A., Zalzala, A. M. S., & Kumar, A. (2016). Disruption of things: A model to facilitate adoption of IoT-based innovations by the urban poor. Procedia Engineering, 159, 199–209. https://doi.org/10.1016/j.proeng.2016.08.159	4
106	Ryan, W. G., Fenton, A., Ahmed, W., & Scarf, P. (2020). Recognizing events 4.0: the digital maturity of events. International Journal of Event and Festival Management, 11(1), 47–68. https://doi.org/10.1108/IJEFM-12-2019-0060	3
107	Sanchez, F., Monticolo, D., Bonjour, E., & Micaëlli, J.-P. (2019). Towards a Better Modelling and Assessment of Project Management Maturity in Industry 4.0. In F. Bonjour, E and Krob, D and Palladino, L and Stephan (Ed.), Complex Systems Design & Management (pp. 235–235). GEWERBESTRASSE 11, CHAM, CH-6330, SWITZERLAND: SPRINGER INTERNATIONAL PUBLISHING AG. https://doi.org/10.1007/978-3-030-04209-7_21	1
108	Santos, R. C., & Martinho, J. L. (2019). An Industry 4.0 maturity model proposal. Journal of Manufacturing Technology Management. https://doi.org/10.1108/JMTM-09-2018-0284	-
109	Santos-Neto, J. B. S. dos, & Costa, A. P. C. S. (2019). Enterprise maturity models: a systematic literature review. Enterprise Information Systems, 13(5), 719–769. https://doi.org/10.1080/17517575.2019.1575986	3
110	Sari, T., Gules, H. K., & Yigitol, B. (2020). Awareness and readiness of Industry 4.0: The case of Turkish manufacturing industry. Advances in Production Engineering & Management, 15(1), 57–68. https://doi.org/10.14743/apem2020.1.349	1
111	Satar, S. B. A., Hussin, A. R. C., & Ali, Y. S. (2018). Drivers of Internet of Things Adoption in Oil and Gas Industry. Advanced Science Letters, 24(10), 7364–7370. https://doi.org/10.1166/asl.2018.12943	4
112	Schumacher, A., Erol, S., & Sihn, W. (2016). A Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises. In Procedia CIRP (Vol. 52, pp. 161–166). Elsevier B.V. https://doi.org/10.1016/j.procir.2016.07.040	-
113	Schumacher, A., Nemeth, T., & Sihn, W. (2019). Roadmapping towards industrial digitalization based on an Industry 4.0 maturity model for manufacturing enterprises. Procedia CIRP, 79, 409–414. https://doi.org/10.1016/j.procir.2019.02.110	-
114	Sepasgozar, S. M. E., & Davis, S. (2019). Digital construction technology and job-site equipment demonstration: Modelling relationship strategies for technology adoption. Buildings, 9(7). https://doi.org/10.3390/BUILDINGS9070158	3
115	Sfondrini, N., Motta, G., & Longo, A. (2018). Public cloud adoption in multinational companies: A survey. In Proceedings - 2018 IEEE International Conference on Services Computing, SCC 2018 - Part of the 2018 IEEE World Congress on Services (pp. 177–184). 10662 LOS VAQUEROS CIRCLE, PO BOX 3014, LOS ALAMITOS, CA 90720-1264 USA: IEEE COMPUTER SOC. https://doi.org/10.1109/SCC.2018.00030	3
116	Sheen, D. P., & Yang, Y. (2018). Assessment of Readiness for Smart Manufacturing and Innovation in Korea. In 2018 IEEE Technology and Engineering Management Conference, TEMSCON 2018. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/TEMSCON.2018.8488424	5
117	Shin, J., Park, Y., & Lee, D. (2018). Who will be smart home users? An analysis of adoption and diffusion of smart homes. Technological Forecasting and Social Change, 134, 246–253. https://doi.org/10.1016/j.techfore.2018.06.029	4
118	Shrouf, F., & Miragliotta, G. (2015). Energy management based on Internet of Things: Practices and framework for adoption in production management. Journal of Cleaner Production, 100, 235–246. https://doi.org/10.1016/j.jclepro.2015.03.055	3

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ID	Publication	EC
119	Simetinger, F., & Simetinger, F. (2019). The Universal Dimensions of Industry 4.0 Maturity Models from the Business Informatics Perspective Industry 4.0 Specifics in IT Management and IT Governance View project THE UNIVERSAL DIMENSIONS OF INDUSTRY 4.0 MATURITY MODELS FROM THE BUSINESS INFORMATICS PERSPECTIVE. In J. Dvoulety, O and Lukes, M and Misar (Ed.), PROCEEDINGS OF THE 7TH INTERNATIONAL CONFERENCE INNOVATION MANAGEMENT, ENTREPRENEURSHIP AND SUSTAINABILITY (IMES 2019) (pp. 820–833). UNIV ECONOMICS, PRAGUE, W CHURCHILL SQ 4, PRAGUE 3, 130 67, CZECH REPUBLIC: OECONOMICA PUBLISHING HOUSE. Retrieved from https://www.researchgate.net/publication/334375790	1
120	Sivathanu, B. (2018). Adoption of internet of things (IOT) based wearables for healthcare of older adults – a behavioural reasoning theory (BRT) approach. Journal of Enabling Technologies, 12(4), 169–185. https://doi.org/10.1108/JET-12-2017-0048	4
121	Sivathanu, B. (2019). Adoption of industrial IoT (IIoT) in auto-component manufacturing SMEs in India. Information Resources Management Journal, 32(2), 52–75. https://doi.org/10.4018/IRMJ.2019040103	1
122	Sjödin, D. R., Parida, V., Leksell, M., & Petrovic, A. (2018). Smart Factory Implementation and Process Innovation: A Preliminary Maturity Model for Leveraging Digitalization in ManufacturingMoving to smart factories presents specific challenges that can be addressed through a structured approach focused on people, processes, and technologies. Research Technology Management, 61(5), 22–31. https://doi.org/10.1080/08956308.2018.1471277	-
123	Stentoft, J., Adsbøll Wickstrøm, K., Philipsen, K., & Haug, A. (2020). Drivers and barriers for Industry 4.0 readiness and practice: empirical evidence from small and medium-sized manufacturers. Production Planning and Control. https://doi.org/10.1080/09537287.2020.1768318	3
124	Sternad, M., Lerher, T., & Gajsek, B. (2018). Maturity Levels for Logistics 4.0 Based on Nrw'S Industry 4.0 Maturity Model. In D. Dujak (Ed.), Business Logistics in Modern Management (Vol. 18, pp. 695–708). GAJEV TRG 7, OSIJEK, 31 000, CROATIA: EKONOMSKI FAKULTET OSIJEKU-FAC ECONOMICS OSIJEK.	4
125	Stich, V., Gudergan, G., & Zeller, V. (2018). Need and Solution to Transform the Manufacturing Industry in the Age of Industry 4.0 – A Capability Maturity Index Approach. In Y. CamarinhaMatos, LM and Afsarmanesh, H and Rezgui (Ed.), IFIP Advances in Information and Communication Technology (Vol. 534, pp. 33–42). GEWERBESTRASSE 11, CHAM, CH-6330, SWITZERLAND: SPRINGER INTERNATIONAL PUBLISHING AG. https://doi.org/10.1007/978-3-319-99127-6_3	3
126	Strasser, M., Weiner, N., & Albayrak, S. (2016). A maturity framework to evaluate smart city service solutions. In C. Kyriakides, E and Kyriacou, E and Ellinas, G and Louca, S and Mavromoustakis, C and Michael, D and Vassiliou, V and Hadjichristofi, G and Georgiou, J and Panayiotou, C and Paschalidou, A and Loizou, C and Pattichis (Ed.), Proceedings of the 18th Mediterranean Electrotechnical Conference: Intelligent and Efficient Technologies and Services for the Citizen, MELECON 2016. 345 E 47TH ST, NEW YORK, NY 10017 USA: IEEE. https://doi.org/10.1109/MELCON.2016.7495461	4
127	Tortorella, G. L., Cawley Vergara, A. Mac, Garza-Reyes, J. A., & Sawhney, R. (2020). Organizational learning paths based upon industry 4.0 adoption: An empirical study with Brazilian manufacturers. International Journal of Production Economics, 219, 284–294. https://doi.org/10.1016/j.ijpe.2019.06.023	3
128	Tortorella, G. L., Giglio, R., & van Dun, D. H. (2019). Industry 4.0 adoption as a moderator of the impact of lean production practices on operational performance improvement. International Journal of Operations and Production Management, 39(6/7/8, SI), 860–886. https://doi.org/10.1108/IJOPM-01-2019-0005	3
129	Tripathi, S. (2019). System Dynamics perspective for Adoption of Internet of Things: A Conceptual Framework. In 2019 10th International Conference on Computing, Communication and Networking Technologies, ICCCNT 2019. 345 E 47TH ST, NEW YORK, NY 10017 USA: IEEE. https://doi.org/10.1109/ICCCNT45670.2019.8944664	-

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ID	Publication	EC
130	Trotta, D., & Garengo, P. (2019). Assessing Industry 4.0 Maturity: An Essential Scale for SMEs. In Proceedings of 2019 8th International Conference on Industrial Technology and Management, ICITM 2019 (pp. 69–74). 345 E 47TH ST, NEW YORK, NY 10017 USA: IEEE. https://doi.org/10.1109/ICITM.2019.8710716	-
131	Trstenjak, M., Cajner, H., & Opetuk, T. (2019). Industry 4.0 readiness factor calculation: Criteria evaluation framework. FME Transactions, 47(4), 841–845. https://doi.org/10.5937/fmet1904841T	3
132	Tsao, Y. C. (2019). A continuous approximation approach for supply network design considering radio frequency identification adoption. RAIRO - Operations Research, 53(5), 1843–1860. https://doi.org/10.1051/ro/2018112	3
133	Unterhofer, M., Rauch, E., Matt, D. T., & Santiteerakul, S. (2019). Investigation of Assessment and Maturity Stage Models for Assessing the Implementation of Industry 4.0. In IEEE International Conference on Industrial Engineering and Engineering Management (Vol. 2019-December, pp. 720–725). IEEE Computer Society. https://doi.org/10.1109/IEEM.2018.8607445	3
134	Vrchota, J., & Pech, M. (2019). Readiness of enterprises in Czech Republic to implement industry 4.0: Index of industry 4.0. Applied Sciences (Switzerland), 9(24). https://doi.org/10.3390/app9245405	3
135	Wagire, A. A., Joshi, R., Rathore, A. P. S., & Jain, R. (2020). Development of maturity model for assessing the implementation of Industry 4.0: learning from theory and practice. Production Planning and Control. https://doi.org/10.1080/09537287.2020.1744763	-
136	Wang, L., Zhang, L., Xu, C., Wu, H., Li, Y., & Sun, H. (2020). Three-Dimensional Maturity Model of Regional Power Users against the Background of the Ubiquitous Power Internet of Things. IEEE Access, 8, 20215–20223. https://doi.org/10.1109/ACCESS.2020.2965543	4
137	Wiesner, S., Gaiardelli, P., Gritti, N., & Oberti, G. (2018). Maturity models for digitalization in manufacturing - applicability for SMEs. In G. Moon, I and Lee, GM and Park, J and Kiritsis, D and VonCieminski (Ed.), IFIP Advances in Information and Communication Technology (Vol. 536, pp. 81–88). HEIDELBERGER PLATZ 3, D-14197 BERLIN, GERMANY: SPRINGER-VERLAG BERLIN. https://doi.org/10.1007/978-3-319-99707-0_11	3
138	Wunderlich, P., Veit, D. J., & Sarker, S. (2019). Adoption of sustainable technologies: A mixed-methods study of German households. MIS Quarterly: Management Information Systems, 43(2), 673–691. https://doi.org/10.25300/MISQ/2019/12112	3
139	Yan, B., Jin, Z., Liu, L., & Liu, S. (2018). Factors influencing the adoption of the internet of things in supply chains. Journal of Evolutionary Economics, 28(3), 523–545. https://doi.org/10.1007/s00191-017-0527-3	3
140	Ziaei Nafchi, M., & Mohelská, H. (2020). Organizational Culture as an Indication of Readiness to Implement Industry 4.0. Information, 11(3), 174. https://doi.org/10.3390/info11030174	3

Appendix B

JIF analysis

This appendix presents the Journal Impact Factor (JIF) analysis, conducted on the twelve scientific articles from the initial short-list as described in chapter 3. Table B.1 contains three columns. The first column states the index (ID), the second column states the publication, and the third column states the JIF. These impact factors are derived from Web of Science and represent the JIF of the release year of the respective publication. The articles with a JIF lower than 1.0 have been deducted from the final short-list.

Table B.1: Journal Impact Factor (JIF) analysis

ID	Publication	JIF
1	Arnold, C., & Voigt, K. I. (2019). Determinants of Industrial Internet of Things Adoption in German Manufacturing Companies. International Journal of Innovation and Technology Management, 16(6). https://doi.org/10.1142/S021987701950038X	0.720
2	Botha, A. P. (2018). Rapidly arriving futures: Future readiness for industry 4.0. South African Journal of Industrial Engineering, 29(3 Special Edition), 148–160. https://doi.org/10.7166/29-3-2056	0.488
3	Colli, M., Berger, U., Bockholt, M., Madsen, O., Møller, C., & Wæhrens, B. V. (2019). A maturity assessment approach for conceiving context-specific roadmaps in the Industry 4.0 era. Annual Reviews in Control, 48, 165–177. https://doi.org/10.1016/j.arcontrol.2019.06.001	4.987
4	Ehie, I. C., & Chilton, M. A. (2020). Understanding the influence of IT/OT Convergence on the adoption of Internet of Things (IoT) in manufacturing organizations: An empirical investigation. Computers in Industry, 115, 103166. https://doi.org/10.1016/j.compind.2019.103166	4.769
5	Mahmoud, M. A., & Grace, J. (2019). Towards the adoption of smart manufacturing systems: A development framework. International Journal of Advanced Computer Science and Applications, 10(7), 29–35. https://doi.org/10.14569/ijacsa.2019.0100705	0.160
6	Mittal, S., Khan, M. A., Purohit, J. K., Menon, K., Romero, D., & Wuest, T. (2020). A smart manufacturing adoption framework for SMEs. International Journal of Production Research, 58(5), 1555–1573. https://doi.org/10.1080/00207543.2019.1661540	4.577
7	Mittal, S., Khan, M. A., Romero, D., & Wuest, T. (2018, October 1). A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs). Journal of Manufacturing Systems. Elsevier B.V. https://doi.org/10.1016/j.jmsy.2018.10.005	5.105
8	Pacchini, A. P. T., Lucato, W. C., Facchini, F., & Mummolo, G. (2019). The degree of readiness for the implementation of Industry 4.0. Computers in Industry, 113, 103125. https://doi.org/10.1016/j.compind.2019.103125	3.954

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ID	Publication	JIF
9	Rauch, E., Unterhofer, M., Rojas, R. A., Gualtieri, L., Woschank, M., & Matt, D. T. (2020). A maturity level-based assessment tool to enhance the implementation of industry 4.0 in small and medium-sized enterprises. Sustainability (Switzerland), 12(9), 3559. https://doi.org/10.3390/SU12093559	2.567
10	Santos, R. C., & Martinho, J. L. (2019). An Industry 4.0 maturity model proposal. Journal of Manufacturing Technology Management. https://doi.org/10.1108/JMTM-09-2018-0284	3.385
11	Sjödin, D. R., Parida, V., Leksell, M., & Petrovic, A. (2018). Smart Factory Implementation and Process Innovation. Research-Technology Management, 61(5), 22–31. https://doi.org/10.1080/08956308.2018.1471277	2.449
12	Wagire, A. A., Joshi, R., Rathore, A. P. S., & Jain, R. (2020). Development of maturity model for assessing the implementation of Industry 4.0: learning from theory and practice. Production Planning and Control, 1–20. https://doi.org/10.1080/09537287.2020.1744763	3.605

Appendix C

Data extraction forms

This appendix presents the data extraction forms used to analyze the academic publications from the short-list (Table 3.7). The template used to extract the data is presented in Table C.1. The first column represents the associated research question as introduced in chapter 2, and the second column the answer to the question (if possible).

Table C.1: Template data extraction form

RQ	Answer
RQ1	*Name of the readiness, maturity, adoption model*
RQ2	• *Dimension 1* • *Dimension 2* ⋮ • *Dimension n*
RQ3	- *Model weakness 1* - *Model weakness 2* ⋮ - *Model weakness n*
RQ4	+ *Model strength 1* + *Model strength 2* ⋮ + *Model strength n*
RQ5	• *Measurement method 1* • *Measurement method 2* ⋮ • *Measurement method n*

The following extraction forms follow the same order as listed in Table 3.7. Note that some publications may present multiple models/frameworks. In addition, fields are left blank occasionally. In this case, no clear answer on the research question could be formulated by reading the publication.

Table C.2: An overview of a smart manufacturing system readiness assessment (Jung et al., 2016)

RQ	Answer
RQ1	Smart Manufacturing System Readiness Level (SMSRL)
RQ2	• C1: organizational maturity • C2: IT maturity • C3: performance management maturity • C4: information connectivity maturity
RQ3	- The index provides a real-numbered level, which does not lend itself readily to a definitional level.
RQ4	+ Real numbered levels can be used in quantitative analysis. + Because the SMSRL provides an indication of the current state with respect to a reference model, it allows the reference model to evolve as new technologies emerge and become available. Therefore, the assessment piece, by design, is kept independent of the reference model (future proof). + Descriptive and comparative purpose
RQ5	• Counting measure • Activity maturity scoring scheme • Incidence matrix-based similarity measure • Incidence scoring scheme

Table C.3: The degree of readiness for the implementation of Industry 4.0 (Pacchini et al., 2019)

RQ	Answer
RQ1	I4.0 readiness model
RQ2	• IoT • Big data • Cloud computing • Cyber physical system • Autonomous robot • Additive manufacturing • Augmented reality • Artificial intelligence Measured on four levels: L0, L1, L2, L3. Final degree of readiness is measured by taking the average of the sum of degrees of adoptions of the enabled technologies (mathematical approach).
RQ3	- Current model relies on eight enabling technologies, the same can be said in relation to the number and content of the perquisites. - Some readers can argue that the enabling technologies cannot have the same impact as far as I4.0 implementation is concerned (no weightiness). - The model does not include interrelationships among enabling technologies that can affect the degree of readiness. - Application only considered one manufacturing company (limited evaluation).
RQ4	+ User-friendly tool that identifies actions needed to improve the degree of readiness of companies for I4.0.
RQ5	• Semi-structured interviews

Table C.4: Assessing industry 4.0 readiness of enterprises (Rajnai and Kocsis, 2018) (model 1/4)

RQ	Answer
RQ1	PwC maturity model of Industry 4.0
RQ2	• Business • Products and services • Integration of value chain • Data analytics • Agile IT architecture • Compliance and security • Organization and culture Four maturity levels are defined in each of the dimensions: L1 (digital novice), L2 (vertical integrator), L3 (horizontal collaborator), L4 (digital champion).
RQ3	- ...
RQ4	+ Setting a qualitative assessment of the enterprise to devise an action plan.
RQ5	• ...

Table C.5: Assessing industry 4.0 readiness of enterprises (Rajnai and Kocsis, 2018) (model 2/4)

RQ	Answer
RQ1	Acatech Industry 4.0 maturity model
RQ2	• Organizational structure • Resources • Information system • Culture Six maturity levels: L1 (computerization), L2 (connectivity), L3 (visibility) , L4 (transparency), L5 (predictive capacity), L6 (adaptability).
RQ3	- ...
RQ4	+ ...
RQ5	• Questionnaire aimed at functional areas of the enterprise.

Table C.6: Assessing industry 4.0 readiness of enterprises (Rajnai and Kocsis, 2018) (model 3/4)

RQ	Answer
RQ1	Forrester digital maturity model
RQ2	• Culture • Technology • Organization • Insights Four maturity levels: L1 (skeptics), L2 (adopters), L3 (collaborators), L4 (differentiators).
RQ3	- ...
RQ4	+ ...
RQ5	• Questionnaire

Table C.7: Assessing industry 4.0 readiness of enterprises (Rajnai and Kocsis, 2018) (model 4/4)

RQ	Answer
RQ1	The industry 4.0 readiness model of the IMPULS foundation of VDMA
RQ2	• Strategy and organization • Smart factory • Smart operations • Smart products • Data-driven services • Employees These dimensions are decomposed into 18 fields. Six maturity levels: L0 (outsider), L1 (beginner), L2 (intermediate), L3 (experienced), L4 (expert), L5 (top performer).
RQ3	- ...
RQ4	+ ...
RQ5	• Questionnaire, and the output is used to calculate the readiness score as a weighted average of the readiness scores of the six dimensions.

Table C.8: Development of a Digitalization Maturity Model for the Manufacturing Sector (Canetta et al., 2018)

RQ	Answer
RQ1	Digitalization Maturity Model
RQ2	• Strategy • Processes • Technologies • Products & Services • People Four maturity levels: L1 (absence), L2 (novice), L3 (intermediate), L4 (expert).
RQ3	- No prescriptive purpose
RQ4	+ Provides both a descriptive and comparative purpose.
RQ5	• Questionnaire (36 questions over the five dimensions)

Table C.9: A maturity assessment approach for conceiving context-specific roadmaps in the Industry 4.0 era (Colli et al., 2019)

RQ	Answer
RQ1	360 Digital Maturity Assessment (360DMA)
RQ2	• Governance • Technology • Connectivity • Value creation • Competencies Six maturity stages: L0 (none), L1 (basic), L2 (transparent), L3 (aware), L4 autonomous), L5 (integrated).
RQ3	- There is a need for a large team of experts to perform the assessment process (relies heavily on qualitative analysis: therefore maybe not applicable to SMEs).
RQ4	+ Provides specific improvement recommendations via dialog with the assessed companies (qualitative data from interviews).
RQ5	• Workshops • Questionnaire (25 questions) • Expert interview workshops

Table C.10: Contextualizing the outcome of a maturity assessment for Industry 4.0 (Colli et al., 2018)

RQ	Answer
RQ1	360 Digital Maturity Assessment (360DMA)
RQ2	See Table C.9.
RQ3	See Table C.9.
RQ4	See Table C.9.
RQ5	See Table C.9.

Table C.11: Maturity Models and tools for enabling smart manufacturing systems: Comparison and reflections for future developments (De Carolis et al., 2017) (model 1/3)

RQ	Answer
RQ1	Digital Readiness Assessment MaturitY (DREAMY)
RQ2	• Process • Monitoring & Control • Technology • Organization Five maturity levels: ML1 (initial), ML2 (managed), ML3 (defined), ML4 (integrated and inter-operable), ML5 (digital-oriented).
RQ3	- ...
RQ4	+ Focus on business processes + Because of the modular structure of the model, other value-added process areas can be included. + Descriptive and prescriptive
RQ5	• Interviews (200 scoring questions) • Case-studies

Table C.12: Maturity Models and tools for enabling smart manufacturing systems: Comparison and reflections for future developments (De Carolis et al., 2017) (model 2/3)

RQ	Answer
RQ1	Smart Manufacturing Readiness Level (SMSRL)
RQ2	See Table C.2.
RQ3	See Table C.2.
RQ4	See Table C.2.
RQ5	See Table C.2.

Table C.13: Maturity Models and tools for enabling smart manufacturing systems: Comparison and reflections for future developments (De Carolis et al., 2017) (model 3/3)

RQ	Answer
RQ1	Manufacturing Operations Management (MOM) Capability Maturity Model
RQ2	• Scheduling • Dispatching • Execution management • Resource management • Definition management • Data collection • Tracking • Performance analysis Six maturity levels: L0, L1, L2, L3, L4, L5.
RQ3	- Resource heavy (832 questions) - Lacks improvement strategies based on the results.
RQ4	+ Provides a benchmark (comparative purpose)
RQ5	• Questionnaire (832 questions)

Table C.14: Assessing the IT and software landscapes of industry 4.0-enterprises: The maturity model SIMMI 4.0 (Leyh et al., 2017)

RQ	Answer
RQ1	System Integration Maturity Model Industry 4.0 (SIMMI)
RQ2	• Vertical integration • Horizontal integration • Digital product development • Cross-sectional technology criteria Five maturity stages: stage 1 (basic digitization level), stage 2 (cross-departmental digitization), stage 3 (horizontal and vertical digitization), stage 4 (full digitization), stage 5 (optimized full digitization).
RQ3	- In this publication, the model has not been evaluated or tested.
RQ4	+ Descriptive and prescriptive purpose
RQ5	• Maturity grid which can be filled in via interviews.

Table C.15: Application of SIRI for Industry 4.0 Maturity Assessment and Analysis (Lin et al., 2019)

RQ	Answer
RQ1	Smart Industry Readiness Index (SIRI)
RQ2	• Vertical integration • Horizontal integration • Integrated product lifecycle • Automation • Connectivity • Intelligence • Workforce learning & development • Leadership competency • Inter- and intra-company collaboration • Strategy & governance Six maturity levels for each dimension (L0-L5), with different naming. In L3, the dimension is implemented.
RQ3	- ...
RQ4	+ The index draws on the reference architectural model for industry 4.0 (RAMI 4.0).
RQ5	• Interviews • Questionnaire • Focus groups

Table C.16: A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs) (Mittal et al., 2018a) (model 1/6)

RQ	Answer
RQ1	Three-stage maturity model in SMEs towards Industry 4.0
RQ2	Five maturity levels: L1 (initial), L2 (managed), L3 (defined), L4 (transform), L5 (detailed business model).
RQ3	- ...
RQ4	+ ...
RQ5	• ...

Table C.17: A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs) (Mittal et al., 2018a) (model 2/6)

RQ	Answer
RQ1	Connected enterprise maturity model
RQ2	• Information infrastructure • Controls and devices • Networks • Security policies
RQ3	- ...
RQ4	+ Technology as key-enabler + Descriptive and prescriptive
RQ5	• ...

Table C.18: A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs) (Mittal et al., 2018a) (model 3/6)

RQ	Answer
RQ1	A smartness assessment framework for smart factories using analytic network process
RQ2	• Leadership • Process • System & automation • Performance Five maturity levels: L1 (checking), L2 (monitoring), L3 (control), L4 (optimization), L5 (autonomy).
RQ3	- ...
RQ4	+ ...
RQ5	• ...

Table C.19: A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs) (Mittal et al., 2018a) (model 4/6)

RQ	Answer
RQ1	Development of an assessment model for Industry 4.0: industry 4.0 maturity model
RQ2	• Asset management • Data governance • Application management • Process transformation • Organizational alignment Six maturity levels: L0 (incomplete), L1 (performed), L2 (managed), L3 (established), L4 (predictable), L5 (optimizing).
RQ3	- ...
RQ4	+ ...
RQ5	• ...

Table C.20: A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs) (Mittal et al., 2018a) (model 5/6)

RQ	Answer
RQ1	Maturity and readiness model for Industry 4.0 strategy
RQ2	• Smart products and services • Smart business processes • Strategy and organization Four maturity levels: L0 (absence), L1 (existence), L2 (survived), L3 (maturity).
RQ3	- Not prescriptive
RQ4	+ Descriptive
RQ5	• Questionnaire

Table C.21: A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs) (Mittal et al., 2018a) (model 6/6)

RQ	Answer
RQ1	Adoption Maturity Model (AMM)
RQ2	• Strategy • Maturity • Performance
RQ3	- Only evaluates the maturity stage of an enterprise that has already started its journey towards Industry 4.0.
RQ4	+ ...
RQ5	• Interviews

Table C.22: Towards a smart manufacturing maturity model for SMEs (SM^3E) (Mittal et al., 2018b)

RQ	Answer
RQ1	Smart Manufacturing Model for SMEs (SM3E)
RQ2	• Finance • People • Strategy • Process • Product Five maturity levels: L1 (novice), L2 (beginner), L3 (learner), L4 (intermediate), L5 (expert).
RQ3	- ...
RQ4	+ ...
RQ5	• ...

Table C.23: A maturity level-based assessment tool to enhance the implementation of industry 4.0 in small and medium-sized enterprises (Rauch et al., 2020)

RQ	Answer
RQ1	Maturity level-based assessment tool of Industry 4.0 for SMEs
RQ2	• Operations • Organization • Socio-culture • Technology Five maturity levels: L1-L5
RQ3	- Requires a great amount of time/resources. - Static inventory of I4.0 concepts (new technologies need to be added manually).
RQ4	+ Radar diagrams are used to visualize the gaps. + Weights are added to prioritize I4.0 concepts.
RQ5	• Questionnaire

Table C.24: An Industry 4.0 maturity model proposal (Santos and Martinho, 2019)

RQ	Answer
RQ1	Industry 4.0 maturity model proposal
RQ2	• Organizational strategy, structure, and culture • Workforce • Smart factories • Smart processes • Smart products and services Six maturity levels: L0-L5
RQ3	- Only descriptive
RQ4	+ ...
RQ5	• Questionnaire

Table C.25: Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises (Schumacher et al., 2016)

RQ	Answer
RQ1	Industry 4.0 maturity model
RQ2	• Products • Customers • Operations • Technology • Strategy • Leadership • Governance • Culture • People Five maturity levels: L1-L5
RQ3	- Only descriptive
RQ4	+ Easy-to-use self-assessment
RQ5	• Questionnaire

Table C.26: Roadmapping towards industrial digitalization based on an Industry 4.0 maturity model for manufacturing enterprises (Schumacher et al., 2019)

RQ	Answer
RQ1	Industry 4.0 realization model
RQ2	• Technology • Products • Customers and partners • Value creation processes • Data & information • Corporate standards • Employees • Strategy and leadership Four maturity levels: L1-L4
RQ3	- ...
RQ4	+ Descriptive and prescriptive, provides a roadmap for enterprises.
RQ5	• Questionnaire (65 questions)

Table C.27: Smart Factory Implementation and Process Innovation (Sjödin et al., 2018)

RQ	Answer
RQ1	Smart factory maturity model
RQ2	• People • Process • Technology Four maturity levels: L1 (connected technologies), L2 (structured data gathering and sharing), L3 (real-time process analytics and optimization), L4 (smart, predicable manufacturing).
RQ3	- ...
RQ4	+ ...
RQ5	• ...

Table C.28: Assessing Industry 4.0 Maturity: An Essential Scale for SMEs (Trotta and Garengo, 2019)

RQ	Answer
RQ1	Industry 4.0 maturity model
RQ2	• Strategy • Technology • Production • Products • People Five maturity levels: L1-L5
RQ3	- ...
RQ4	+ The crucial role played by employees and HRM in securing the successful implementation of Industry 4.0 is often neglected, but included in this model.
RQ5	• Questionnaire

Table C.29: Development of maturity model for assessing the implementation of Industry 4.0: learning from theory and practice (Wagire et al., 2020)

RQ	Answer
RQ1	Industry 4.0 maturity model
RQ2	• People and culture • Industry 4.0 awareness • Organizational strategy • Value chain and processes • Smart manufacturing technology • Product and services-oriented technology • Industry 4.0 base technology Four maturity levels: L1 (outsider), L2 (digital novice), L3 (experienced), L4 (expert).
RQ3	- Each item (38 maturity items) must be assessed, resource heavy.
RQ4	+ Descriptive, prescriptive + Includes organizational awareness + Weights per maturity dimension and weights per maturity item
RQ5	• Questionnaire

Table C.30: A smart manufacturing adoption framework for SMEs (Mittal et al., 2020)

RQ	Answer
RQ1	SM adoption framework
RQ2	• ...
RQ3	- ...
RQ4	+ ...
RQ5	• Interviews

Table C.31: Understanding the influence of IT/OT Convergence on the adoption of Internet of Things (IoT) in manufacturing organizations: An empirical investigation (Ehie and Chilton, 2020)

RQ	Answer
RQ1	IT/OT convergence adoption model
RQ2	• IT Governance • IT Infrastructure • Staff collaboration • Interoperability
RQ3	- IoT enablers that were identified may not be exhaustive.
RQ4	+ Identifies IT/OT enablers for succesful IoT adoption in manufacturing.
RQ5	• ...

Table C.32: System Dynamics perspective for Adoption of Internet of Things: A Conceptual Framework (Tripathi, 2019)

RQ	Answer
RQ1	Conceptual adoption framework of IoT using System Dynamics
RQ2	• Technical factors • Personal factors • Organizational factors
RQ3	- No clear dimensions that can be measured.
RQ4	+ Identifies technical, personal, and organizational factors (total: 11) that positively and negatively influence adoption of IoT.
RQ5	• ...

Appendix D

Inductive coding procedure

This appendix presents the inductive coding procedure as described in chapter 5. On the next few pages, Table D.1 and Table D.2 present the inductive coding results for the identified dimensions of I4.0 readiness and maturity assessment models respectively. Both tables contain five columns. The first column states the index, the second column the model name, the third column the author(s) or institution, the fourth column the identified dimensions, and the final column the associated code given to the associated dimension.

Table D.1: Inductive coding procedure of dimensions of I4.0 readiness assessment models

Index	Model name	Author(s)/institution	Identified dimension	Dimension code
1	SMSRL	Jung et al. (2016)	"Organizational"	Strategy and Organization
			"IT"	Technology
			"Performance management"	Operations
			"Information connectivity"	Connectivity
2	I4.0 readiness model	Pacchini et al. (2019)	"IoT"	Technology
			"Big data"	Technology
			"Cloud computing"	Technology
			"Cyber physical system"	Technology
			"Autonomous robot"	Technology
			"Additive manufacturing"	Technology
			"Augmented reality"	Technology
			"Artificial intelligence"	Technology
3	IMPULS	IMPULS Foundation	"Strategy and organization"	Strategy and Organization
			"Smart factory"	Technology
			"Smart operations"	Operations
			"Smart products"	Products and Services
			"Data-driven services"	Products and Services
			"Employees"	People
4	DREAMY	De Carolis et al. (2017)	"Process"	Process
			"Monitoring & Control"	Operations
			"Technology"	Technology
			"Organization"	Strategy and Organization
5	SIRI	Lin et al. (2019)	"Vertical integration"	Integration
			"Horizontal integration"	Integration
			"Integrated product lifecycle"	Integration
			"Automation"	Technology
			"Connectivity"	Connectivity
			"Intelligence"	Strategy and Organization
			"Workforce learning & development"	People
			"Leadership competency"	People
			"Inter- and intra-company collaboration"	Collaboration
			"Strategy & governance"	Strategy and Organization
6	I4.0 readiness model	Akdil et al. (2018)	"Smart products and services"	Products and Services
			"Smart business processes"	Process
			"Strategy and organization"	Strategy and Organization

Table D.2: Inductive coding procedure of dimensions of I4.0 maturity assessment models

ID	Model name	Author(s)/institution	Identified dimension	Dimension code
1	PwC I4.0 maturity model	PwC	"Business"	Strategy and Organization
			"Products and services"	Products and Services
			"Integration of value chain"	Integration
			"Data analytics"	Operations
			"Agile IT architecture"	Technology
			"Compliance and security"	Operations
			"Organization and culture"	Culture
2	Acatech I4.0 maturity model	acatech	"Organizational structure"	Strategy and Organization
			"Resources"	Products and Services
			"Information system"	Technology
			"Culture"	Culture
3	Digital Maturity Model	Forrester	"Culture"	Culture
			"Technology"	Technology
			"Organization"	Strategy and Organization
			"Insights"	Products and Services
4	Digitalization Maturity Model	Canetta et al. (2018)	"Strategy"	Strategy and Organization
			"Processes"	Process
			"Technologies"	Technology
			"Products and services"	Products and Services
			"People"	People
5	360DMA	Colli et al. (2019)	"Governance"	Strategy and Organization
			"Technology"	Technology
			"Connectivity"	Connectivity
			"Value creation"	Operations
			"Competencies"	Products and Services
6	MOM	De Carolis et al. (2017)	"Scheduling"	Operations
			"Dispatching"	Operations
			"Execution management"	Operations
			"Resource management"	Operations
			"Definition management"	Operations
			"Data collection"	Operations
			"Tracking"	Operations
			"Performance analysis"	Operations

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Table D.2 – continued from previous page

ID	Model name	Author(s)/institution	Identified dimension	Dimension code
7	SIMMI	Leyh et al. (2017)	"Vertical integration"	Integration
			"Horizontal integration"	Integration
			"Digital product development"	Products and Services
			"Cross-sectional technology criteria"	Technology
8	Connected Enterprise Maturity	Rockwell Automation	"Information infrastructure"	Technology
			"Controls and devices"	Technology
			"Networks"	Technology
			"Security policies"	Process
9	Three-stage maturity model	Ganzarain and Errasti (2016)	n.a.	n.a.
10	Smartness Assessment Framework	Lee et al. (2017)	"Leadership"	Strategy and Organization
			"Process"	Process
			"System & automation"	Technology
			"Performance"	Operations
11	I4.0 maturity model	Gökalp et al. (2017)	"Asset management"	Operations
			"Data governance"	Operations
			"Application management"	Technology
			"Process transformation"	Process
			"Organizational alignment"	Strategy and Organization
12	AMM	Scremin et al. (2018)	"Strategy"	Strategy and Organization
			"Maturity"	Process
			"Performance"	Operations
13	SM3E	Mittal et al. (2018b)	"Finance"	Strategy and Organization
			"People"	People
			"Strategy"	Strategy and Organization
			"Process"	Process
			"Product"	Products and Services
14	I4.0 maturity model	Rauch et al. (2020)	"Operations"	Operations
			"Organization"	Strategy and Organization
			"Socio-culture"	Culture
			"Technology"	Technology
15	I4.0 maturity model	Santos and Martinho (2019)	"Organizational strategy, structure, and culture"	Strategy and Organization
			"Workforce"	People
			"Smart factories"	Operations
			"Smart processes"	Process
			"Smart products and services"	Products and Services

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Table D.2 – continued from previous page

ID	Model name	Author(s)/institution	Identified dimension	Dimension code
16	I4.0 maturity model	Schumacher et al. (2016)	"Products"	Products and Services
			"Customers"	People
			"Operations"	Operations
			"Technology"	Technology
			"Strategy"	Strategy and Organization
			"Leadership"	People
			"Governance"	Operations
			"Culture"	Culture
			"People"	People
17	I4.0 realization model	Schumacher et al. (2019)	"Technology"	Technology
			"Products"	Products and Services
			"Customers and partners"	People
			"Value creation processes"	Process
			"Data & information"	Technology
			"Corporate standards"	Strategy and Organization
			"Employees"	People
			"Strategy and leadership"	Strategy and Organization
18	I4.0 maturity model	Sjödin et al. (2018)	"People"	People
			"Process"	Process
			"Technology"	Technology
19	I4.0 maturty model	Trotta and Garengo (2019)	"Strategy"	Strategy and Organization
			"Technology"	Technology
			"Production"	Operations
			"Products"	Products and Services
			"People"	People
20	I4.0 maturity model	Wagire et al. (2020)	"People and culture"	People
			"Industry 4.0 awareness"	People
			"Organizational strategy"	Strategy and Organization
			"Value chain and processes"	Process
			"Smart manufacturing technology"	Technology
			"Products and services-oriented technology"	Technology
			"Industry 4.0 base technology"	Technology