

Changeable, Agile, Reconfigurable & Virtual Production

A maturity model for assessing Industry 4.0 readiness and maturity of manufacturing enterprises

Andreas Schumacher^{a,b,*}, Selim Erol^b, Wilfried Sihm^{a,b}^aFraunhofer Austria Research GmbH, Theresianumgasse 7, 1040 Vienna, Austria^bVienna University of Technology, Institut of Management Science, Theresianumgasse 7, 1040 Vienna, Austria* Corresponding author. Tel.: +43-1-58801-33046; fax: +43-1-58801-33094; E-mail address: andreas.schumacher@fraunhofer.at

Abstract

Manufacturing enterprises are currently facing substantial challenges with regard to disruptive concepts such as the Internet of Things, Cyber Physical Systems or Cloud-based Manufacturing – also referred to as Industry 4.0. Subsequently, increasing complexity on all firm levels creates uncertainty about respective organizational and technological capabilities and adequate strategies to develop them. In this paper we propose an empirically grounded novel model and its implementation to assess the Industry 4.0 maturity of industrial enterprises in the domain of discrete manufacturing. Our main goal was to extend the dominating technology focus of recently developed models by including organizational aspects. Overall we defined 9 dimensions and assigned 62 items to them for assessing Industry 4.0 maturity. The dimensions “Products”, “Customers”, “Operations” and “Technology” have been created to assess the basic enablers. Additionally, the dimensions “Strategy”, “Leadership”, Governance, “Culture” and “People” allow for including organizational aspects into the assessment. Afterwards, the model has been transformed into a practical tool and tested in several companies whereby one case is presented in the paper. First validations of the model’s structure and content show that the model is transparent and easy to use and proved its applicability in real production environments.

© 2016 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license

[\(http://creativecommons.org/licenses/by-nc-nd/4.0/\)](http://creativecommons.org/licenses/by-nc-nd/4.0/).

Peer-review under responsibility of the scientific committee of the Changeable, Agile, Reconfigurable & Virtual Production Conference 2016

Keywords: Industry 4.0; Maturity Model; Strategic Management; Change Management

1. Introduction

Manufacturing companies around the world are facing substantial challenges due to recent environmental, societal, economic and technological developments. To meet these challenges manufacturing companies of the future will need capabilities for managing their whole value-chain in an agile and responsive manner. Companies will need virtual and physical structures that allow for close cooperation and rapid adaption along the whole lifecycle from innovation to production and distribution [1].

Current state-of-the-art in production technology can be described as mainly driven by increasing efficiency regarding manufacturing processes. However, this focus of advances in manufacturing efficiency takes place on the individual firm rather than on the whole supply chain. Advances can also be

seen on the organizational-economic level, e.g. Lean Management, on the manufacturing technology level, e.g. Laser technology, additive manufacturing, robotics [2] on the material level, e.g. semi-conductors, nano materials, carbon fibres, thin-films, biomaterials [3], on the information technology level, e.g. RFID, embedded systems. All these advances have led to significant but isolated gains in process efficiency and product quality.

Hence, for decades to come both academics and practitioners envision significant efficiency gains mainly through consequent digital integration and intelligentization [4] of manufacturing processes [5]. Accordingly, integration will need to take place on horizontal level (across all participants in the entire value-chain) and on vertical level (across all layers of automation). Fully integrated and networked factories, machines and products then will be able

to act in an intelligent and partly autonomous way that requires minimal manual interventions [6].

Recent concepts such as the Internet of Things, Industrial Internet, Cloud-based Manufacturing [7] and Smart Manufacturing address these requirements in part and are commonly subsumed by the visionary concept of a Fourth Industrial Revolution (Industry 4.0) [8]. Industry 4.0 refers to recent technological advances where the internet and supporting technologies (e.g. embedded systems) serve as a backbone to integrate physical objects, human actors, intelligent machines, production lines and processes across organizational boundaries to form a new kind of intelligent, networked and agile value chain.

It is obvious that such a far reaching vision will lead to an increased complexity of manufacturing processes on the micro and macro level [9]. Especially small- and medium sized manufacturing companies are uncertain about the financial effort required for the acquisition of such new technology and the overall impact on their business model.

Experiences from several strategic orientation workshops [10] with various companies have shown that companies have serious problems to grasp the overall idea of Industry 4.0 and particular concepts hereof. On the one hand, they are not able to relate it to their specific domain and their particular business strategy. On the other hand, they experience problems in determining their state-of-development with regard to the Industry 4.0 vision and therefore fail to identify concrete fields of action, programs and projects. To overcome growing uncertainty and dissatisfaction in manufacturing companies regarding the idea of Industry 4.0, new methods and tools are needed to provide guidance and support to align business strategies and operations.

In this paper we will describe the results of a recent research effort where we developed a maturity model and a related tool to systematically assess manufacturing companies' state-of-development in relation to the Industry 4.0 vision. Our maturity model serves both a scientific and a practical purpose. The scientific purpose aims at gaining solid data about the current state of manufacturing companies and their Industry 4.0 strategies to extract potential success factors. The practical purpose of this work aims at enabling a company to rigorously evaluate their own Industry 4.0 maturity and reflect the fitness of current strategies.

The paper is structured as follows. In section 2 we discuss existing maturity or readiness models in the relating domain and derive our research contribution. Followed by section 3 where our concepts of organizational maturity are described as well as the framework to develop the Industry 4.0 Maturity Model. In Section 4 we introduce the resulting model and details about the procedure to assess maturity. In section 5 we outline first findings from a preliminary evaluation by discussing the results of a case study conducted in a manufacturing company. Finally, in section 6 we conclude about main findings, limitations of the model and define future research.

2. Existing maturity and readiness models in relevant domains

In general, the term “maturity” refers to a “state of being complete, perfect, or ready” [11] and implies some progress in the development of a system. Accordingly, maturing systems (e.g. biological, organizational or technological) increase their capabilities over time regarding the achievement of some desirable future state. Maturity can be captured qualitatively or quantitatively in a discrete or continuous manner [12].

Maturity models are commonly used as an instrument to conceptualize and measure maturity of an organization or a process regarding some specific target state. Labelled synonymously are readiness models with the goal to capture the starting-point and allow for initializing the development process. We understand the difference between readiness and maturity in the matter that readiness assessment takes place before engaging in the maturing process whereas maturity assessment aims for capturing the as-it-is state whilst the maturing process. In the production domain recent readiness and maturity models have been proposed for example in energy and utility management [13], in eco design manufacturing [14] or lean manufacturing [15]. With regard to the domain of Industry 4.0 the following models and tools for assessing readiness or maturity have been published:

Table 1. Existing Industry 4.0 readiness and maturity models.

Model Name	Institution/ Source	Assessment Approach
IMPULS – Industrie 4.0 Readiness (2015)	VDMA, RWTH Aachen, IW Consult [16]	Assessment in 6 dimension including 18 items to indicate readiness in 5 levels; barriers for progressing to the next stage are defined as well as advice how to overcome them
Empowered and Implementation Strategy for Industry 4.0 (2016)	Lanza et al. [17]	Assessment of Industry 4.0 maturity as a quick check and part of a process model for realization; gap-analyses and toolbox for overcoming maturity-barriers are intended; no details about items and development process offered
Industry 4.0 / Digital Operations Self Assessment (2016)	PricewaterhouseCoopers [18]	Online-self assessment in 6 dimensions; focus on digital maturity in 4 levels; application as consulting tool as fee for assessment is required in 3 of the 6 dimensions; no details about items and development process offered
The Connected Enterprise Maturity Model (2014)	Rockwell Automation [19]	Maturity model as part of a five-stage approach to realize Industry 4.0; technology focused assessment in 4 dimensions; no details about items and development process offered (white paper)

I 4.0 Reifegradmodell (2015)	FH – Oberösterreich [20]	Assessment of maturity in 3 dimensions including 13 items for maturity indication; maturity is assessed in 10 levels; no details about items and development process offered (development process not finished)
------------------------------	--------------------------	-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------

We want to acknowledge that the development of the readiness model “IMPULS – Industrie 4.0 Readiness” is based on a comprehensive dataset and details about dimensions, items and the approach to assessment are offered. The model is scientifically well grounded and its structure and results explained in transparent manners. The other approaches listed in table 1 offer less details regarding the development process, structure and assessment-methodology and therefore no base for detailed comparison. Other models and tools we found do not offer any details regarding structure and content and are therefore not listed.

Our Industry 4.0 Maturity Model presented in this work aims for an extension of existing models and tools through its strong focus on organizational aspects. Moreover, we aimed for transforming the abstract concepts of smart manufacturing into items that can be measured in real production environments. Finally, we intentionally offer detailed information about the models structure and the assessment procedure to ensure transparency for the enterprises applying our tool.

3. Background and methodology

With regard to the envisioned Fourth Industrial Revolution, we understand maturity of an industrial enterprise as the state of advancement of internal and external conditions that support Industry 4.0's basic concepts such as the vertical and horizontal integration of manufacturing systems and enterprises as well as the digital integration of engineering across the entire value chain.

The framework methodology we have used to develop our model is based on Becker's step-by-step process for the development of maturity models [21] which has a strong theoretical foundation in Hevner's design science approach [22] and offers a rigorous methodology. Following Becker's procedure, a multi-methodological development approach was carried out including a systematic literature research and review, expert interviews, conceptual modelling and validations as well as testing of the new model in the field.

We carried out a development procedure that includes three distinct phases. An initial phase to create complete understanding of the domain of Industry 4.0, a core development phase to design and architect the model's structure as well as a practically applicable tool and an implementation phase to validate the resulting tool in real life application. The first steps contained the evaluation of domain complexities and a gap analysis of existing maturity models applicable to assess Industry 4.0 maturity. Semi-structured interviews conducted with practitioners and researchers assisted at determining the underlying problem and the validation of our research effort as a solution to the problem.

The experts interviewed (duration of around 60min following pre-defined open questions) supported our initial assumptions regarding the problems when implementing Industry 4.0 in practice:

- Companies perceive the concepts of Industry 4.0 as highly complex with no strategic guidance offered
- Companies lack a clear idea of Industry 4.0 resulting in uncertainty regarding benefits and outcomes
- Companies fail to assess their own capabilities in Industry 4.0 which restrains from taking any coordinated measures

In a next step we performed extensive systematic literature research in German and English literature on maturity models resulting in more than 3400 findings. At the time we carried out the literature research we found no similar model that is applicable on the domain of Industry 4.0 has been published. However, the comparison of existing models in other domains suggests a design strategy where the basic architecture of already successfully tested assessment tools serves as a starting point for designing our new model. We considered 72 works on maturity models for further analyses, as they offer relevant frameworks or practically tested assessment tools. From these works we derived concepts relevant for the structure of our model, e.g.: the maturity levels (commonly 5 levels whereby 1 is the lowest), the dimensions (maturity assessed in 4 to 16 dimensions), the mode of assessment (self-assessment or through external auditor) or the mode of representation (numerical representation commonly visualized using radar charts). With the help of concept mapping techniques, we extracted characteristics of existing maturity models and evaluated them for their applicability for our model and domain.

In phase two of the development procedure the overall design of the model, the maturity items as well as maturity levels and their characteristics were defined. Thereby, we used the official recommendations for implementing Industry 4.0 from the German Government [23] as a basis and included scientific works, studies and reports as well the experience from our orientation workshops. We defined a total of 62 maturity items that are unequally grouped into nine organizational dimensions.

Once we completed the development, the third phase contained transformation of the model into a practically usable tool and the conceptualization of an adequate media for distribution. Finally, we employed the assessment tool in two industrial enterprises to validate it for real-life application and collect feedback for further improvements.

4. Industry 4.0 Maturity Model

In order to facilitate different analyses of Industry 4.0 maturity, the proposed model includes a total of 62 maturity items which are grouped into nine company dimensions. Table 2 provides an overview on the dimensions together with some exemplary items to support understanding.

Table 2. Dimensions and maturity items of Industry 4.0 Maturity Model.

Dimension	Exemplary maturity item
Strategy	Implementation I40 roadmap, Available resources for realization, Adaption of business models, ...
Leadership	Willingness of leaders, Management competences and methods, Existence of central coordination for I40, ...
Customers	Utilization of customer data, Digitalization of sales/services, Customer's Digital media competence, ...
Products	Individualization of products, Digitalization of products, Product integration into other systems, ...
Operations	Decentralization of processes, Modelling and simulation, Interdisciplinary, interdepartmental collaboration, ...
Culture	Knowledge sharing, Open-innovation and cross company collaboration, Value of ICT in company, ...
People	ICT competences of employees, openness of employees to new technology, autonomy of employees, ...
Governance	Labour regulations for I40, Suitability of technological standards, Protection of intellectual property, ...
Technology	Existence of modern ICT, Utilization of mobile devices, Utilization of machine-to-machine communication, ...

I40...Industry 4.0, ICT...Information and Comm. Technology

The evolution path each item undergoes five maturity levels where level 1 describes a complete lack of attributes supporting the concepts of Industry 4.0 and level 5 represents the state-of-the-art of required attributes. Measuring, determining and representing the enterprise's maturity follows a three-step procedure (Figure 1) which we integrated in an easy-to-handle, software-supported tool.

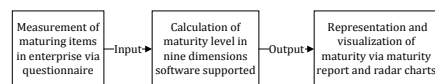


Fig. 1. Three step procedure to assess Industry4.0 maturity.

Evaluation of maturity through the maturity items within an enterprise is conducted by using a standardized questionnaire consisting of one closed-ended question per item. Each question requires an answer to a Likert-scale reaching from 1- "not distinct" to 5- "very distinct". For example, for the item "Implementation of an Industry 4.0 roadmap" in the dimension "Strategy" the question reads as shown in Table 3.

Table 3. Exemplary question to measure a maturity item.

External Question	1	2	3	4	5
Do you use a road map for the planning of Industry 4.0 activities in your enterprise?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

1...Not implemented, 5...Fully implemented

It is important to stress that the questionnaire can only be answered properly, if all respondents have a basic understanding of the concepts of Industry 4.0. External consulting or group sessions can therefore increase the

questionnaire's representability and the maturity model's accuracy. Responses to the questionnaire then serve as data-input for the software tool to calculate and represent the maturity level.

From the expert interviews we found that not all items seem to have the same importance for developing towards a mature enterprise in the sense of Industry 4.0. For example, in the dimension "Technology" the "existence of modern Information and Communication Technology (ICT)" might have a different contribution to Industry 4.0 maturity than the item "utilization of mobile devices". Therefore, expert ratings were included into the development procedure to find out the item's maturity-contribution on the one hand, and to validate the maturity item's practical meaningfulness on the other hand.

E-mail based distribution of 123 questionnaires to practitioners and researchers resulted in 23 responses. Practical importance of each maturity items was rated on a Likert-scale reaching from "not important" (rating = 1) to "very important" (rating = 4). For example, the item "Existence of modern Information and Communication Technology (ICT)" was rated with an average importance of 3.5 out of 4 whereas "utilization of mobile devices" was rated with 3.2. The overall-average of the 23 ratings for 62 items is 3.2 out of 4 which supports the meaningfulness of the model's content.

In a next step the maturity level (M_D) of each dimension results from calculating the weighted average of all maturity items (M_{Dii}) within its related dimension. The weighting-factor (g_{Dii}) equals the average importance rating from all 23 experts for each item. The maturity level is calculated using the following Formula:

$$M_D = \frac{\sum_{i=1}^n M_{Dii} * g_{Dii}}{\sum_{i=1}^n g_{Dii}}$$

M ...Maturity
 D ...Dimension
 i ...Item
 g ...Weighting Factor
 n ...Number of Maturity Item

As maturity models tend to fail if they are too complex thus practical not applicable, we adjusted the level of detail and mode of representation to practical needs of industrial companies. Therefore, we transformed our model into an easy-to-use assessment tool that can be used by companies to self-assess their Industry 4.0 maturity. After receiving responses to the questionnaire (e.g. questionnaire integrated into a webpage), the answers are processed in software supported manners and the results are automatically calculated and summarized in a compact maturity report consisting of eleven pages. The first pages of the report contain the maturity dashboard depicting all maturity levels in nine dimensions at-a-glance, followed by determinations and definitions of the maturity levels and their characteristics. Finally, the detailed results of the items in the nine dimensions are presented and serve as the bases for strategic decisions and the definition of specific projects and programs. In order to evaluate the content and structure of our model, as well as for testing practical usability of the assessment tool, we conducted two case studies in industrial enterprises. The results of one case-study are presented in the next chapter.

5. Case-study in Industrial Enterprise

In the following, results obtained from a case-study with an Austrian manufacturing enterprise with around 400 employees which designs and manufactures aerospace components and test equipment are presented. To ensure accuracy of results, we have chosen an organization that already is engaged in Industry 4.0 and therefore possesses required basic knowledge and understanding about its basic concepts.

The company received a questionnaire per e-mail to allow for reflected assessment of their internal situation on their own time. Although self-assessment of the maturity items is a valid method and easy to conduct, we are aware that most companies at the time do not possess the required knowledge about Industry 4.0 to self-assess the maturity of their own company. Following the second phase of the assessment procedure (see Figure 1), the response then was inserted into the software tool to calculate the maturity levels and to create the maturity report. In Figure 2 the maturity level in nine dimensions is visualized. A radar chart is used to depict the overall result at-a-glance.

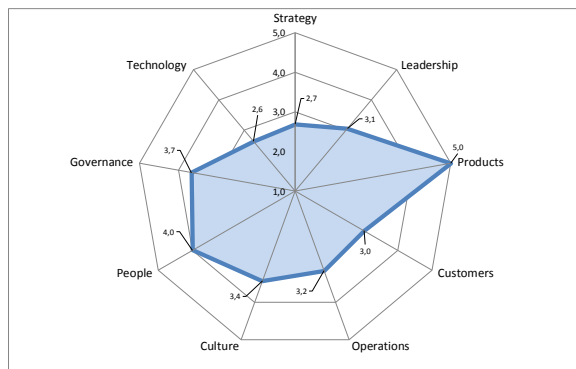


Figure 2: Radar chart visualizing Industry 4.0 maturity in nine dimensions.

To increase understanding about the model's systemic, the assessment and calculation of the dimension Nr. 1 named "Strategy" is presented in detail. The company self-assessed the six contained maturity items with maturities (M_{DII}) between 1 and 5 (see Figure 3):

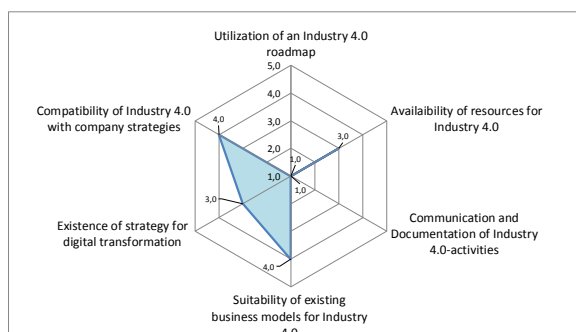


Figure 3: Detailed results for dimension Strategy.

M_{111} (Utilization of an I4.0 roadmap) = 1; (g_{111}) = 3,2
 M_{112} (Availability of resources) = 3; (g_{112}) = 3,5
 M_{113} (Comm. and Docum. of I40-activities) = 1; (g_{113}) = 3,0
 M_{114} (Suitability of business models) = 4; (g_{114}) = 2,9
 M_{115} (Strategy for digital transformation) = 3; (g_{115}) = 3,4
 M_{116} (Alignment of I40 with comp.-vision) = 4; (g_{114}) = 3,4

The relating weighting factors (g_{DII}) are also presented in the respective line of the item. Using the formula presented earlier, the maturity of the dimension "Strategy" (M_1) is now calculated resulting in an maturity-level of 2,7 out of 5.

$$M_1 = \frac{\sum_{i=1}^n M_{11i} \cdot g_{11i}}{\sum_{i=1}^n g_{11i}} = \frac{1 \cdot 3,1 + 3 \cdot 3,5 + 1 \cdot 3,0 + 4 \cdot 2,9 + 3 \cdot 3,4 + 4 \cdot 3,4}{3,1 + 3,5 + 3,0 + 2,9 + 3,4 + 3,4} = 2,7$$

The level 2.7 out of 5 is the lowest rating of all nine dimensions. It is caused mainly by the missing "utilization of an Industry 4.0 roadmap" as well as missing "communication and documentation of Industry 4.0 activities".

The seemingly high maturity level in the dimension "Products" (see Figure 2) is justifiable, as the manufactured aerospace components naturally show highly mature characteristics in regard to Industry 4.0. For example, measured maturity items in this dimension were (among others) "the possibility to integrate products into other systems", "the autonomy of products", the "flexibility of product characteristics" or "the possibility to digitalize products". It is plausible that components for the application in aerospace possess product characteristics that lead to a high rating of these maturity items. The high maturity levels in other dimensions seem accurate as well, as the chosen company is considered an early adaptor of the concepts of Industry 4.0 by several technical journals in Austria.

To enable assessment in five levels comprehensive knowledge about the potential of Industry 4.0 regarding all items is required. Therefore, either the individuals within the company possess or gain enough knowledge, or an external auditor is invited to support critical assessment. An effective approach to support reflected assessment of the company's own situation is to present advanced industry cases in the respective dimension (benchmarking).

We collected feedback from the assessed enterprise regarding clarity of the questionnaire, transparency and consistency of the tool and understandability of the modes of representation which was positive throughout. Analysis of the applied assessment procedure in the research team led to the identification of necessary improvements and potential further developments which will be discussed in the next section.

6. Conclusion

The research work presented here aimed for the development of a maturity model and a related tool for assessing the Industry 4.0 maturity of manufacturing enterprises. The model has been developed using a multi-methodological approach including a systematic literature review, conceptual modelling and qualitative and quantitative methods for empirical validation.

In contrast to other approaches the major contribution of this research effort is the inclusion of various organizational aspects resulting in a more comprehensive model. However,

the transformation of the model in a handy software tool also enabled its application in practice. First experiences from the field show that manufacturing companies are able to use the results of their self-assessment as a solid point of reference for further strategic measures.

From a scientific point of view, we developed a conceptual model of maturity for Industry 4.0. This conceptual model allows us to collect data on the state-of-development of manufacturing companies across different industries and to identify additional success factors for effective Industry 4.0 strategies.

Currently our model targets manufacturing companies that are producing physical goods in-house with their own manufacturing machinery, have a determined customer group (B2B or B2C) and have distinct structures (possibility to analyse processes). These constraints result from the defined maturity dimensions and maturity items as the calculation-mechanism requires responses to each item and N/A-answers are not allowed.

Future research activities will mainly aim at a method to identify company-specific target states, improved accuracy of the maturity items as well as defining strategic steps to reach the indented maturity levels. Furthermore, road maps to improve maturity of specific items and related dimensions will be developed to allow for determining strategic programs and projects. Based on the findings of this generic maturity model, a more domain specific model for the assessment of Industry 4.0 maturity in automotive manufacturing companies is planned.

On a final note, the maturity model is not intended as an easy route towards attaining Industry 4.0 maturity. However, our maturity model can assist with the difficult task of reflecting on the current capabilities regarding Industry 4.0 and the subsequent decision on respective strategies and action plans.

References

- [1] David M. Gligor and Mary C. Holcomb, "Understanding the role of logistics capabilities in achieving supply chain agility: a systematic literature review," *Supp Chain Mngmnt*, vol. 17, no. 4, pp. 438–453, Jun. 2012.
- [2] O. de Weck, D. Reed, S. Sarma, and M. Schmidt, "Trends in Advanced Manufacturing Technology Research," MIT, 2013.
- [3] J. Nukeaw and W. Pecharpa, *Advances in Material Science and Technology*, vol. 802, TTP, 2013.
- [4] J. Zhou, "Digitalization and intelligentization of manufacturing industry," *Adv. Manuf.*, vol. 1, no. 1, pp. 1–7, Mar. 2013.
- [5] G. Lanza, B. Haefner, and A. Kraemer, "Optimization of selective assembly and adaptive manufacturing by means of cyber-physical system based matching," *CIRP Annals - Manufacturing Technology*, vol. 64, no. 1, pp. 399–402, 2015.
- [6] L. Monostori, "Cyber-physical Production Systems: Roots, Expectations and R&D Challenges," *Procedia CIRP*, vol. 17, pp. 9–13, 2014.
- [7] R. Gao, L. Wang, R. Teti, D. Dornfeld, S. Kumara, M. Mori, and M. Helu, "Cloud-enabled prognosis for manufacturing," *CIRP Annals - Manufacturing Technology*, vol. 64, no. 2, pp. 749–772, 2015.
- [8] R. Berger, "INDUSTRY 4.0 – The new industrial revolution," www.rolandberger.com, 03-Jun-2014. [Accessed: 21-Dec-2015].
- [9] G. Schuh, T. Potente, R. Varandani, and T. Schmitz, "Global Footprint Design based on genetic algorithms – An 'Industry 4.0' perspective," *CIRP Annals - Manuf. Technology*, vol. 63, no. 1, pp. 433–436, 2014.
- [10] S. Erol, A. Schumacher, and W. Sihn, "Strategic guidance towards Industry 4.0 – a three-stage process model," in *Proc. of International Conference on Competitive Manufacturing 2016 (COMA16)*, Stellenbosch, South Africa.
- [11] J. A. Simpson, E. S. C. Weiner, and Oxford University Press, Eds., *The Oxford English dictionary*, 2nd ed. Oxford: Oxford; New York: Clarendon Press; Oxford University Press, 1989.
- [12] M. Kohlegger, R. Maier, and S. Thalmann, "Understanding Maturity Models Results of a structured Content Analysis," presented at the I-KNOW '09 and I-SEMANTICS '09, Graz, Austria, 2009.
- [13] E. W. . Ngai, D. C. K. Chau, J. K. L. Poon, and C. K. M. To, "Energy and utility management maturity model for sustainable manufacturing process," *International Journal of Production Economics*, vol. 146, no. 2, pp. 453–464, Dec. 2013.
- [14] D. C. A. Pigosso, H. Rozenfeld, and T. C. McAlloone, "Ecodesign maturity model: a management framework to support ecodesign implementation into manufacturing companies," *Journal of Cleaner Production*, vol. 59, pp. 160–173, Nov. 2013.
- [15] M. A. Maasouman and K. Demirli, "Assessment of Lean Maturity Level in Manufacturing Cells," *IFAC-PapersOnLine*, vol. 48, no. 3, pp. 1876–1881, 2015.
- [16] K. Lichtblau, V. Stich, R. Bertenrath, M. Blum, M. Bleider, A. Millack, K. Schmitt, E. Schmitz, and M. Schröter, "IMPULS - Industrie 4.0-Readiness," *Impuls-Stiftung des VDMA, Aachen-Köln*, 2015.
- [17] G. Lanza, P. Nyhuis, S. M. Ansari, T. Kuprat, and C. Liebrecht, "Befähigungs- und Einführungsstrategien für Industrie 4.0," *Karlsruhe / Hannover*, 01-02/2016.
- [18] PricewaterhouseCoopers, "The Industry 4.0 / Digital Operations Self Assessment," 2016.
- [19] Rockwell Automation, "The Connected Enterprise Maturity Model," Rockwell Automation.
- [20] FH - Oberösterreich, "I 4.0 Reifegradmodell," n.d.
- [21] J. Becker, R. Knackstedt, and J. Pöppelbuß, "Developing Maturity Models for IT Management: A Procedure Model and its Application," *Business & Information Systems Engineering*, vol. 1, no. 3, pp. 213–222, Jun. 2009.
- [22] A. R. Hevner, T. M. Salvatore, J. Park, and S. Ram, "Design Science in Information Systems Research," *MIS Research Center*, pp. 75 – 105, 2004.
- [23] H. Kagermann, W. Wahlster, and J. Helbig, "Deutschlands Zukunft als Produktionsstandort sichern. Umsetzungsempfehlungen für das Zukunftsprojekt Industrie 4.0," *DFKI und Deutsche Post*, 2013.