Life Cycle-Oriented Evaluation of Cyber-Physical Systems

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Abstract: Cyber-physical systems as technical enabler of “Industrie 4.0” (I4.0) have been discussed in many published papers. The application of I4.0-technologies allows for an intelligent interconnection between product development, logistics, customers and production. As a result, it is expected that the implementation of I4.0-technologies contributes to the protection of economic wealth of companies and society. This trend enables innovative processes and products right up to new business models. Nevertheless, companies often hesitate to invest in I4.0-solutions. The uncertainty of the benefit of using I4.0 is one reason making an economic consideration of I4.0-solutions necessary. Therefore, a structured analysis and evaluation of I4.0-solutions in form of CPS is the topic of this paper. Firstly, the evaluation requirements are described. One main requirement is the life cycle-oriented analysis of CPS, because not only the implementation costs and expenditures are important, but also the prospective costs and benefits of the application of CPS. Afterwards, a decision theory-based procedure model is suggested to handle the complexity of a life cycle-oriented evaluation. Within the description of the steps of the procedure model, characteristics and challenges regarding the evaluation of CPS are discussed. Additionally, instruments and methods, which support the evaluation of CPS, are presented.

1 INTRODUCTION

The implementation of cyber-physical systems (CPS), especially in value creation processes, has become an often discussed topic for companies, since the “Industrie 4.0” (I4.0)-development arised. I4.0 is a term resulting from a project initiated by the German government with the aim of protecting Germany as competitive manufacturing base (Sendler, 2013). The main objective of I4.0 was considered to be the interconnection via internet, which leads to a merger of the physical and virtual world. The CPS are the technical enabler for this connection (Kagermann, 2014). The implementation of I4.0-solutions by means of CPS enables new products, processes, business models and possibilites to manage the value chain processes with new ideas to organize the production (Kagermann, Wahlster, Helbig, 2013).

The technical opportunities of the application of I4.0/CPS have been discussed in many academic papers. Nevertheless, many companies are hesitating to invest in these solutions because of the fear of high implementation costs and the uncertain benefit. Thus, an economic consideration of I4.0 is necessary as well. Some studies have been published discussing the economic impact of I4.0-solutions, e. g. Obermaier et al. conducted a process- and potential analysis for an ex-ante assessment of investments in I4.0 (Obermaier, et al, 2015). An ongoing research project is examining this economic issue for the intralogistics (IPRI, 2017). In other papers economic influences of I4.0 are investigated as well (for an overview see Braccini and Margherita, 2019), but mostly for special purposes like the design and examination of the productivity of a warehouse management system for smart logistics (Lee, et al, 2017).

The model that is presented in this paper has an universal character, it is not developed for a special branch or scope. When examining the economic impact of the application of I4.0-solutions, it is not sufficient to analyse only the acquisition costs at the beginning. Also the follow-up costs, e. g. for maintenance and recycling, have to be analysed. Additionally, the benefits of the usage of I4.0-solutions by means of CPS have to be considered. Thus, a life cycle-oriented analysis is essential.

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Within this analysis, various challenges like the complexity of CPS or the uncertainties, especially for input data and the expected benefit, exist. Therefore, a set of evaluation tools is necessary. Thus, the objective of this paper is to present the draft of such a one. A life cycle-oriented analysis is conducted by e. g. Thiede, who presents the Life Cycle Assessment (LCA) as a method to evaluate the environmental sustainability of cyber-physical production systems – but without considering the economic perspective (Thiede, 2018).

The following paper is divided into four sections. After the introduction, the terms I4.0 and CPS are explained and the necessity of a life cycle-oriented evaluation of CPS is justified in more detail. Afterwards, model requirements are posed and finally, a general structure for a procedure model for a life cycle-oriented evaluation of CPS with suggestions for single evaluation instruments and methods that can be used within it, is presented as a basis for following studies. The procedure model is generally applicable for evaluating all dimensions of sustainability – the economic, the ecological and the social one, with the possibility to include existing approaches like LCA for CPS. However, this paper mainly focuses on the economic evaluation considering technical aspects as a basis.

2 CYBER-PHYSICAL SYSTEMS

2.1 Cyber-Physical Systems as Enabler of Industrie 4.0

CPS are the technical basis of I4.0-solutions, which include the connection of the production with modern information and communication technology on the basis of internet technologies. Beyond the technical controllability of more flexible production and supplier industries a profound economical change is possible. A shift of the classical customer-supplier-relation is expected, as the traditional supply chains are broken up. Different areas of industry, e. g. machinery and plant engineering, have to be enabled to develop new products and services as well as business models with the help of digital technologies (Drossel, et al, 2018).

For I4.0, no homogeneous definition exist. Therefore, different interpretations of the term were compared and the following definition was developed (based on an analysis of different definitions for I4.0): I4.0 is the utilization of the Internet of Everything in the production domain. On the basis of real-time available intelligent data, elements like humans, things, and services are linked and exchange information. The crosslinking in form of integration of IT-systems occurs internet-based – in vertical as well as in horizontal direction. The crosslinking takes place within companies, but also cross-company and leads to a merger of the physical and virtual world. CPS technically enable this (based e. g. on Roy, 2017).

2.2 Cyber-Physical Systems and Their Elements

As mentioned in chapter 2.1, CPS act as technical enabler of I4.0. Thus, they form the technical base for the realization of the visions and ideas within I4.0. For CPS, heterogeneous definitions do exist as well. In Broy`s definition different aspects regarding the functions and components of CPS are included. He explains that the objective of CPS is the connection of embedded systems with help of world-wide networks. This enables a direct connection and back coupling between the digital and the physical world. This interaction of embedded systems, based on software systems and interfaces, creates new system-functionalities (Broy, 2010).

Beyond the connection between the physical and digital world as well as the enabling of new system functionalities, the following characteristics are essential for a CPS. Access through networks needs to be transportable and transregional; additionally, time requirements exist. More characteristics are the existence of sensors and actuators and the connection within the systems and between different systems. CPS should be applicable within difficult physical environments and for long-time operations as well (Broy, 2010).

A possible visualization of the structure of CPS is presented below.

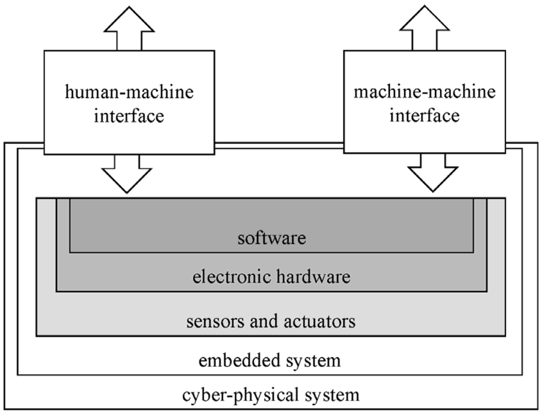

Figure 1: Structure of a CPS (based on Broy, 2010, Siepmann, 2016).

The general structure of the CPS shows that different elements encounter each other. This leads to technical, but also economic challenges (Broy, 2010).

2.3 Life Cycle-Oriented Analysis of Cyber-Physical Systems

As shown in chapter 2.2, CPS consist of various elements, e. g. the physical system and the included software. While a machine can be used over some years, software life cycles are much shorter, sometimes only last some weeks (Drossel, et al, 2018).

To show the life cycles of the elements, life cycle concepts provide support options. The aim of life cycle concepts is to identify specific phases of a life cycle and to visualize the time references of processes (Herrmann, 2010). The considered objects of life cycle models vary, e. g. organisations, technologies or products can be in focus (e. g. Höft, 1992). A lot of models that describe life cycles do exist.

One possibility to outline a life cycle is the system life cycle referring to complex systems (Wildemann, 1982). In general terms, a system is a number of elements which coact with each other to serve a special purpose (e. g. Schenk, Wirth, 2004). The life cycle phases of the system life cycle model are the initiation phase, the planning phase, the realisation phase, the use phase and the decommissioning phase (more details about the phases: e. g. in Wildemann, 1982). Normally the phases are not strictly separated, often they are characterized by an iterative and parallel sequence (Wildemann, 1982).

As the characteristics of CPS in chapter 2.2 show, CPS are systems that consist of different elements. The system life cycle is an option to model, analyse, evaluate and design the life cycle of a CPS and its elements. The elements have own life cycles, too. These heterogeneous life cycles enhance the complexity of analysing CPS. Hence, a structured analysis of CPS including the life cycles of the different elements and their costs and benefits is necessary.

3 MODEL REQUIREMENTS FOR A LIFE CYCLE-ORIENTED EVALUATION OF CYBER-PHYSICAL SYSTEMS

For the implementation of evaluations in general as well as for the realisation of life cycle-oriented evaluations various requirements have to be met. The requirements consist of diverse criteria which should be adhered to enable a problem adequate evaluation and assessment (Meynerts, 2017).

Models in general have to meet formal requirements, e g. applicability/profitability, rationality, acceptance, and closeness to reality (e. g. Meynerts, 2017; Schmidt, 2014). To meet the demand of applicability/profitability, the level of complexity needs to be as low as possible. Thus, support in form of IT-systems can be used to reach an appropriate level between benefits and costs of model building and usage (Faßbender-Wynands, 2001). The rationality is a very important requirement, as the model needs to have the capability to enable the decision maker to select the best and rational solution. To examine the rationality, the guidance of the normative decision theory is advisable (Schmidt, 2014). Additionally, the model has to be structured as simple as possible, so that it can be applied without a lot of background knowledge. Thus, the acceptance of the users can be enhanced (Meynerts, 2017). Nevertheless, the contents of the model have to show closeness to reality to support a well-founded and rational decision-making (Schmidt, 2015).

Beside the general model requirements the specialities of a life cycle-oriented evaluation have to be noted. The key task of a life cycle-oriented evaluation is to model the life cycle with its phases, activities and the resulting monetary consequences. Therefore, life cycle models (as mentioned in chapter 2.3) have to be considered as a basis for identifying and analysing decision interdependences and problem formulations (Kemminer, 1999), because not only the acquisition costs, but also the follow-up costs as well as the arising benefit should be included for decision-making. In this context, the considered objects and their costs have to be broken down into their components (Meynerts, 2017, Kemminer, 1999). Furthermore, forecast models should be included to estimate the costs and benefits over the complete life cycle and to involve uncertainties (e. g. Dhillon, 1989). Finally, appropriate calculation methods for a determination of the life cycle-oriented success have to be chosen (e. g. Riezler, 1996).

Beside the formal and the life cycle-specific requirements, the characteristics of CPS have to be considered within the evaluation model. Especially the different kinds of elements a CPS consists of should be investigated separately, as mentioned regarding the life cycle-oriented evaluation, too. This comes along with heterogeneous life cycles, which implicate different lifetimes of the elements.

For the analysis of the life cycle of a CPS and its elements, a structured approach is necessary.

Therefore, a procedure model is recommended to enable a transparent and significant evaluation of CPS (e. g. Faßbender-Wynands, 2001).

4 PROCEDURE MODEL FOR A LIFE CYCLE-ORIENTED EVALUATION OF CYBER-PHYSICAL SYSTEMS

Procedure models are models that describe procedures of special projects or processes in an idealising and abstracting way (e. g. Hesse, et al, 1992).

The procedure model should take into account the requirements mentioned in chapter 3. Therefore, the theory of decision-making can be used as a basis. The basic model of decision theory consists of different elements: objectives and preferential relations, alternatives like actions, states of environment and result functions (for more details about decision theory see Sieben and Schildbach, 1994).

The procedure model suggested in the following is appropriate for the structuring of decision problems and the various activities and instruments for the evaluation of CPS. It is based on preliminary studies (e. g. Götze, et al, 2010; Weber, 2013) as well as engineering approaches. The model enables the evaluation of product- and process-based action alternatives and consists of several linked levels. To handle the variety of possible configurations and influencing variables in a structured way, the evaluation task can be divided into different parts.

This facilitates the detailed analysis of evaluation tasks on subordinated levels (e. g. the evaluation of software components within the CPS). The obtained values can be merged within the top level to enable the evaluation of the different alternatives. The determination of the steps of the procedure model follows the differentiation of the elements of decision models according to the basic model of decision theory. The majority of the steps refers to one of the elements of this basic model (Götze, et al, 2014).

Figure 2 shows the top level of the procedure model. Additionally, it is shown, how the evaluation task can be divided into sub tasks. Within the step *S0: Determination of goal(s) and scope of study* the concern and conditions of the study are determined closer (Ferry, Flanagan, 1991). Thus, the objective of the analysis has to be defined. In the light of CPS, it can be the development and choice of I4.0-solutions which have the lowest negative monetary impact or the highest economic success along their life cycle. Beside the economic ones, also other objectives, e. g. ecological ones, are possible, too. The superior

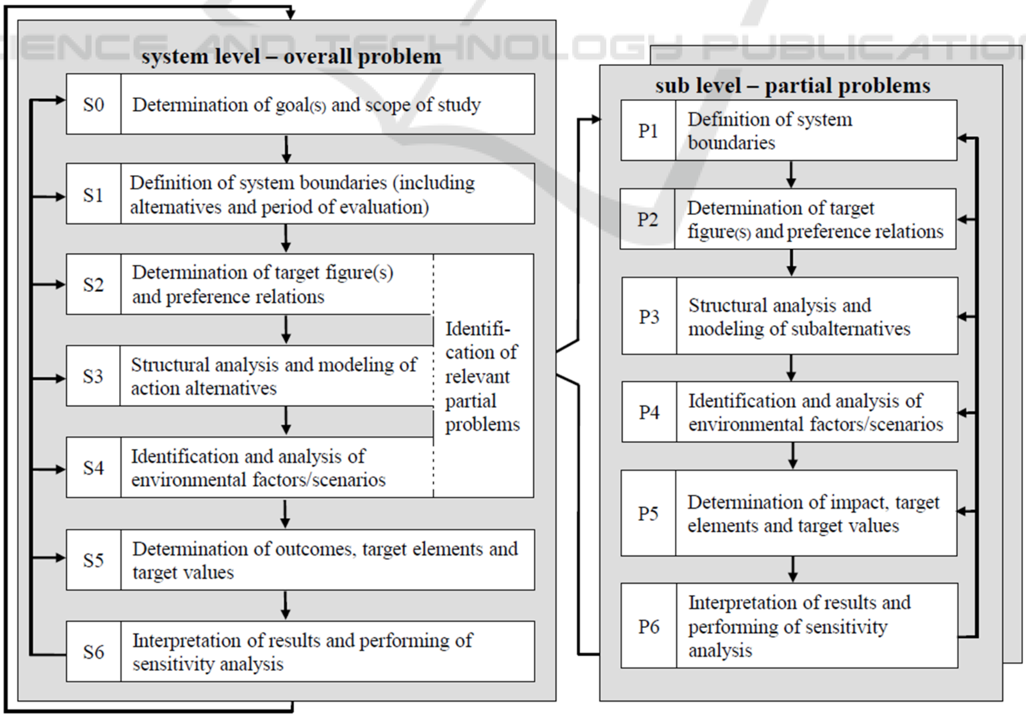

Figure 2: Procedure model for evaluation of CPS (based on Weber, T., 2013, Meynerts, L., 2017).

objective needs further specification regarding the results to decide why the analysis is necessary. In this regard, a reason for an analysis can be to identify relevant solution approaches, to choose a suitable supplier and, as the most important cause, to find the most advantageous alternative. Depending on the goals of the study, the scope has to be defined as well to enable a well-founded decision-making including the relevant influences (Meynerts, 2017).

Step *S1: Definition of system boundaries (including alternatives and period of evaluation)* is necessary to determine the relevant system boundaries. First, the system under study and the different alternatives have to be distinguished. This can be a CPS or a combination of different CPS – so within the production area it can be one or more machines right up to a whole factory. Furthermore, it has to be determined, which environmental statuses (e. g. legal background like existing data privacy acts) have to be integrated in the evaluation. Additionally, the evaluation period as well as the life cycle phases which are considered have to be defined (Götze, et al, 2014). Therefore, a system- and project-analysis should be conducted.

In step *S2: Determination of target figure(s) and preference relations* the relevant technical, economic, social and/or ecological target figures have to be defined while analysing the determined requirements (see S0). An example for an economic target figure is the net present value; a possible ecological target figure is the global warming potential. Afterwards, these figures have to be weighted to define their priorities. For this purpose, preference relations, e. g. preferences regarding the type of target, risk or time, can be used (Meynerts, 2017, Götze, et al, 2014). The choice of suitable evaluation methods to determine the target figures is necessary within this step, too. As I4.0-solutions in form of CPS are normally causing long-term effects, for economic targets reference can be made to established methods such as the net present value method (Götze, Northcott, Schuster, 2015).

Then step *S3: Structural analysis and modeling of action alternatives* follows. It means that the objects (e. g. one CPS, a system of different CPS) and related decision alternatives have to be selected, analysed and modeled. Therefore, product- and process-related modelling approaches like the I-T-O-model can be used (Götze, Hache, Schmidt, Weber, 2011). If partial alternatives exist, it can be useful to explore them detailed within a sub level (Götze, et al, 2014).

The next step is *S4: Identification and analysis of environmental factors/scenarios*. The effects resulting from the different alternatives are affected by a lot of environmental factors, which arise from within or from outside of the company. Environmental factors can influence the payments and costs directly, like market prices of technical assets. Additionally, they might also determine the way of usage of the CPS and its sub systems in an indirect way. Examples therefore are the customer demand or legal guidelines. The determination of environmental factors depends on subjective assessment (Meynerts, 2017). Additionally, the interdependencies between the factors should be analysed, e. g. with causal diagrams (e. g. Coyle, 1996). As a result, environmental scenarios can be built. In terms of decision theory, this is the step of developing the states of environment (Götze, et al, 2014). Therefore, forecast models should be used as well (e. g. von Reibnitz, 1992).

Step *S5: Determination of outcomes, target elements and target values* is characterized by the forecast of costs or payments within the different life cycle phases or the forecast of benefits (monetary and non-monetary). Regarding the estimation of costs, revenues or payments, methods of the development- and development-concurrent cost calculation are suggested (Ehrlenspiel, et al., 2007). Additionally, instruments such as check lists or expert reports for technical figures are applicable. In case of economic figures, instruments like traditional cost accounting, budgeting or activity based costing are recommended. If ecological target figures are included, instruments like Life Cycle Assessment can be utilized. The Social Life Cycle Assessment or other instruments of the Human Resource Management are suitable, if social target figures exist. As a result, the values of target figures are determined. If more than one target figure exists, the decision value has to be ascertained with help of methods of multicriteria decision-making (Götze, et al, 2014). For applying the various instruments, basic approaches of knowledge management are recommended to facilitate a valid database (Köhler, 2012).

Within the last step *S6: Interpretation of results and performing of sensitivity analysis* the final decision-making follows, e. g. in form of choice of the CPS that will be realized. Therefore, the determined target figures are compared (Meynerts, 2017). However, the results should be interpreted carefully because of the high complexity, the limited availability of data and the uncertainties involved. Thus, it is advisable to conduct sensitivity analyses to show the consequences of deviations of the influencing variables on the target values. Alternatively, critical values of the influencing variables can be identified (Götze, et al, 2014; Götze, et al, 2015).

The different steps within all levels of the process model are connected among each other in form of information flows and feedback loops and the results of one step can be input of another one (Götze, et al, 2014).

A special challenge within the model is posed by the division of the evaluation tasks and the related formation of sub levels. It depends on the structure of the evaluation object and different approaches for the division are possible (for more information about the possibilities see Götze, et al, 2014).

5 CONCLUSION

The presented procedure model enables a structured analysis and evaluation of CPS and supports the decision-making regarding the use of CPS. The decomposition into sub levels fosters the transparency of the evaluation. This is important, especially because of the typical complexity of the evaluation object. CPS consist of different elements and various challenges for their evaluation exist. This especially refers to the handling of the heterogeneous life cycles of the elements and the data acquisition. Thus, a division into partial problems seems to be unavoidable.

As shown in chapter 4, various instruments can be used within the different steps and partial problems. Following studies should focalize on the concretisation of the model and its steps. Therefore, existing studies (e. g. Götze, et al, 2014), which focus on other evaluation objects, can be used as a basis. Additionally, a refinement of the instruments applied to the model, like the net present value method, is necessary. Such refinements, for instance, should refer to the precise determination of CPS-related benefits as well as the integration of replacement decisions.

REFERENCES

Broy, M., 2010. Cyber-Physical Systems – Wissenschaftliche Herausforderungen bei der Entwicklung. In: *Broy, M., Cyber-Physical Systems – Innovation durch softwareintensive eingebettete Systeme*.

Braccini, A. M., Margherita, E. G., 2019. Exploring Organizational Sustainability of Industry 4.0 under the Triple Bottom Line: The Case of a Manufacturing Company. In: *Sustainability, Volume 11, Issue 1, pp. 36 ff*.

Coyle, R.G., 1996. System Dynamics Modeling: A Practical Approach. London.

Dhillon, B.S., 1989. Life Cycle Costing: Techniques, Models and Applications. New York.

Drossel, G., Ihlenfeldt, S., Langer, T., Dumitresco, R., 2018. Cyber-Physische Systeme – Forschen für die digitale Fabrik. In: *Neugebauer, R., Digitalisierung – Schlüsseltechnologien für Wirtschaft & Gesellschaft. Berlin Heidelberg, pp. 197–222)*.

Ehrlenspiel, K., Kiewert, A., Lindemann, U., 2007. Kostengünstig Entwickeln und Konstruieren: *Kostenmanagement bei der integrierten Produktentwicklung. Berlin, 6th edition*.

Faßbender-Wynands, E., 2001. Umweltorientierte Lebenszyklusrechnung: Instrument zur Unterstützung des Umweltkostenmanagements. Wiesbaden.

Ferry, D. J. O., Flanagan, R., 1991. Life Cycle Costing: A radical approach. Report 122 Construction Industry Research and Information Association (CIRIA). London.

Götze, U., Schmidt, A., Weber, T., 2010. Vorgehensmodell zur Abbildung und Analyse des Lebenszykluserfolgs von Werkstoffen – Konzeption und beispielhafte Veranschaulichung. In: *Materialwissenschaft und Werkstofftechnik, Volume 41, Issue 6, pp. 464–475*.

Götze, U., Hache, B., Schmidt, A., Weber, T., 2011. Methodik zur kostenorientierten Bewertung von Prozessketten der Werkstoffverarbeitung. In: *Materialwissenschaft und Werkstofftechnik, Volume 42, Issue 7, pp. 647–657*.

Götze, U., Schmidt, A., Symmank, C., Kräusel, V., Rautenstrauch, A., 2014. Zur Analyse und Bewertung von Produkt-Prozessketten-Kombinationen der hybriden Produktion. In: *Neugebauer, R.; Götze, U.; Drossel, W.-G. (Hrsg.): Energetisch-wirtschaftliche Bilanzierung – Diskussion der Ergebnisse des Spitzentechnologieclusters eniPROD: 3. Methodenband der Querschnittsarbeitsgruppe "Energetisch-wirtschaftliche Bilanzierung" des Spitzentechnologieclusters eniPROD, pp. 21–32. Auerbach*.

Götze, U. Northcott, D., Schuster, P., 2015. Investment Appraisal – Methods and Models. Berlin, Heidelberg.

Herrmann, C., 2010. Ganzheitliches Life Cycle Management. Berlin Heidelberg.

Hesse, W., Merbeth, G., Frölich, R., 1992. Software-Entwicklung: Vorgehensmodelle, Projektführung, Projektverwaltung. München.

Höft, U., 1992. Lebenszykluskonzepte – Grundlage für das strategische Marketing- und Technologiemanagement. Berlin.

International Performance Research Institute (IPRI), 2017. IPRI-Pressemitteilung vom 02.02.2017 – IPRI-Forschungsprojekt „Industrie 4.0 profitabel“ startet. Stuttgart.

Kagermann, H., 2014. Chancen von Industrie 4.0 nutzen. In: *Bauernhansl, T. et al. Industrie 4.0 in Produktion, Automatisierung und Logistik. Anwendung, Technologien, Migration, pp. 603–614. Wiesbaden*.

Kagermann, H., Wahlster, W., Helbig, J., 2013. Deutschlands Zukunft als Produktionsstandort sichern – Umsetzungsempfehlungen für das Zukunftsprojekt Industrie 4.0 – Abschlussbericht des Arbeitskreises Industrie 4.0.

Kemminer, J., 1999. Lebenszyklusorientiertes Kosten- und Erlösmanagement, Wiesbaden.

Köhler, S., 2013. Kostenorientiertes Wissensmanagement in den Konstruktionsprozessen des Maschinenbaus. Chemnitz.

Lee, C.K.M., Lv, Y., Ng, K.K.H., Ho, W., Choy, K.L., 2017. Design and application of Internet of things-based warehouse management system for smart logistics. In: *International Journal of Production Research, Volume 56, Issue 8, pp. 1–16*.

Meynerts, L., 2017. Lebenszyklusorientierte Wirtschaftlichkeitsanalysen und – bewertungen im Rahmen der Fabrikplanung – Entwicklung eines Analyse- und Bewertungsinstrumentariums unter besonderer Berücksichtigung der Energieeffizienz. Chemnitz.

Obermaier, R., Hofmann, J., Kirsch, V., 2015. Konzeption einer Prozess- und Potenzialanalyse zur Ex-ante Beurteilung von Industrie 4.0-Investitionen – Zur Methodik einer Abschätzung von Wirtschaftlichkeitspotenzialen. In: *Controlling, Volume 27, Issue 8/9, pp. 485–492*.

Pahl, G. Feldhusen, J., Grote, K.-H., 2013. *Pahl/Beitz Konstruktionslehre. Berlin, 8th edition*.

Riezler, S., 1996. Lebenszyklusrechnung: Instrument des Controlling strategischer Projekte. Wiesbaden.

Roy, D.T., 2017. Industrie 4.0 – Gestaltung cyber-physischer Logistiksysteme zur Unterstützung des Logistikmanagements in der Smart Factory, Berlin.

Schenk, M., Wirth, S. 2004. Fabrikplanung und Fabrikbetrieb. Berlin.

Schmidt, S., 2014. Investitionsentscheidungen unter Unsicherheit – Eine vergleichende Gegenüberstellung individueller und kapitalmarktorientierter Konzeptionen zur Entscheidungsvorbereitung. Chemnitz.

Sendler, U., 2013. Industrie 4.0 – Beherrschung der industriellen Komplexität mit SysLM Systems Lifecycle Management. In: *Sendler et al., Industrie 4.0 – Beherrschung der industriellen Komplexität mit SysLM, pp. 1–19*.

Sieben, G., Schildbach, T., 1994. Betriebswirtschaftliche Entscheidungstheorie. Düsseldorf.

Siepmann, D., 2016. Industrie 4.0 – Struktur und Historie. In: *Roth, A., Einführung und Umsetzung von Industrie 4.0 – Grundlagen, Vorgehensmodell und Use Cases aus der Praxis, pp. 17–82*.

Spath D., Ganschar, O., Gerlach, S., Hämmerle, M., Krause, T., Schlund, S., 2013. *Produktionsarbeit der Zukunft – Industrie 4.0. Stuttgart*.

Thiede, S., 2018. Environmental Sustainability of Cyber Physical Production Systems. In: Procedia CIRP, *The 25th CIRP Conference on Life Cycle Engineering, Volume 69, pp. 644–649*.

Von Reibnitz, U., 1992. Szenario-Technik – Instrumente für die unternehmerische und persönliche Erfolgsplanung. Wiesbaden.

Weber, T., 2013. Lebenszyklusorientierte Analyse und Steuerung des Werkstofferfolges, Chemnitz.

Wildemann, H., 1982. Kostenprognosen bei Großprojekten. Stuttgart.