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Multi-Criteria Evaluation of Manufacturing Systems 4.0 under Uncertainty

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Abstract

Introducing Manufacturing Systems 4.0 is essential for the existence of competing industrial companies. Nevertheless, knowledge about benefits of Manufacturing Solutions 4.0 is limited. This paper introduces an approach to evaluate Manufacturing Systems 4.0. Uncertainty is integrated via fuzzy set theory and stochastic models. The financial impact of non-monetary criteria is directly modelled. A Monte-Carlo Simulation aggregates criteria in a probability distribution of the projects net present value (NPV). Comparing distributions of different alternatives determines the most favorable alternative and analyses potential and risk. Through this concept understanding of Manufacturing Systems 4.0 is improved and their benefits are displayed comprehensively.

Keywords: Manufacturing System 4.0; Manufacturing System Evaluation; Evaluation Uncertainty

1. Introduction

Dynamic markets with shortening lead times, increasing customer expectations and ever growing competition in a globalizing world force producing companies to improve their manufacturing systems. Such systems need to adapt autonomously, without failure and at the highest possible speed to changing requirements. Manufacturing Systems 4.0 achieve these goals through sensors, interconnectivity and automated intelligent controllers. Such manufacturing systems are also called Cyber-Physical Manufacturing Systems and even a strategic change of business models can be induced by such systems in order to increase for instance the focus on service offers and customer relations. [1]

Despite their importance, several barriers exist when introducing Manufacturing Systems 4.0. On the one hand, high investment cost are related to Manufacturing Systems 4.0. On the other hand, there is no clear vision and strategy on how to implement Cyber-Physical Manufacturing Systems. Additionally, the knowledge about the utilization and the benefits of these technologies is limited. [2]

Thus, this paper introduces an evaluation method which specifically concentrates on Manufacturing System 4.0. Uncertainty is considered within the method and quantitative and qualitative criteria are used as input data. The method will be used to model strategic implications of manufacturing systems in a comprehensive and transparent way.

2. Literature overview

The research about the evaluation of manufacturing systems is reviewed regarding the integration of strategic implications and uncertainty. Moreover, the use of qualitative criteria, complete financial evaluation, comprehensibility, transparency and flexibility is considered. The reviewed evaluation methods can be split into two categories.

The first category focuses on the comprehensibility and transparency aspect but lacks adequate uncertainty integration and the possibility of a complete financial evaluation. Rivera and Frank display the economic potential in cost time graphs and include improvements through material savings, cycle time acceleration and minimization of waiting time [3]. Gracanin et al. adapt cost time profiles to optimize value streams [4]. Searcy uses quantitative descriptors which are weighted via an analytical hierarchy process to evaluate the application of lean methods in manufacturing systems [5]. Sobczyk and Koch

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structure their method around a value stream model and evaluate the manufacturing system based on modules regarding cost, inventory, production resources, company financials and other company-specific factors [6]. Kolakowski et al. combine an utility analysis for non-monetary criteria and a net present value (NPV) calculation for all monetary or monetary-transformable criteria [7, 8]. Briel focuses on a key performance indicator (KPI) based analyses of adaption investments in manufacturing systems comprising system's life cycle [9]. Peter evaluates lean methods via modelling of impact chains corresponding to certain KPIs [10]. Niemann applies dynamic life cycle controlling to evaluate and optimize manufacturing systems through simulating system adaptions and benchmarking the cost per part against other alternatives [11]. Kirsch evaluates Manufacturing Systems 4.0 via scale-based surveys of qualitative criteria and compares their fulfillment with the financial advantages of the manufacturing solutions [12]. Winkler et al. aggregate and combine the overall equipment effectiveness (OEE) including time losses because of inventory and production processes with a similar logistic-focused indicator to display the overall efficiency of a manufacturing system [13].

The second category comprises methods which integrate uncertainty and result in a comprehensive financial evaluation. However, due to the complex modelling approach for financial impacts and uncertainty considerations comprehensibility, transparency and flexibility are not considered in an adequate way. Reinhart et al. simulate stochastic criteria in a Monte-Carlo Simulation. They consider market demand uncertainty in a decision tree and conduct the final evaluation in a cost model comprising both models mentioned earlier [14]. Consequently, Reinhart at. al combines the Monte-Carlo Simulation of quantitative criteria and the transformation of qualitative criteria in a fuzzy neuronal network to calculate a probability distribution of the NPV [15, 16]. Möller uses the real option pricing theory to evaluate the performance of manufacturing systems which are subjected to dynamic environments [17]. Wunderlich conducts simulation-based cost analyses, production process analyses and investment analyses under uncertainty to determine the advantages of manufacturing systems [18]. Jondral uses simulation-based cost time graphs in combination with utility analyses and NPV calculations for the evaluation of lean method applications in manufacturing systems [19]. Peters uses the backward induction solution of a Markov decision process based on OEE and Monte-Carlo Simulation of market demands to create an investment strategy for manufacturing systems under uncertainty [20].

In conclusion, the literature review displays that there are already evaluation methods in place. However, these methods can be split into two categories whereof neither category is able to fulfill all presented requirements. Furthermore, none of the mentioned previous work focuses on Cyber-Physical Manufacturing Systems. The method introduced in this paper focuses on the presented imbalance of complexity and comprehensibility throughout the analysed evaluation methods for manufacturing systems and particularly takes Manufacturing Systems 4.0 into account.

3. Evaluation method

The comprehensive evaluation of Manufacturing Systems 4.0 under uncertainty is crucial to maintain a competitive production system. The evaluation method has to be applied in the factory planning process depicted in Figure 1.

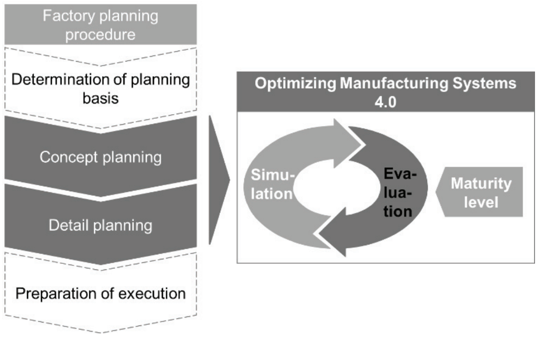

Fig. 1: Optimizing Manufacturing Systems 4.0

Especially the combination of real time based digital simulation and evaluation enables companies to iteratively enhance their factory plan with limited effort [21]. A maturity level model can be used to further adapt the evaluation to different technology standards.

The presented evaluation method consists of a five step approach and is illustrated in Figure 2.

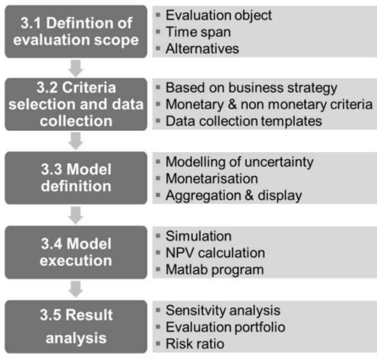

Fig. 2: The evaluation process

First, the evaluation scope consisting of the evaluation object, the time span and the alternatives is defined. Following this, non-monetary and monetary criteria are chosen based on the business strategy of the company and the collection of data is conducted, ideally using standardized templates. The subsequent definition of the evaluation model includes the modelling of uncertainty, monetary transformation of non-monetary criteria as well as the aggregation of criteria and the decision on how to display the results. Next, the model is executed in a simulation of the projects NPV. In this case a Matlab program is used for the calculations. Finally, the evaluation results are analysed, e.g. in a sensitivity analysis or by calculating and visualizing certain risk indicators. In the following chapters these process steps are explained in more detail.

3.1. Definition of evaluation scope

The scope of the evaluation is determined by the evaluation object, the time span of the evaluation and the possible investment alternatives.

The evaluation object defines the subject and the system boundaries of the evaluation, for example a specific production line. The basis are the company strategy as well as the investment program of the company. The time span determines the temporal extent of the evaluation which is relevant for the calculation of the NPV. Additionally, the investment alternatives have to be selected. Again, the company's strategy can lead to certain specifications for possible technologies and solutions.

3.2. Criteria selection and data collection

The selection of evaluation criteria is based on deductions from the business strategy and expert knowledge. Company-specific strategic goals are represented by the selection of adequate criteria.

In general, profitability is an essential target. Hence, the selection of monetary criteria in terms of financial values has to be conducted. Based on the manufacturing systems life cycle different kinds of expenses can be selected as criteria. Kolakowski et al. give a basic life cycle based overview of the expenses related to investments in manufacturing systems which can be used to select the monetary criteria [7]. Moreover, specific expenses can be added to represent the influence of Cyber-Physical Manufacturing Systems, for example payments for non-manufacturing personal which might be affected by the horizontal integration of information flow or required to manage increased information technology effort.

Some criteria cannot be expressed monetarily. Thus, in addition to the monetary criteria non-monetary criteria have to be selected. Comprehensive catalogs of non-monetary and qualitative criteria for the evaluation of manufacturing system are, for example, given by Brieke [22] and others [8, 23]. The non-monetary criteria is collected and evaluated by taking additional methods into account. Heger introduces an approach to analyse the transformability of manufacturing systems [24]. As mentioned earlier, the maturity level is measured via Manufacturing System 4.0 maturity level models [25, 26] or via Schindler's technology independent approach [27]. Furthermore, Reinhart et al. propose a method to evaluate the strategic implications of manufacturing systems [28].

The collection of such data can be conducted via interviews, observations or case-specific methods. Case-specific methods are for example estimations, simulations, document analysis, value stream analysis or Methods-Time Measurement (MTM).

3.3. Model definition

After selecting the criteria and collecting the respective data, the evaluation model has to be defined. The presented model consists of three elements: Modelling of uncertainty, monetarisation of non-monetary criteria and the aggregation as well as the display of results. Figure 3 shows the three elements with respect to the different kinds of criteria. In the following paragraphs the three elements are described further.

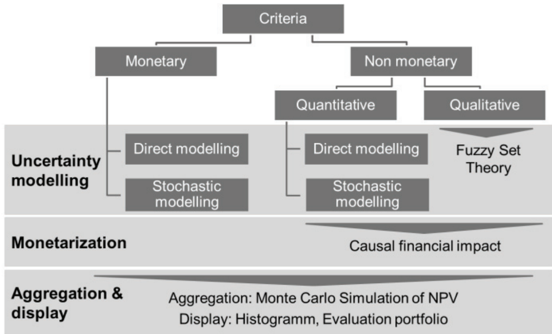

Fig. 3: Three elements of model definition

If the data collection yields results which are uncertain, two kinds of uncertainty are considered within this model: Stochastic and linguistic uncertainty.

Uncertain, quantitative criteria, monetary as well as non-monetary, are modelled via probability distributions. Especially, the modelling of non-standard beta distributions via three point estimations is recommended. Therefore only a pessimistic, a most-likely and an optimistic estimated value are necessary to deduct the probability distribution for the criteria [29]. In case of qualitative criteria, the data is usually given in the form of words. The utilization of words within the evaluation inherently yields uncertainty about the precise meaning of terms like for instance "good". The meaning depends on several factors such as what is described and who is describing it. This uncertainty is called linguistic uncertainty [15]. In the presented method the widely applied fuzzy set theory is used to quantify semantic terms and to model the linguistic uncertainty [30]. Therefore, the description of a qualitative criteria is standardized in well-defined and ranked terms and the required data are collected. The relative percentage of each standardized description of a term forms the membership value of predefined triangular membership functions. The center of area regarding the filled membership functions is the quantitative value corresponding to the former qualitative criteria. Figure 4 illustrates an example of the application of the fuzzy set theory.

Criterion description	Membership value
Very negative	0
Negative	0
Neutral	0,275
Positive	0,392
Very positive	0,625

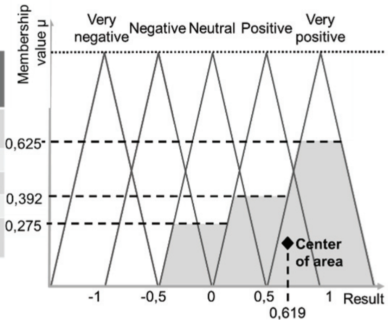

Fig. 4: Application of fuzzy set theory

The determination of the financial impact of a non-monetary criterion on one or several monetary criteria is called monetarisation. Therein, the impact is expressed in monetary terms and added to the defined monetary criteria for each period. The determination of the financial impact of a non-monetary criterion depends on the knowledge about the causal dependencies between the non-monetary and the monetary criterion. If the dependency is not known direct determination, estimation, simulation or implementation of a neuronal networks are methods to quantify the financial impact.

Otherwise, in case of a known dependency the financial impact can be quantified by direct determination, estimation, simulation, regression analysis, determination of grid points and graphic modelling. Moreover, a mathematical modelling of the financial impact via discrete functions, section-wise defined functions or continuous functions is conducted. Brieke [22] and VDI [23] give an overview of well-known financial impacts of non-monetary criteria. Additionally, financial impacts for Manufacturing Systems 4.0 technologies are essential for a valid evaluation of such systems. Nonetheless, each evaluation requires the definition of specific financial impacts.

In the aggregation phase the projects NPV is calculated under consideration of all monetary criteria (MC) and all financial impacts (FI) of non-monetary criteria, as shown in the following mathematical formula. Here, T and t depict the evaluation periods, r is the interest rate, I and i correspond to the monetary criteria and J as well as j denote the non-monetary criteria.

$$\text{NPV} = \sum_{t=1}^{T} \left(\sum_{i=1}^{I} \left(MC_{i,t} + \sum_{j=1}^{J} FI_{j,i,t} \right) * (1+r)^{-t} \right) \quad (1)$$

The NPV calculation is conducted several times within the Monte-Carlo Simulation. For each iteration of the Monte-Carlo Simulation new samples are drawn for the stochastic criteria and used as input for the NPV calculation. Finally, the result of the Monte-Carlo Simulation is a probability distribution of the NPV.

In order to display the results of the Monte-Carlo Simulation, different methods are applicable. First, the depiction as histogram can be used in case of the comparison of a minor number of alternatives. The interpretation of the expected value and the standard deviation for each alternative can be used to analyse the risk related to it.

If the target of the project is given by a minimal threshold for the NPV, the evaluation portfolio is a method to compare several alternatives. Therefore, the fraction of the standard deviation σ divided by the expected value μ is depicted on the y-axis and the fraction of the expected value divided by a predefined target value is shown on the x-axis. Company-specific and risk-dependent decision thresholds are set and the alternatives can be categorised as risk or chance, as shown in Figure 5. [31]

In order to further analyse a single alternative with respect to its potential and risk, the so-called risk ratio is calculated. The probability distribution is split into two parts by the target value. For each half a new expected value is calculated and the spread between the advantageously expected value and the target value yields the chance. The margin between the disadvantageously expected value and the target value depicts the risk. The division of the chance value by the risk determines the risk rate. A risk rate greater than one means more chance than risk and, vice versa, a risk ratio less than one means that the alternative has a higher probability to miss the target than to exceed the target. [31]

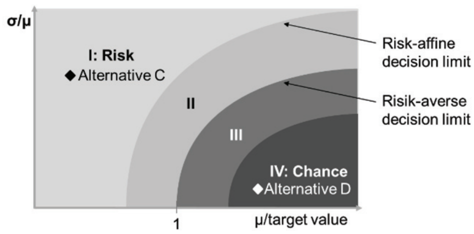

Fig. 5: The evaluation portfolio

In conclusion, the comparison of histograms for the different alternatives is used, if a target value is unknown and only a small number of alternatives has to be compared. The evaluation portfolio is applicable for a greater number of alternatives and if target value and decision limits are set. To further analyse the risk and chance of a single alternative relative to the target value, the risk ration is calculated.

3.4. Model execution

After collecting the relevant data and modelling the evaluation process, the model can be coded and executed. The large number of calculations related to the Monte-Carlo Simulation results in a high computational effort.

The requirements for the selection of an adequate software tool are given by the mathematical calculations of the model and the selected methods for data collection and result display. For instance the software needs to support the modelling of fuzzy set theory as well as random drawing from specific probability distributions. Statistic calculations and approximations are necessary. Additionally, the modification and the import of large data sets have to be applicable. The display of the results needs to be adaptable to company-specific standards. Eventually, the selected software should be well-known and documented to facilitate the programming.

After programming the model including all financial impact functions, the data has to be checked and entered according to the designed functions of the financial impact. The calculation process depends on the software, hardware, the amount of modelled functions and the number of simulation iterations. Eventually, the resulting probability distribution are used to support decision making.

3.5. Result Analysis

Before presenting the result for investment decision support, crucial criteria or modelling assumption are analysed. The resulting probability distribution is interpreted based on histograms, the evaluation portfolio and the risk ratio. Additional risk indicators are also applicable and selected for specific cases.

Moreover, a sensitivity analysis is conducted to analyze the impact of varying model input or monetarisation function parameters. Especially, the assessment of uncertain criteria is recommended. If the sensitivity analysis yields a high variation margin for the NPV, measures for decreasing the uncertainty should be taken.

Finally, the information from the result display and the result analysis can be used within the decision making process.

4. Application

The presented evaluation method has been applied to assess a semi-automated assembly line regarding a cyber-physical adaption investment in form of a case study. The assembly line is part of the Learning Factory on Global Production at the wbk Institute of Production Science, Karlsruhe Institute of Technology (KIT) [32]. The output of the assembly line are electric seat adjustment motors.

The base assembly line comprises seven manual, one semi-automated, two fully-automated work stations and one manual quality control station. The cyber-physical adaption is equipped with a RFID tracking of the manufactured parts. Moreover, a Manufacturing Execution System is embedded to enable fast production control and information distribution. Machine set-up procedures and the quality control station are fully automated based on video-optic input. The evaluation time span are four years.

The criteria selection results in sixteen qualitative and quantitative, non-monetary criteria to precisely assess the advantages of cyber-physical technologies. All necessary monetary criteria are selected. Data is collected through estimations.

The evaluation model includes fuzzy set theory to evaluate linguistic uncertainty as well as stochastic modelling via beta distributions to depict the stochastic uncertainty. Monetarisation functions are defined for each of the sixteen non-monetary criteria. The aggregation is conducted through a Monte-Carlo Simulation and the results are displayed as histograms and evaluation portfolio. Finally, the risk ratio is calculated to evaluate the results.

MatLab is used to program and execute the evaluation model. Additional toolboxes and scripts allow the fulfillment of all requirements mentioned in Chapter 3.4.

The computational results show that the cyber-physical adaption is feasible and exceeds the target value whereas the base assembly line falls short of the target value. Hence, the cyber physical adaption is preferred with a nearly neutral risk ration close to one.

5. Summary and Outlook

This paper introduces a five-stepped evaluation method for Manufacturing Systems 4.0 under uncertainty. First, the evaluation scope is set. Consequently, relevant monetary and non-monetary criteria are selected based on the company's strategic goals and planned implementations of cyber-physical technologies. Respective data are collected. Next, a multi-criteria evaluation model is used which integrates linguistic and stochastic uncertainty, quantification of qualitative criteria, monetarization of non-monetary criteria and adaptive display methods. Conducting a Monte-Carlo Simulation yields a probability distribution of the NPV. Several risk indicators and analyses are suggested to analyse the risk and potentials of the evaluated manufacturing system.

Future research has to increase the focus on criteria which are specific to cyber-physical technologies and respective monetarization functions. Moreover, a transparent approach for integrating interdependencies between criteria has to be integrated.

The presented evaluation model can be adapted in several ways to show the technological and the resulting financial advantages of Manufacturing Systems 4.0. The measurement of the technological potential of a manufacturing system and the capabilities of the applied technologies are assessed in a maturity level model. In the presence of Cyber-Physical Manufacturing Systems, a specific maturity level model will be developed.

In practice, the presented method further closes the knowledge gap on the benefits of Manufacturing Systems 4.0. A balance between complex modelling of multi-criteria uncertainty and efficient, understandable application needs to be maintained for the evaluation method.

The implementation of Manufacturing Systems 4.0 is improved by a structured and practice-based approach. Through these concepts an improved understanding of Cyber-Physical Manufacturing Systems is achieved. Moreover, chance and risk of introducing Manufacturing Systems 4.0 are displayed for decision makers in a transparent and comprehensive way.

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