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Analysis of Interactions and Support of Decision Making for the Implementation of Manufacturing Systems 4.0 Methods

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Abstract

For the successful implementation of Manufacturing Systems 4.0 (MS4.0) in medium-sized companies, a structured introduction process is required. Main objective of this process is the analysis and evaluation of MS4.0 methods in order to select those that suit best for each company. The foundation of this process is a structure model to classify and describe MS4.0 methods. A subsequent analysis of interactions among the methods supports the identification and evaluation of effective implementation strategies. Thereby, a model based on system dynamics is applied. Based on the results, the methods are strategically and financially evaluated to select the MS4.0 methods suited for implementation. Finally, a method roadmap can be derived to support management for the strategic decisions in regards of MS4.0 methods.

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Keywords: Manufacturing System; Analysis; Evaluation; Digital Manufacturing System

1. Introduction and objectives

The industrial sector currently undergoes major transformations, mostly influenced by so-called “Manufacturing Systems 4.0” (MS4.0). In the framework of MS4.0, medium-sized companies need guidance to fully understand the chances and potentials with respect to the implementation of new digital production methods [1]. This is essential to enable companies to develop individual and long-term strategies to successfully face future business challenges. Major challenge for today’s research is to define and develop possible stress-resistant implementation approaches.

The objective of this paper is the analysis of MS4.0 methods. Therefore, this paper is structured by a multi-level approach: Structuring relevant methods, interaction analysis of MS4.0 methods and evaluation of related results. Based on this a MS4.0 method roadmap can be derived which enables medium-sized companies to implement new MS4.0 methods and processes and to support strategic management. Regarding innovation, this approach extends existing implementation approaches by including structure, interactions and implementation of MS4.0 methods.

MS4.0 methods are described by a systematical approach to reach operative targets of companies by using modern MS4.0 technologies. The overall solution approach is tested and validated along business-related use cases.

2. Literature review

To support the introduction of MS4.0 in medium-sized companies, knowledge transfer of technologies and methods of MS4.0 is required. An important first step to reach this target is a structured overview of technologies and methods to present available options. This process aims to structure MS4.0 methods. While several models focus on basic technologies, others present methods or maturity levels. Further major differences between models are the basic structuring principle, which the model is based on, and their presentation form.

Basic principles for structuring MS4.0, can be differentiated by their value drivers (e.g. [2]), technological

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aspects (e.g. [3]) or maturity levels (e.g. [4]). Connected to the basic **structuring principles**, the **presentation form** is an important factor for the comprehensibility of a model. Presentation forms are often 2-dimensional models like the concentric circles of the Digital Compass [2] or more complex 3-dimensional models like RAMI 4.0 [3]. Another important difference is their **individual focus** on technologies or methods. The Digital Compass [2] and the VDMA Toolbox [4] focus on MS4.0 methods and have a more application-orientated approach to structure MS4.0. RAMI 4.0 [3] focuses more on basic technologies.

Besides basic structuring, **maturity indices** are an essential part of classifying MS4.0. A maturity index allows the assessment of the degree of development within a certain topic. This supports its introduction, since the current situation can be described, a target situation can be defined and solutions can be determined. In regards to MS4.0 several maturity indices have been developed. Some models e.g. the VDMA Toolbox [4] focus on the assessment of the development within a method (internal maturity levels) and other models like acatech's "Industrie 4.0 Maturity Index" [5] allow the determination of the position of a method in the development of MS4.0 itself (external maturity levels). A further characteristic of MS4.0 maturity indices is the possibility to evaluate a total company. For example the VDMA Readiness model [6] allows a good overall evaluation by offering a scoring model and by taking several MS4.0 production methods into account. The "Industrie 4.0 Maturity Index" [5] however only allows an overall graphically scoring. The VDMA Toolbox [4] does not offer an overall score, but assessing the current maturity level for all considered methods, it gives an impression of the overall status of development.

Successful implementation of MS4.0 is a complex process which requires a high level of know-how and comprehensive information. While there are many papers focusing on benefits of MS4.0 in general, almost no researchers approach the process of planning, transforming and implementing [7].

A well-chosen **modeling approach** is crucial for analysis of MS4.0 systems. Depending on the grade of complexity and detail of the production systems, it can be differentiated between descriptive to dynamic approaches on the one hand and qualitative, quantitative, simulation-based or graphical approaches on the other hand [8]. A highly adaptable model, well fitted for this approach, is **system dynamics**.

While system dynamic models lead to a complete overview and a classification of interactions in general of regarding production systems, stochastic models (i.e. discrete event simulation (DES)), focus more on a tactical or operative level. Concluding, the implementation of a system dynamics model aids strategic thinking and in addition, provides transparency and ensures dynamic complexity [9].

System Dynamics is a modeling method that includes various elements of a system and provides an insight on the systems dynamic behavior under uncertainty [10]. The main concept of the model of system dynamics are so-called feedback loops that can cumulate or decrease certain interactions [11]. Aull [12], Dombrowski [8] and Peter [14] use the concept of system dynamics to analyze and evaluate interactions among lean production.

To verify the results of business and implementation strategies the use of **key performance indicators** (KPIs) is a common used management tool which for example enables to quantify production systems. KPIs can be connected to KPI systems that provide information about correlations of different categories [15]. Stricker shows an approach to simplify the large set of KPIs and to categorize them [15].

Implementation strategies of MS4.0 methods depend on interactions as well as on the structure of underlying production systems. **Production structures** can be described by the variants of products and the flexibility of the structures [16]. Depending on the individual settings of production systems, effective implementation strategies can vary.

Concluding, before the implementation of MS4.0, production systems have to fulfill certain **basic requirements** [17]. Systematic definition of processes, well based standards and transparency are essential for successful transformation.

In general, evaluation methods of investments in production systems often focus only on evaluating the financial benefits [7]. The most popular instrument for evaluating investments is the **NPV method** [18]. Since they account for monetary benefits, economic methods can just partly evaluate MS4.0 as they are characterized by their strategic impact. Using merely classic financial evaluation methods for the investment may even indicate a negative result, since MS4.0 are high-cost investments with a significant **strategic benefit**, which is indicated by qualitative criteria that cannot be directly monetarized [19,20]. There are few methods in literature that combine monetary and strategic evaluation methods for the evaluation of investments. One of the first researchers to introduce a combined **strategic and monetary evaluation** method was Zangemeister, who developed a three-step model to evaluate work systems. In the first and second step, economic methods are used for monetary and indirect monetary criteria, and non-monetary criteria are assessed in a weighted scoring model (**WSM**) in the third step [21]. Isensee et al. evaluate investments in RFID technologies in a production environment by monetarizing non-monetary criteria based on **cause-effect-relations** [22]. Westkämper et al. developed a model to evaluate the use of Virtual Reality (VR) in production applications. Thereby, the benefits are categorized into direct (monetary), indirect (quantifiable) and strategic benefits. They suggest using the NPV calculation for direct and activity-based costing or WSM for indirect benefits. For the strategic evaluation, they suggest a **Balanced Scorecard** for the evaluation methods for the implementation of VR [23]. Kolakowski et al. have a similar approach by combining a NPV calculation for monetary and indirect monetary criteria with a WSM for non-monetary criteria [24]. Reinhart et al. developed an approach to integrate qualitative benefits into a monetary evaluation of production systems under uncertainty using the **fuzzy set theory** [25].

All in all, they use extended NPV calculations by transforming non-monetary criteria into monetary benefits. Non-transformable criteria are treated separately, e.g. by applying WSM. Other approaches apply AHP and WSM including both monetary and non-monetary criteria.

3. Analysis of Interactions and Support of Decision Making for the Implementation of MS4.0 methods

3.1. Structuring of MS4.0 methods

To support the introduction of MS4.0 methods, a structured presentation is required. As basis for the method selection, the structuring needs to fulfill several requirements: intuitively, quickly understandable and usable in the industrial practice. Additionally, MS4.0 methods need to be defined, integrating internal and external maturity levels. Internal maturity levels describe development levels within an MS4.0 method while external maturity levels classify the method within the whole development of MS4.0.

Structure: A structuring process that meets those requirements is designed. It classifies MS4.0 methods using categories within three hierarchically structured areas of a house model, which can be seen in figure 1. The basis of the house represents basic technologies of MS4.0, which are essential for all further applications. The applications of MS4.0 in the industrial production are represented by the categories of the columns of the house. Combined applications in the production are included in the roof.

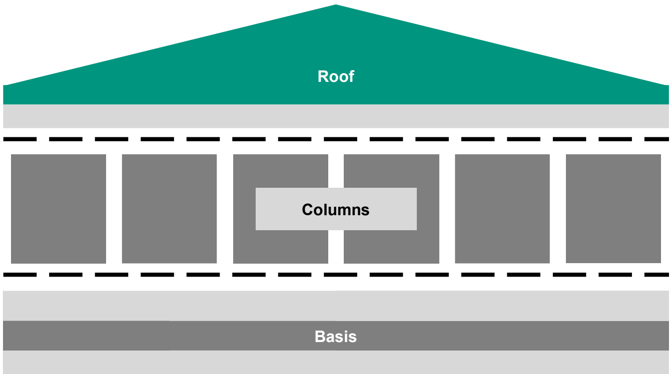

Fig. 1. House-model to structure MS4.0

Each category consists of at least one MS4.0 method. Each method is a cluster of existing applications of MS4.0 from the industrial practice. While the categories are generic and serve as general structure, the methods are specific and allow an accurate allocation of application examples. Examples of MS4.0 methods are paperless manufacturing and product localization, which are part of the category "Traceability".

Profiles to explain MS4.0 methods: In order to define MS4.0 methods, profiles are used for categorization. A profile can be created similar to those by Greitemann [26] but adjusted to MS4.0 methods. The designed profile (see figure 3) includes general information about the method as well as potentials and risks of using the MS4.0 method in industrial practice. It further evaluates to which extent the method targets several factors of production. Finally, information about internal and external maturity levels of the MS4.0 methods are included. In contrary, the internal maturity level of the method is specific for each method and each level is described in the profile. The internal maturity index used in the profiles is the maturity index by Jondral [27] adapted to the needs of MS4.0. The levels considered in this maturity index are "Initial/Ad hoc", "Planned", Defined", "Defined and measurable" and "Optimizing".

Allocating MS4.0 methods to external maturity levels: To determine the position of relevant methods in the bigger picture of MS4.0, external maturity levels can be used. Each maturity level represents further development of MS4.0 and methods are allocated to one or more maturity levels. For this, acatech's "Industrie 4.0 Maturity Index" [5] can be used. This maturity index uses the levels: "Computerization", "Connectivity", "Visibility", "Transparency", "Predictive capacity" and "Adaptability".

A MS4.0 method allocation is not unambiguous. If a method is allocated to more than one external maturity level, it means, that early development stages of the method represent a lower maturity level, while later development stages of the method reach one of the higher maturity levels. For example, the method of paperless manufacturing reaches the levels "Visibility" and "Transparency".

In total the external maturity index can be used to examine the current status of MS4.0 in a company and formulate development targets. Figure 2 shows for example, how a company might want to reach an advanced level of paperless manufacturing.

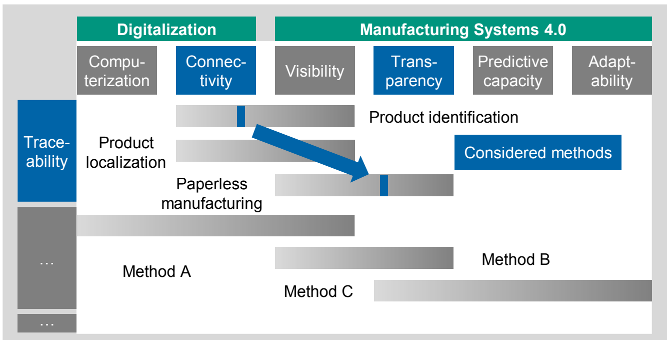

Fig. 2. Allocation of MS4.0 methods

In order to do this, relations with other methods need to be considered, which means that e.g. the methods of identifying and localizing goods need to be implemented to allow paperless manufacturing to be improved. The overall maturity level would be now "Transparency" instead of "Connectivity" in the category of "Traceability".

3.2. Concept interaction analysis of MS4.0 methods

This paper introduces a concept to enable decision makers to identify and evaluate efficient implementation strategies for MS4.0 methods. It shows an approach which generates a recommendation for an implementation order based on complexity and individual frameworks. In addition, the introduced concept supports its recommendations with statistical evidence via key performance indicators. A more detailed presentation with focus on the theoretical understanding of the approach can be found in Liebrecht [13].

The concept of interaction analysis can be separated in five different aspects: Definition of strategic targets and problem statement, qualitative analysis, quantitative analysis, simulation and evaluation.

The approach starts with the process of defining strategic targets and problem statements. Therefore, relevant MS4.0 methods have to be identified. While there is a large spectrum of various methods, this approach supplies a set of MS4.0 methods, that can be identified as most crucial in today's science. The set of MS4.0 methods can be extended and substituted by the individual needs of the companies.

The next step is to identify fitted KPI systems to measure the implementation performance. Main aspect of using KPIs is being able to control and influence the implementation process. As mentioned before, Stricker [15] introduces a KPI set which supports management in identifying KPIs based on their individual frameworks.

The following part is most essential for reliability and accurateness of this concept. Constitutive to selecting relevant MS4.0 methods and KPIs, correlations and interactions have to be identified and quantified for further progress. Both, interactions among MS4.0 methods or correlations between MS4.0 methods and KPIs, can be identified by interviewing experts on MS4.0, digitalization and IT. To ensure expedient results, experts need to be provided with all connected information on settings, structures and frameworks. Connected to the principle of Aull, qualitative correlations between MS4.0 methods can be separated into two groups: supportive and presuming. Due to the fact that the transformation is a long-term process another factor is integrated for estimating interactions and correlations. The stage of completion of examined MS4.0 methods plays an important role for the process. While qualitative connections among methods can be found early in the transformation process, quantitative connections can vary during progress of time. Methods that are partly implemented, but not well integrated in productions systems can cause a negative effect on the performance of other methods. Almost identical to the interactions among MS4.0 methods is to identify and quantify correlations between MS4.0 methods and key performance indicators. This ensures the measurability of the implemented methods and how they influence different parts of production. Additionally, the stage of completion analogy is applied for correlations between methods and key performance indicators.

Having completed to gather all relevant information on interactions and correlations, next step is to transfer all information into a system dynamic model. This can be done using a simulation and modeling software. As mentioned, the method of system dynamics examines systems that change over time and due to interactions. While modern production systems are very complex it is not possible to involve all internal and external influences. As a result, simulation software has to be capable to involve the factor of uncertainty.

One of the last steps is to simulate all possible sets of MS4.0 methods in the new system dynamics model and to document the variance of the earlier selected key performance indicators. This enables a statistical analysis of all KPIs to identify effective sets of methods and develop efficient implementation strategies fitted individual setting and frameworks. Results can be illustrated in a roadmap that can be used as a supporting management tool for MS4.0 implementation. The results of the created roadmap are driven by its high grade of individuality. Therefore, a general transferability is not provided.

3.3. Implementation of Manufacturing Systems 4.0

MS4.0 are mostly embedded systems characterized by a high share of IT and software. In order to evaluate the benefits, companies often struggle with the assessment of the investment. Using merely classic financial evaluation methods for the investment may indicate a negative result, since MS4.0 are high-cost investments with a significant strategic benefit, which is indicated by qualitative criteria and cannot be directly monetarized. [19,20]

Hence, the assessment of the MS4.0 necessitates an evaluation method based on a set of multidimensional (quantitative and qualitative) criteria that takes all important aspects (monetary and strategic) of the investment into account. Additionally, established evaluation methods often lack individuality as well as flexibility, and thus may not represent the strategic long-term targets of the company and the individual requirements. [23,25]

The designed evaluation method consists of three steps. The first step "Strategy analysis" includes the breakdown of the company´s long-term strategy. This step requires a thorough analysis of the company goals and its framework conditions. Based on the results, the next step is the selection of the alternative MS4.0 investments, which will be evaluated. This is a decisive step that should be carried out diligently as only a limited number of system alternatives can be compared. The determined alternatives should all contribute to the strategy of the company. To enable a meaningful evaluation, a detailed description of the chosen MS4.0 is required. Furthermore, an analysis of the spatial and temporal impacts of the system alternative should be included to create a solid foundation of assessing the MS4.0.

The second step is the creation of the specific evaluation system. Therefore, monetary and strategic criteria are selected based on the strategy and individual company goals. In order to assess the economic efficiency of the MS4.0, monetary criteria are part of the evaluation. These criteria consist of cost and income related cash flows that result from the investment.

A selection of possible monetary criteria can be found in [21,28]. Additionally, indirect monetary value criteria are included, which cannot be expressed or rated directly in a monetary way and therefore necessitate a monetarization.

A detailed description of the monetarization process can be found in VDI [28] and Brieke [29]. The strategic criteria are also crucial for the evaluation of MS4.0 as they are often characterized by their qualitative effects. Strategic criteria are non-fiscal target figures, that have a high impact on the company, e.g. transparency or system reliability. It is recommended, that the selection process takes place in a cross-functional team in order to widen the view and keep the system objective. Moreover, the weighting of the strategic criteria should be individually according to the requirements of the company. Therefore, the pair-wise comparison method will be used to reduce the complexity and divide the decision into several smaller sub-decisions which facilitates the aggregation to a final result. This step completes the creation of the evaluation system and the result is an individualized flexible criteria system, which represents the company and its needs.

The third step combines the results of step one and two. The selected system alternative will be assessed by the created evaluation system. First, the monetary criteria will be determined and then aggregated for each system alternative using the NPV, see for details [30]. Second, the strategic criteria will be merged using the defined and weighted strategic criteria performing a benefit analysis.

As a result, there will be two values for each alternative, one representing the monetary and the other the strategic benefit. The values will be plotted into one diagram showing the result of the strategic analysis on the y-axis and the monetary evaluation on the x-axis. The graphs summarize and visualize all results of the evaluation and give a clear picture of the benefits about the different alternatives.

In summary, the method enables a practical, clear concept that integrates qualitative and quantitative aspects of the MS4.0 alternatives for a company to evaluate the benefits of an investment.

4. Results

Currently, the introduced approach and the following exemplary results are validated and tested within the research project “Intro 4.0” [31]. In the industrial practice, the MS4.0 house is the starting point for the evaluation of available MS4.0 methods. The house provides a structured overview of methods over different categories, which are adapted to the individual needs of the companies for further evaluation. After a first selection of MS4.0 methods, the method profiles can be used to get a more detailed knowledge foundation. Figure 3 gives an example of a method profile. It shows the profile of the paper-free manufacturing at era-contact GmbH. Companies can also use this profile to get an impression of further development within this method by taking the internal maturity levels into consideration. After analyzing the methods using their method profiles, decision makers can match them to the external maturity levels of the “Industrie 4.0 Maturity Index” [5].

Taking a look at the paperless manufacturing being based on the methods product identification and product localization, it can be matched to the maturity levels “Visibility” and “Transparency”. Having introduced the concept of interactions between MS4.0 methods and all connected frameworks, this paper focusses on the implementation and its results.

While paperless manufacturing can be identified as the main target in this example, the other two methods are sub steps during the process of implementation. Paperless manufacturing is defined by the target to design processes and production

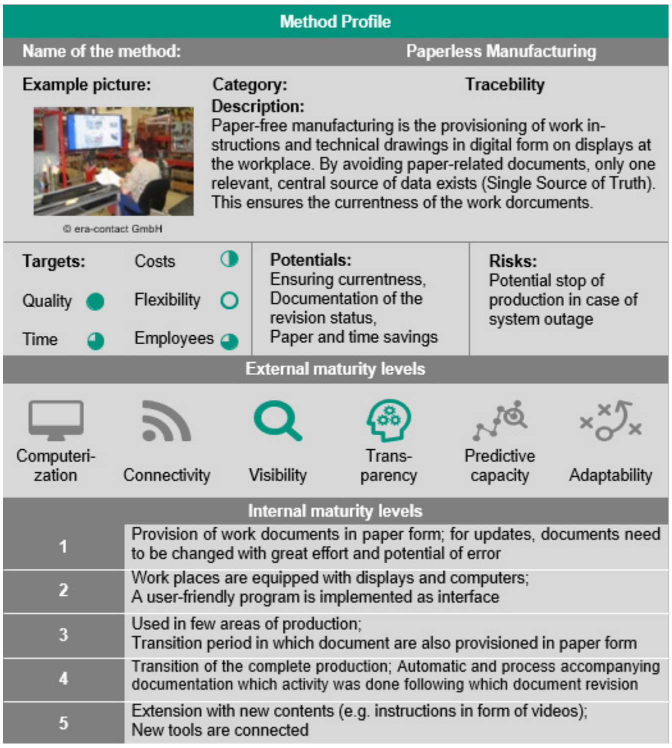

Fig. 3. Profile for paperless manufacturing

using modern communication and information technologies. The main goal is to implement those processes and systems without using analog communication mediums [32]. Product identification enables the state of the art production systems to read, process and transfer information during processing the products. This can be implemented by using the technology of RFID-tags. Highly connected to product identification is product localization. Production systems can localize all products within the production at all times [32]. First step is to identify and classify the interactions between the method of paperless manufacturing and the remaining methods. Next step is to identify and quantify the interactions between paperless manufacturing and relevant KPIs. The process is very similar to the step before, but extended by another detail level, the stage of completion of used MS4.0 methods. The interaction between a MS4.0 method and a KPI can verify from a positive to a negative correlation. While a negative correlation can be found in early levels of the stage of completion, positive correlation will apply through ongoing implementation

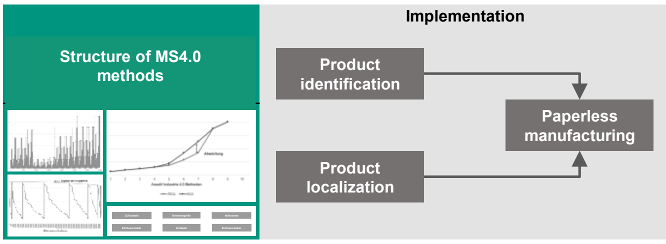

Fig. 4. Implementation roadmap of MS4.0 methods

process. The variation from negative to positive correlation can be explained due to the higher level of complexity in the beginning, and a delayed increase of process performance. As mentioned before, the quality of preceding expert interviews is essential for the quality of this interaction model. To generate a fully integrated simulation model, next step is to simulate possible implementation orders based on the number of MS4.0 methods. All implementation combinations can be analyzed by reviewing the influence on connected KPIs. The variation of KPIs and the exemplary roadmap of MS 4.0 methods are illustrated in figure 4. Possible optimization potentials regarding detail grade and scope of the simulation model are identified, discussed and evaluated within “Intro 4.0” [31].

In order to make a final decision on further investment regarding MS4.0, chapter 3.3 describes a multi-criteria decision process that includes individual company requirements. This method was applied using selected monetary and strategic criteria, e.g. transparency. All alternatives “paperless manufacturing”, “product localization” and “identification” have been evaluated based on the designed decision system and resulted in the decision to further implement the concept of paperless production as strategic benefits compensate the high investment costs.

5. Conclusion

Concluding, this paper shows an approach which enables companies to fully understand the chances and potentials in the framework of MS4.0, in order to develop individual and long-term strategies to fit new business challenges. As introduced, this paper can be clustered in structuring relevant methods, interaction analysis of MS4.0 methods and evaluation of connected results. The multi-level approach ensures an analysis to the fullest extent. The resulting method roadmap can be described as a very effective management tool which enables decision makers to reach their predefined targets during the process of implementation of MS4.0. As a recommendation for future research, the method roadmap has to be evaluated for its adaptability and usability in a real production environment.

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