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The Impact Of Manufacturing Execution Systems On The Digital Transformation Of Production Systems - A Maturity Based Approach

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Abstract

With the focus of manufacturing companies on the digital transformation, Manufacturing Execution Systems are market-ready, modular software solutions for manufacturing companies to integrate the value-adding and supporting processes horizontal and vertical in the company. Companies, especially small and medium-sized companies, face high internal and external costs for the implementation of the MES modules. An advantage of MES is the possibility to implement the systems in a continually, module-by-module approach, with the benefit of timely distributed investments. By realizing fast improvements, companies can use the benefits for further module implementations. This paper proposes a maturity model to measure the impact of an MES on the digital transformation of the company's production systems. The model fulfils two purposes. The first, companies can measure the impact based on the difference between its current maturity index and the potential index of an implemented MES. The second is, the user can identify what impact an MES has in general on the digital transformation since the developed maturity model is derived from an established industry 4.0 maturity model. The development of the maturity model is based on the methodologies of AKKASOGLU and focuses on the further development of an established model. As an outlook, the application of the model will be described briefly. The proposed maturity model can directly be used by practitioners and offers implications for further development of MES functionalities.

Keywords

Digitalization; Manufacturing Execution System; MES; Maturity Model, Maturity Index;

1. Introduction

Digitalization and horizontal and vertical integration promise to be a way of responding to the challenges of reducing costs, increasing quality, shortening delivery times and fluctuating and difficult-to-predict customer demands. The goal of digitalization is to integrate the physical and digital worlds to accelerate decision-making and business operations. [1] The goal is to empower companies to learn from data. In production, this means in concrete terms that near-real-time data and information are used to create a control loop with production planning and control. [2]

Companies, which are dealing with digital transformation in production, must concern the implementation and use of Manufacturing Execution Systems (MES). Currently available MES cover many of the requirements of a digitalized production system. More than capturing and distributing data in real-time, MES are capable of connecting different areas of the production and the supporting processes to enable the company to build a digital shadow of their production system and the processes within. [3] Digital shadows are digital models of the relevant business processes of the company filled with in real time acquired data which are used for analyses and data based decision making [4] Therefore, MES are a relevant part of realizing the digital transformation in production companies.

During the implementation of an MES, companies face many challenges. One of the biggest hurdles, especially for small and medium-sized companies, are the high internal and external costs for the implementation. [5] To tackle this hurdle companies can spread costs over a longer period with a successive implementation. This time can cover from two up to more than five years based on the number of implementation iterations and factory locations in which an MES has to be implemented. Due to the modular structure of MES, companies have to choose which functions and modules to implement first concerning the highest benefits within the successive implementation approach. Here companies face the unsolved challenge to estimate the benefits of the MES implementation ex-ante. MES are complex systems due to their extensive functions and modular structure. The effects of implementation on the various areas affected are difficult or impossible to assess due to the systems complexity.

To address this challenge and support companies, this paper presents a way to assess the impact of an MES implementation with a maturity model. Maturity models represent a relevant assessment tool in the literature and practice to make complex issues easily assessable. In recent time, many maturity models were presented which help companies to assess their status-quo in digitalization and plan their next steps. Since there is no maturity model, for assessing the impact of an MES implementation, a new maturity model has to be derived. [6–8]

2. State of the Art on the assessment of the impact of implementations

This section presents the state of the research in the fields of impact and benefit assessment for implementations of IT systems especially for business applications in production management.

The ex-ante assessment of the impact is a well-known field in the research of information systems and business software. Nevertheless, no approach truly fulfils all needs of practitioners. The difficulties are measuring tangible and intangible benefits and combining both categories in an easy-to-use method. In this section, the presented approaches can be divided into system-specific and general approaches. The general approaches present models to assess IT performance and the investments in IT systems. These approaches are not specific for a kind of IT systems (e.g. MES). The general models need to be adapted by the companies before the usage and they need IT system specific knowledge for the functionalities and the expected impact of the system. Therefore, these models mostly lack the practicability for companies to easy measure the impact of an MES due to the effort of transferring the models for the specific use case. [9,10] In [9] a model to assess the direct effects of IT on the efficiency of the production planning and control is presented, while in [10] the HÄNSCH presents an approach to monetarize the effects of intangible benefits.

MES-specific approaches tend to address the mentioned challenge. KLETTI presents a tool to calculate the Return of Invest of a MES implementation. This calculator focuses on some specific areas where it is easy to calculate the benefits in terms of reduces cost, stocks or rework. [11] With this approach, KLETTI neglects different areas and intangible benefits of the MES. OBERMAIER AND KIRSCH present a paper, which addresses the benefits of an MES implementation in the area production by a comparison of three different KPIs before and after the implementation. [12] Their paper delivers a first quantified assessment/evaluation of the impact of an implementation, but it is not easily transferable to other companies due to different status-quos before the implementation. The VEREIN DEUTSCHER INGENIEURE presents a norm regarding the costs and benefits of an MES. The norm gives a holistic overview the tangible and intangible benefits. [5] It lacks a methodology to assess the benefit of implementation quantified but it describes the effect chains between MES modules and the benefits.

3. Research methodology

To derive a maturity model to measure the impact of an MES, the methodology by AKKASOGLU will be used. Akkasoglu proposes a nine stepped approach to derive a maturity model that is shown in Figure 1. The first three steps are for preparation. The first three steps cover the determination of the need and the specification of the requirement as well as the analysis of existing maturity models. [13] These steps were covered by the first two sections of the paper. The focus of the paper lies on the construction phase that consists of four steps to set-up the maturity model. These steps will be covered in this paper. The first step of the construction phase covers the design of a reference model to describe the area of assessment. Therefore, the production system based on the reference model of MEISSNER will be described [14]. The second step covers the deduction of maturity objects. The maturity objects should be significant for assessing the maturity levels of the production system. In the paper, the maturity objects will be derived by selecting the tasks of the reference model that are supported by an MES. The third step of the construction phase is the weighting of the maturity objects. For this paper, there is no need in weighting the objects since every tasks is weighted the same for the construction of the maturity model. The applying company can do a weighing of the tasks individually. The last step is setting-up the maturity model with maturity levels in a matrix. In this paper, the matrix also shows to which maturity level the tasks will be supported by an MES. The last two steps of AKKASOGLU's methodology are summed up in the application phase.

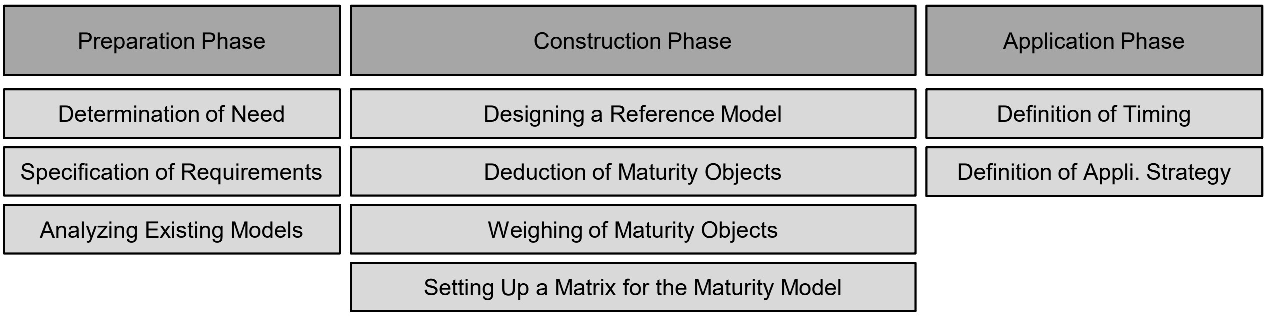

Figure 1: Methodology for designing a maturity model by AKKASOGLU [13]

4. Maturity Model for assessing the impact of a Manufacturing Execution System

In this section, the paper presents the approach and the results of the described steps. The steps for designing the maturity model and assessing the impact of an MES on the production system will be described in the following subsections.

4.1 Design of a reference model

This section deals with the design of the reference model. The reference model should define and mark out the area of investigation. The reference model is a generalized version of the area of investigation and should be detailed enough to be applicable but not so detailed that the effort for the assessment increases unnecessary. [13] In this case, the rough structure for the designed reference model is based on the model for production companies by MEISSNER. MEISSNER structures the production system in seven areas. The areas cover the design and development, industrial engineering, production planning and control, production and assembly, quality assurance, maintenance management as well as production logistics. [14] For each of the areas, standard literature and norms were used to identify the key processes and tasks. The 105 identified key processes and tasks were grouped in 25 task groups. In Figure 2 the process for the design of the reference model is shown. The area of design and development was described based on the VDI 2221 and the 19 tasks are divided into the groups of main, supporting and cross-cutting activities. [15] The area of industrial engineering consists of 11 tasks in of the three groups preparing tasks, the creation of the routing and NC programming. [16] Production planning and control (PPC) is structured based on the Aachen PPC model and structures the total of 30 tasks into eight groups. The groups cover the production program planning, the production demand planning and in-house production planning and control, the planning and control of procurement, inventory management, order management, data management and controlling. [17] The area of production and assembly consist of the group of execution, where the two tasks are divided into value-adding and conditional-value-adding activities. The second group of the area production and assembly contains the two supporting activities of acquisition and provision of information. [18] The area of production logistics consists of five tasks, which are split into the groups of planning and execution. [19,20] The area of quality assurance covers 19 tasks in five groups. The four groups of planning, execution and analysis of quality assurance tasks as well as the test equipment management are located in the quality forward chain. The tasks group complaint management covers five activities and is covering the quality backward chain. [21] The Maintenance management covers 17 relevant tasks in three groups. The groups are divided into the planning part of maintenance management, the execution of the maintenance orders as well as the analysis of acquired data. [22] With the 105 tasks the production system and its tasks and processes are described in a holistic way.

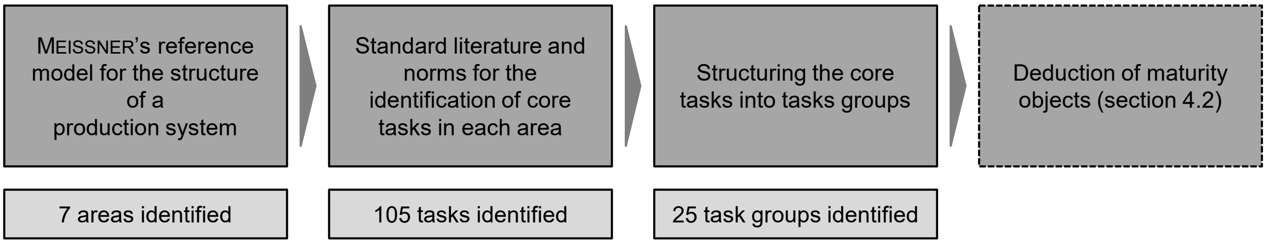

Figure 2: Process for the design of the reference model

4.2 Deduction of maturity objects

The deduction of maturity objects aims for the identification of relevant features of the area of investigation to describe the production system and the impact of the MES on it. Therefore, the papers identifies the tasks, which are supported and influenced by the functionalities of an MES. The structure of functionalities of a general MES is described in the VDI 5600 norm. There, the MES is structured into ten modules with various sub-functionalities. [23] KLETTI describes many functionalities of the modules based on the system of HYDRA, a German MES developed by the company MPDV. [3] With the explanations of the norm and KLETTI, relevant tasks of the above mentioned had to be identified to fill the matrix with the production system's tasks supported by an MES. The method for identification is based on three cases. The first case for support of a task or process is given if the function and the task are named the same. As an example, this case is given for the MES function of data acquisition and the task of data quality acquisition. The second case if the content-related consistency between the MES function and the task. For example, the MES functions of detailed planning are supporting the tasks of setting up an order sequence. The third case represents a partial support of the MES for tasks. Here, information that is used in the corresponding function can be useful for the supported core task. There is neither name- nor content-related consistency on this case. In Figure 3, the identified tasks of production planning and control as well as the support of the MES module form the VDI 5600 are shown. Here it can be seen, that production program planning as well as procurement planning and control are not supported by an MES. The rest of the tasks groups is supported by at least one of the MES modules.

Production Planning and Control (Supports ↓)	MES Modules (VDI 5600)									
	Order Management	Equipment and Maintenance Management	Data Acquisition	Energy Management	Detailed Planning and Control	Information Management	Performance Analysis	Material Management	Personnel Management	Quality Management
Production Program Planning										
Production Demand Planning	●				●					
In-house production planning and control	●	●		●	●	●		●	●	●
Procurement Planning and Control										
Order Management	●					●	●	●		
Inventory Management			●				●	●		●
Controlling	◑	◑	◑	◑	◑	●	●	◑	◑	◑
Data Management	●	●	●	●	●	●		●	●	●

● Case 1 & 2: Tasks are supported by MES
◑ Case 3: Tasks are supported indirectly by MES

Figure 3: Task-Function-Matrix for the tasks of production planning and control

The support of an MES function was checked for each task and summarized by the task groups. With the methodology, 66 of the 105 tasks and 22 of 26 tasks groups were identified as relevant maturity objects to measure the impact of an MES on the production system. The Figure 4 and Figure 5 (Section 4.3) present the identified task groups. Task groups without a support from an MES were left blank.

4.3 Design of the maturity matrix and impact of Manufacturing Execution Systems on the production system

The last step of the construction phase is to set up the maturity model, which will be done in a matrix. The tasks groups are represented as a line in the matrix. The maturity levels will be represented in a column. SCHUH ET AL. presented the acatech Industrie 4.0 Maturity Index as the result of an applied research process in 2017 and it was updated in 2020 with the experience gained while applying it. The acatech Industrie 4.0 maturity Index consists of four key areas with six maturity levels. The four key areas are resources, information systems, organization, and culture. [4] In the further, this maturity model will be used due to its usage and further development and due to the dissertation of SCHMITZ.

The acatech Industrie 4.0 maturity model has six maturity levels. The first two level *Computerization* and *Connectivity* represent the basis of Automation. The following four levels of *Visibility*, *Transparency*, *Predictability* and *Adaptability* represent the levels of Industry 4.0 and the digitalization. The maturity level of *Visibility* describes the capability of a company to have real-time data acquisition of all relevant processes. With the so-called digital shadow companies can analyse what is happening in the processes. The next level describes the capability of a company to analyse the data from the digital shadow to get insights on the correlations between events. Therefore, the company needs diagnostic analytics. Based on the digital shadows and the correlations, the fifth maturity level describes the state in which a company can use the acquired data to make prognostics on future events. This enables companies to construct realistic scenarios for the decision-making. The last maturity level describes the capability of autonomous decision-making by the systems through the evaluation, selection and initiation of measures based on predicted scenarios. [4]

To measure the impact of the MES, an information system, a metric is needed. SCHMITZ presents a metric to measure the maturity levels of information management in his dissertation. He develops a morphology to assess the maturity levels on 11 features. The features are split in the three groups. The first group represents features of the information logistics, which sums up the acquisition and distribution of information. The second group covers features of the data quality, data interfaces and transparency and connectivity of the IT system landscape. The last group covers the features of the IT infrastructure like data management, infrastructure management and the user interface. Each feature is described by forms, which are assigned to a maturity level by means of typologization. The maturity level can be determined by evaluating each feature and its form found in the company. Since information systems carry out the tasks of information management, this paper uses the metric to assess the impact of an MES.

Each task was assessed with the morphology by SCHMITZ and his assessment methodology described in his dissertation. [1] In Figure 4 and Figure 5, the result of the assessment is shown. Dark grey areas show that each assessed task in the group reached the marked maturity level by using an MES, whereas the crossed areas are indicating that an MES supports some tasks to a higher and therefore marked maturity levels. In the following, the figures and the impact are explained.

An MES can assist the support activities within the processes of *design and development* with the diagnostic analysis of the acquired quality data from production processes and the quality controls. With the identified correlations, the design and development can improve the product design in change requests or in new products. The *industrial engineering* get support from the MES by the better integration of data from different systems like ERP, CAD and PLM with data from the production. Especially in the planning of the routing, the acquired production data and its analysis helps the department in defining the processing and set-up times. In addition, the functions from information management help by saving and distributing of NC programs to machines with respect to the production plan.

The tasks and processes of *production planning and control* profit a lot from the usage of an MES. The demand planning and the in-house production planning and control profit from the availability of real-time data for the planning process as well as the analysis functions, which helps to analyse correlation between planning tasks and the latter execution in the production and assembly. The MES functions for fine planning support the production system by providing capabilities for optimization and simulation of the in-house planning and control. These functions enable the simulation of different planning scenarios and the selection of the best production plan. The MES functions of material management enhance the capabilities of the inventory management by giving transparency over the work in progress on the shop floor. The MES realizes tracking and tracing of products along the manufacturing and assembly processes. This also support the tasks of the order management and the controlling of the production system, since the status and progress of the order is tracked almost in real-time. With the data acquisition and analysis functions of the MES, the order management can identify correlations and root causes for deviations and derive reaction measures. The MES supports the data management with improvements in the data quality of the master data and transaction data. Latter data quality is improved by the possibilities of sensor integration and automatic data acquisition as well as functions for plausibility checks while manual inputting data. MES supports the production planning and control in such a way that they reach at least the maturity level of *Visibility*. Some tasks are even enabled to reach the maturity level *Adaptability*.

The tasks of the *production and assembly* are enabled to reach the maturity level of *Transparency*. The MES supports the execution tasks by data acquisition, automatic workflows and the presentation of user and tasks-specific information. It enables the paperless production. Here the MES functions of order management, information management as well as the data acquisition are used.

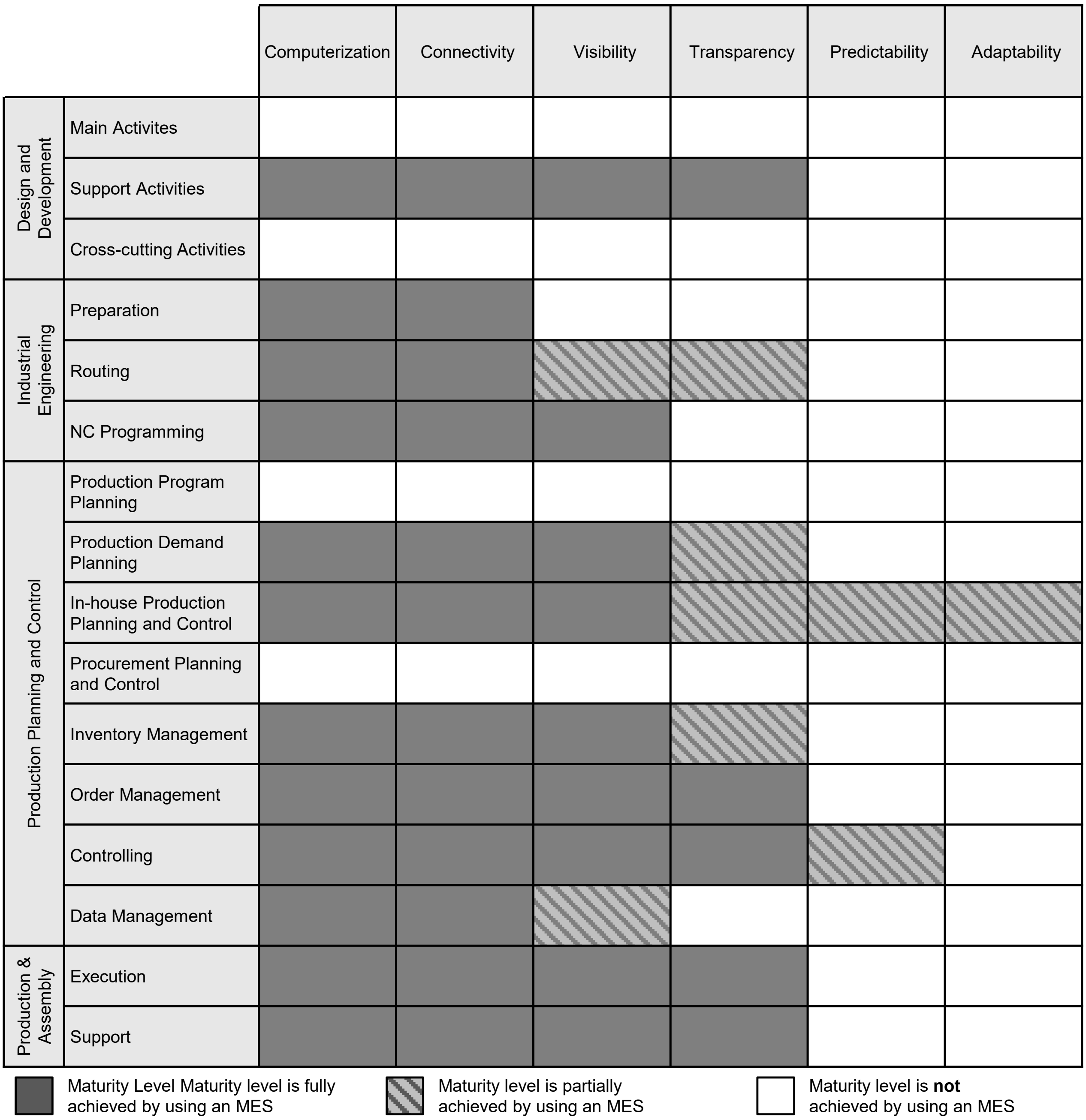

Figure 4: Impact of an MES on the production system (1/2)

In Figure 5, the impact of an MES on the areas of *production logistics*, *quality assurance* and *maintenance management* is shown. The tasks *production logistics* are supported similar to the production processes. The MES has not a big impact on the executional tasks in the logistic area since the MES functions are designed around the manufacturing and assembly processes. Therefore, the focus on the logistics tasks is lesser due the historical development. The planning of the production tasks is connected to the fine planning of production and it provides a synchronisation of manufacturing and transport operations. An MES enables the *production logistic* to reach the *Transparency* level of the maturity model.

The area of *quality assurance* also profits from the MES integration The MES functions of the module quality management enhance all tasks of the area. The quality planning is supported by the MES in the preparation of test plans by the automatic identification of test characteristics from digital component drawings. The execution of the test plans profits by the data acquisition functions and the possibility of an MES to integrate test equipment with interfaces to transfer data. The analysis functions enable not only the analysis of quality data but also its correlation with acquired machine and production data. Through the possibilities of tracking and tracing the tasks of quality data analysis can reach the *Transparency* level. The tasks of test equipment management do not experience any impact in the area of industry 4.0 through the use of an MES. They are supported in such a way that the level of *Connectivity* is reached since the MES takes over repetitive tasks and manages the data of the test equipment without linking it to the digital shadow of the acquired data. The complaint management is supported by an MES to reach a least the level of *Connectivity* since some tasks are just supported by managing data without further support, but the tasks of the error and root-cause analysis can be supported by the analysis functions of an MES. Here, the acquired data is analysed and correlations are drawn. This supports the quality operators in identifying the error and selecting countermeasures.

The area of *maintenance management* profits from the usage of an MES due to the better integration of the maintenance into production. The long-term planning of the maintenance activities profits from the data availability and the insights from identified correlations. An MES enables a strategic shift from time-based to a condition-based maintenance approach. The analysis functions as well as the dedicated maintenance management functions enable the planning tasks to reach maturity levels up to *Transparency*. The controlling and execution profits from the integration to fine planning functions. Here, the planning of planned and unplanned maintenance order is synchronized with the fine planning of production. Since the same functions are used the same maturity level can be achieved. Furthermore, the maintenance operator have access to maintenance instruction and information on MES terminals placed at machines or nearby. Also, they can analyse machine data from machine that need maintenance and can derive implication to the condition. This corresponds to the maturity level of *Transparency*.

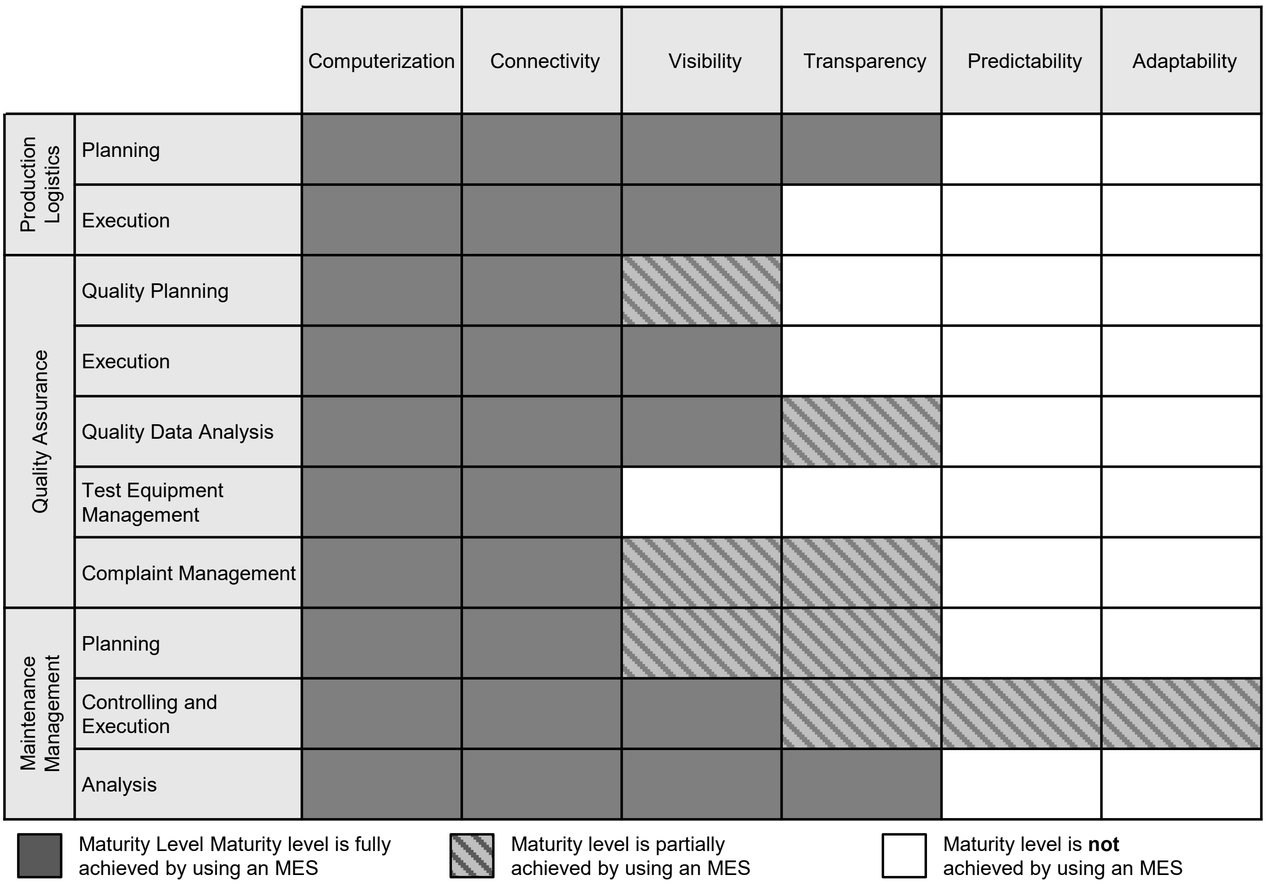

Figure 5: Impact of an MES on the production system (2/2)

5. Conclusion

This paper proposed an adapted maturity model to assess the impact of an MES on the production system. After determining the need for an assessment tool, the acatech Industrie 4.0 maturity model was selected as a basis for the development of a maturity model to measure the impact of an MES. Subsequently, a reference model was built to describe the production system. In the second step, the identified tasks and their groups were reduced accordingly. In the third step, the morphology of SCHMITZ was used in order to have an evaluation logic, which enables the assessment of the impact of an MES on the production system. The impact of an MES on the specific areas of the production system was presented in the maturity matrix. The assessment shows that an MES has different impact on the identified tasks. In many areas, the MES provides support to reach the levels of Visibility and Transparency. Even the higher maturity levels can be reached. With this assessment, practitioners can now assess their own production system area. To do this, they have to determine the maturity level of their company in accordance with the acatech model procedure. By comparing their level with the maturity level supported by the MES, they can identify the areas in the company that would benefit most from an implementation. Relevant MES modules for the high potential areas can be identified with the tasks-function-matrix. In future reserach, based on the model, a procedure can be designed that describes how to apply the models to structure the maturity-based implementation. In addition, the model can be extended for other IT systems that are used in the production. For MES providers, the model can be used to design smart services that support tasks beyond the current state of the art.

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Biography

Markus Fischer, M. Sc. (*1992) has been working as a project manager at the Institute for Industrial Management (FIR) at the RWTH Aachen since 2017. In current position as the leader of the research group Production Control as part of the Production Management department, he supports companies in improving processes by the usage of different IT systems. Also, he is working in the research project “Internet of Production”, which aims to develop data-driven decision support systems.

Prof. Dr.-Ing. Dipl.-Wirt. Ing Günther Schuh (*1958) holds the Chair of Production Systems at the Machine Tool Laboratory (WZL), is a member of the Board of Directors at the Fraunhofer Institute for Production Technology (IPT), Director of the Research Institute for Rationalization e. V. (FIR) at RWTH Aachen University and head of the Production Technology Cluster. He is founder of the Schuh & Co. group of companies based in Aachen, St. Gallen and Atlanta.

Prof. Dr.-Ing. Volker Stich (*1954) has been head of the Institute for Industrial Management (FIR) at the RWTH Aachen University since 1997. Prof. Dr.-Ing. Volker Stich worked for 10 years for the St. Gobain-Automotive Group and lead the management of European plant logistics. In addition, he was responsible for the worldwide coordination of future vehicle development projects.