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Dependencies between MES features and efficient introduction

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Abstract

During the last decade, a lot of procedure models for the introduction of industry 4.0 (I40) or industrial internet of things (IIoT) solutions have been proposed, especially in the German literature. Since they target all kinds of I40 projects they necessarily must be somewhat generic and are missing important details especially for the “implementation phase”. However, even in specific models for introducing manufacturing execution systems (MES) there are a lot of vague hints instead of concrete advice of how to do an effective and efficient introduction. Although it is certainly right that soft factors like finding the right partners and doing a good change management that involves end users early in the process are at least as critical as technical aspects, the latter should not be neglected. In this paper, some desirable features of MES are discussed and how they positively influence the efforts necessary for introducing such a system in a small to medium sized enterprise (SME).

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Keywords: Manufacturing Execution System, MES, Industrie 4.0, procedure model, human-centered design, customization

1. Motivation

Cyber-physical systems, smart products and data-driven processes enable higher quality output in production while minimizing the use of resources. In addition, digitization can help in creating completely new business models for manufacturers. On the other hand, the industry is in a state of transformation due to changing conditions: VUCA world with high volatility, uncertainty, complexity and ambiguity. These factors include but are not limited to globalization, highly dynamic product life cycles, strong competition for limited natural resources, climate change as well as demographic change [12]. The use of digital technologies supports companies in reacting on these developments and

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staying competitive. However, since the introduction of the Industry 4.0 (I40) strategy in Germany in 2012, many SMEs (small and medium enterprises) are still lagging behind in digitizing their production due to a multitude of factors. Frequently mentioned obstacles are for example high investment costs, lack of expertise and personnel expenditure, expenditure of time, no necessity recognizable as monetary benefits are difficult to quantify, lack of skilled employees, data protection, infrastructure and interfaces or (too) long waiting for market maturity [15].

In order not to let SMEs be left behind in the face of pressing needs for digitization, companies must be relieved of their fear of the "new" technologies.

Due to the increasing shortage of skilled workers, SMEs in particular are facing the challenge of employees having to take on tasks that were previously performed by colleagues with much higher qualifications and experience [21]. The new employees therefore need better support, including digital support. Where previously a shout-out sufficed, process-oriented assistance systems can (partially) compensate for the experience gap [21].

Information technology has become a decisive competitive factor, both for supporting internal processes and for efficient networking with business partners and customers [8]. Given the diversity of SMEs, standard offerings from IT service providers can only provide rudimentary adequate support for their production processes [8]. At the same time, there is an increasing need on the part of SMEs to improve transparency regarding existing orders and capabilities, especially against the backdrop of more complex processes. It is therefore necessary to have efficient and effective methods to introduce new IT systems for supporting the production processes in SMEs. Especially manufacturing execution systems (MES) are necessary to achieve the desired transparency. In this paper, existing procedure models for the introduction of I40 solutions are reviewed and an own model with focus on the introduction of a MES is suggested, that provides more detailed advice on the necessary steps and links efficient introduction to features of the MES system.

The rest of the paper is structured as follows. In section two, existing procedure models for I40 are described and their most important aspects are highlighted. As an improvement compared to the review in [24], the description provides an integrated view of the models instead of presenting them next to each other. In section three, further models for the introduction of MES are analyzed. Additional requirements for a procedure model are derived from empirical data in section four. Section five presents the proposal for the detailed procedure model before the paper is concluded with a discussion and outlook.

2. Procedure models for the introduction of I40 solutions

The overall goals of any I40 endeavor should be to gain and keep a competitive position in the market [17]. One way to achieve this is to focus on business model development and customer experience [4] as msg suggests. In contrast to that, Matt et al. stress to think about both horizontal and vertical digitalization [14], which means that both internal process efficiency and cooperation with business partners along the value chain should be addressed. This is in line with Kaufmann, who explicitly mentions the balance between generating added value for the customer and reducing costs / becoming more efficient internally [5]. To set the overall, as well as fine-grained goals, it needs a systematic approach that leads the way to a successful implementation. The review of procedure models in [24] structures the overall approach into five phases as shown in Fig. 1.

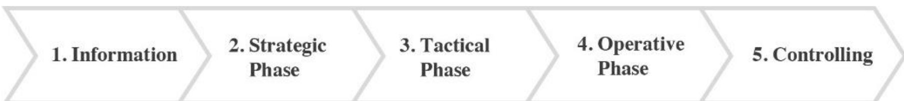

Fig. 1 Sequence of phases for introduction of I40 solutions [24].

Everything should start with an information phase, which has the goal to form a first common understanding between technical and process specialist as well as the manufacturing company. The experts on the procedures in the target company need to gain some understanding about the overall vision of I40 and how well current technologies are suited to already implement it. On the other hand, the consultants need to learn about the company specifics.

The strategic phase is concerned with an in-depth analysis of the current state in the company including processes, machinery, people, culture, organization, and degree of digitalization. Based on that, ideas for improvement are generated and evaluated in the tactical phase before they are implemented in the operative phase. In some procedure models, the operative phase does not even include the implementation, but is only concerned with making a roadmap for the implementation [14]. Finally, in the controlling phase it needs to be checked whether the desired goals were indeed reached.

In [24] 28 models are reviewed. We concentrate on those that are specific to SMEs and add important aspects compared to the already discussed models. Moreover we include white papers of consultancies and other practitioners in our review, because there is a lack of academic treatment of the subject [13]. Since I40 is a topic that is strongly driven from Germany, we also include German literature in the analysis.

During the information phase, new technologies and their potential should be assessed [17]. Matt et al. suggest workshops and seminars in order to reduce information deficits and get a first orientation [14]. Visiting other companies as well as trade fairs to get inspiration and learn about possible approaches is a good addition to that [3,18].

In the strategic phase, a self-assessment of the company regarding their current state on the way to I40 should be the next step after the information phase has reached its goal [14]. They should use a detailed checklist for determining their maturity [5]. Using a maturity model for orientation can be considered good practice [5,10,22]. Kaufmann suggests using a model with the steps 0 (offline), 1 (rudimentary), 2 (connected), 3 (advanced), 4 (action-based), 5 (business model). The well-established acatech maturity model [22] is similar and suggests the steps 1 (computerized), 2 (connected), 3 (visibility), 4 (transparency), 5 (predictability), 6 (adaptable).

After this initial step, a more detailed analysis of the current state in the company is necessary. Process engineering has a huge importance here [17]. Companies should take time for a structured and detailed modeling of the processes and process structures respectively [21]. Besides processes, data is a second key factor for I40. Kaufmann mentions data flows and the ability to perform data analysis as a desirable goal [5]. The association of German engineers (VDI) stresses data even more and demands to enable data access & availability, design data-driven processes and strive for smart usage of data [25]. People should also include the plans for future workplaces into their considerations [18].

In the tactical phase, the overall goals of the company regarding I40 need to be broken down into concrete measures to address the deficits found during the analysis in the strategic phase. This should be done separately for generating ideas of how to implement improvements and their assessment [26]. Idea generation can be supported by creativity methods like design thinking, fostered by consulting and inspired by tools like the I40 toolbox (ibid). The subsequent assessment should include an informed choice between cloud-based systems and self-hosted ones [4] as well as a make or buy decision. During that, decision makers should differentiate between systems of record on the one hand, that need to be stable and long lasting, and systems of engagement on the other hand, that need to be able to quickly adapt to changing market needs [4]. However, these days MES need to be highly flexible although they can also be considered as systems of record (e.g., for audits and customer complaints). The measures that are planned should include the organization, processes, technology and people as fields of action [18]. This demand is in line with the suggestion from acatech that see organization (internal/external), resources, information systems, and culture as the relevant fields. Both proposed fields of action can be seen as an extension of the well-known OPT model (organization, people and technology [6]) and the independently developed HOT-fit model [29]. The authors from Bremen business development further suggest to enable context-based information access via use-case specific user interfaces (UI) [18]. This is in line with the demand for iterative improvement of the UI in [21]. Finally, integration, standard interfaces, data governance (quality), and IT security need to be considered for the implementation. The outcome from the tactical phase is a roadmap of multiple projects that together bring the company a large step towards the vision of I40, but also make sense independent of each other. An investment and capacity plan is required as well [26].

In the operative phase, the measures that were planned need to be implemented. This is where most procedure models from literature get rather vague due to their generic nature. Bildstein and Seidelmann suggest an iterative approach as it is rather standard nowadays in agile software development methods as Scrum [3]. First, pilot project should be identified according to the 80:20 rule. After their successful implementation and evaluation, a rollout in the whole organization can follow (ibid.). A similar suggestion of working with demonstrators and test of I40 ideas before implementing a full blown system can be found in [23] and [21]. All measures taken, decisions made, etc. should be documented thoroughly and hardware restrictions and reliability, esp. if it is consumer hardware should not be underestimated [21].

The final controlling phase is only prescribed in a few models and missing details as well. Bildstein and Seidelmann speak about continuous evaluation of success [3]. The authors from Bremen business development advise companies to sustain their success by repeatedly taking time for innovation, taking part in research projects and establishing a fixed review team to continuously monitor production processes [18].

All models address additional factors, that can be seen as cross-cutting concerns. The most important is the need for a decent change management [17]. This is a complex process that is highly depending on the company culture. However, it can be detailed to at least two aspects. These are early participation of relevant employees in the innovation process [18] and training of personnel on the other hand [23]. Employee qualification is e.g. needed to use data analysis software, to perform advanced queries and interpret the results [15]. Not only technical skills, but also soft factors like developing a technology open mindedness should be trained [10]. Training should be incorporated into daily working procedures [18] in order to close the gap between learning new concepts and practicing them. Microtraining is a good method to achieve that and especially suitable for those whose basic knowledge needs to be refreshed or improved and who need information for immediate use in their daily practice [11]. Using early involvement and training together in an iterative approach to get feedback for further improvements of the system can increase acceptance of the new IT solution which is crucial.

Another soft factor suggested is cooperation in business networks [23]. Especially SMEs are regularly overwhelmed with the tasks necessary to move forward in an I40 project. Business networks can help with co-creation and providing an ecosystem for fruitful discussions [17] as well as provide valuable external perspectives on a company's challenges [18]. However, companies should not rely too much on external help, but also need to develop own in-house competences [17]. Interdisciplinary, cross functional project teams can help with that [1,28]. They should be embedded into flexible communities of practice and frequently engage in social collaboration [18].

3. Introduction of MES systems

To provide more details for the operative phase than the generic models presented in the previous chapter, the scope needs to be restricted to a concrete implementation measure. Since manufacturing execution systems (MES) play such a paramount role for I40 [2,13], the procedure model focuses on the introduction of an MES. MES are one of the major enterprise information systems (EIS) in the company among enterprise resource planning (ERP), supply chain management (SCM) and others [19]. Therefore, the suggested introduction processes are sometimes very close to standard approaches for any kind of software. Wiendahl et al. [27] add at least process assessment and process design as two additional phases for an MES introduction process. After that the suggested process is rather generic with creation of requirements specification, market research, pre-selection and final selection of software before a functional specification is created, a contract is signed and the implementation begins.

However, MES like the other EIS are made of computers, software, people, processes and data [19]. Therefore, people, hardware and data should be included in the model for introduction as well. A rough project plan according to Kletti [7] does that better. It starts where Wiendahl et al. end and suggests performing a (1) product training of key users first. Then (2) a safety and security concept as well as an interface concept should be created and detailed. This is followed by (3) the creation or completion of the infrastructure (network, power, etc.) as well as (4) the definition and procurement of hardware components (server, PCs, etc.). Then (5) the installation of a test and training system can be performed, followed by (6) provisioning of test data. After that, (7) interfaces to other systems need to be defined before the (8) pilot operation can take place (in several stages). Training of system users (9) should be done together with (10) the creation of user documentation or a user manual. Finally, the system can be (11) rolled out (in several stages) before the project can be finished with a (12) project completion meeting.

Going one step further into the details, an important measure as part of the implementation is the **customizing** and there especially the individual adaptation of the user interfaces of the MES software [27]. A clear UI-mask design (e.g., needs-based composition of the selection menus, simplified user guidance through suitable positioning of the buttons) significantly increases acceptance of the new software. Since the configuration involves user-specific adjustments, it is of great importance to document them in detail. In the later operating phase of the MES, this can significantly reduce the effort required to eliminate faults. Furthermore, MES should be chosen, which allow extensive customization without compromising update capabilities.

4. Empirical study

The research work was performed as part of the publicly funded project Moonrise with a total of 19 project partners. Manufacturing companies with 20 to 120 employees and up to 15 million Euros turnover per year from different industries serve as application partners. As part of the project, we conducted qualitative interviews with the participants to find out about their previous experience with the introduction of IT systems in production related areas as well as their goals for the I40 project.

They already knew that they cannot make it without external partners as they typically employ only about one IT specialists per 100 employees. They are also aware of the importance of data for their future production and the capital required to deploy advanced technologies. In line with what is reported in [9], most SMEs are neither data-ready nor do they have the capital to upgrade their existing machinery. Most of their existing machines do not have data gathering capabilities. They desire help with retrofitting these machines with sensors to overcome this limitation with a small budget and need help with imagining what to do with the data. Some application partners do have machines with network interface but did not connect them to the internal network do to either missing ideas of what to do with the data or fear of hacking. Most interviewees use old production equipment as well as aged information systems (sometimes even out of support). They want to make sure that there is a smooth transition from the old to the new systems (parallel operation of both systems for a certain timeframe). Some are also already aware of the need for key user training and several desire a continuous development of the system after first go-live.
The key goals for the introduction of an MES are:

- Reducing the time to find the right information. Paper-based information like machine parameters to be set for a certain tool to produce a specific good need to be found in the respective folder in the archive.
- Avoiding outdated information at the machine. Sometimes, information change and with paper-driven processes it is hard to update the information on the paper in time.
- Getting information about problems in the production process back to the decision makers. Paper-based information allows for free text comments, but still this information does not get to the right people, at least not in a timely manner.
- Make it easier to trace back problems reported by the customer to issues during production with detailed data about production steps performed and material used.
- Get a better overview about what is currently produced, how well machines are used and how long it takes for a certain order to be finished.
- Better recalculation of effective costs compared to planned costs of production.
- Support fine-grained planning of which production order to run on which machine and in which sequence. Whereas coarse planning is done in the ERP systems for several of the application partners, fine-grained planning is done either on paper or with Excel currently.

5. Own procedure model

The Moonrise procedure model can be seen as a kind of "best of" from the models described in section 2 and 3 that stresses the soft factors like co-creation and knowledge exchange in business networks, change management with early involvement of end-users and microtraining-based qualification of employees as well as cross-functional and interdisciplinary teams consisting of experts from the application partner, process consultancies, IT specialists and academia. It further details the steps necessary for the introduction of MES, as well as retrofitting for data collection and data analysis platforms for smart use of data to improve production. In this section, the steps for the MES are presented. For the other aspects, there are different templates and checklists for the operative phase. The remaining procedure models remains the same (see Fig. 2). The resulting model can be described as two intertwined development cycles. For once you have a large cycle to define the single measures that the company plans to implement (phases 3-5). For each measure, there is a make or buy decision including a thorough analysis of available solutions on the market and a rough estimate of costs for developing an own solution, preferably based on an existing open-source project. You also need a prioritization for the different measures and an estimation which of them you can afford to do in parallel in terms of disturbances of the daily operations and in terms of personnel capacity of both external and internal resources. A multi-project management is necessary to capture the dependencies between measures. It is e.g., necessary to do retrofitting measures first to make data available before it makes sense to implement a data collection and analysis platform like an MES or a business analytics suite.

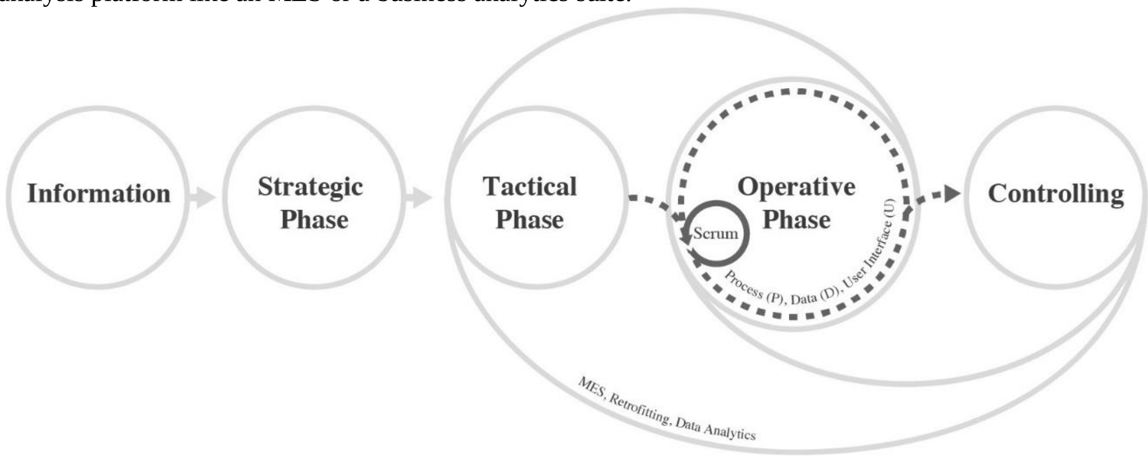

Fig. 2 illustration of own procedure model showing the outer and inner development cycles (own illustration).

For each measure you have an inner cycle that works in an agile manner with a product owner, a scrum master, a product backlog, a sprint backlog and product increments. Typically, the sprint cycles in I40 settings will be more than a week. As in other scrum project, you first must work on the requirements until they are detailed enough for implementation. If the system to be introduced is standard software, the team cares about customization instead of system development.

As highlighted by Wiendahl et al. [27], customization of the MES to be introduced is an important step. To achieve this, the MES must be working according to the production processes of the company, needs to work with the data structures of the company and the UI should be tailored to the need of the end-users to increase acceptance. For this purpose, the MES should provide well-suited means of customization or even better configuration (no programming).

Processes were already captured on a coarse level during the strategic phase according to the procedure model. This is typically done by the process consultants to find potential for improvement. For this later customization, these process models can usually not be reused, because they are too coarse and are not executable. Since customization is usually done by IT specialists, not process consultants, the not-invented-here syndrome will also hinder reuse. We propose to closely relate these two process modeling steps by refining the existing models to become executable and capturing all necessary details for allowing the MES to support the process. This requires process consultants to use the same process notation as the MES. We propose to use the well-established standard BPMN here, which can be reused for customization of HiCuMES, the highly customizable MES [16]. In our iterative approach, first the basic sequences of the processes are documented (P1). Then, special cases need to be captured, if the MES should be able to support them as well (P2). In the next step, interfaces to existing systems should be incorporated into the processes (P3). This includes especially reading or writing data from machines, scales and a CAQ system if present, as well as writing back data to the ERP system. These are modeled in BPMN with service tasks. HiCuMES provides several predefined service tasks with according “code behind” for this. Flowable, an open-source process management solution includes a service registry. Furthermore, the data flow for every process step (what goes in, what comes out) needs to be defined (P4). This is also the link between process modeling and customizing the UI. Finally, some technical aspects need to be added to make sure the processes are executable and fulfil the requirements of the MES (P5). In the case of HiCuMES, this means that operations IDs in HiCuMES need the same ID as the modeled sub-processes in BPMN as well as machine group IDs must match the pool/participant IDs in BPMN.

Data flows (D1) are already partly captured in P4. Unfortunately, BPMN has no explicit data view in contrast to other process modeling standards like ARIS [20]. However, it specifies a data object and a data store model element that can be used to indicate data flows directly in the process model. Flowable has an own GUI editor for defining data fields associated with the data objects, as well as service models that define how the data can be read or written from or to a data store. It supports both databases and RESTful Webservices for that. Signavio has a feature called glossary which is essentially an object repository that allows reusing model elements like data stores. Since Camunda, the process engine used in HiCuMES is missing such features, HiCuMES comes with an own database editor to allow for extensions of the data schema (D2) as well as a schema mapper to map data to and from the internal database to external data stores (D3) like the ERP system, machines or computerized scales. To do so, it supports JSON, XML and CSV/TSV as a data format as well as file system, SMB, CMIS, SOAP, REST and OPC-UA as data access protocols. Fieldbus devices can be accessed using PLC4j in a custom plugin based on the PF4j framework used in HiCuMES. If these tools are directly used for the initial analysis of system interfaces, instead of non-integrated tools like Postman or SOAP-UI, additional synergy between current state analysis and customization can be generated.

However, the hardest part is understanding the semantic meaning of the often cryptic fields in existing systems data schema. No tool can help with that, if no documentation is available (e.g., in OpenAPI format). The only chance is to look at the machines UI and ask the manufacturer which data point is displayed at a specific position in the screen.

Mapping of external data to the MES can be distinguished into master data (D3a) like product types and machine groups as well as movement data (D3b) like production orders or reports of goods produced and wastage. For association of data fields to process steps, the Camunda forms panel inside the BPMN modeler is used (D4).

The **user interface** is directly related to this last step from data modeling D4. To customize it, the application partner needs to decide on which data should be visible on which screen, and how it should be labeled (U1). This can be done in HiCuMES using the forms panel [16] which therefore allows for fine-grained control over which fields are shown on which UI mask, so that the UI becomes contextualized and shows for every process step exactly the required information. As a next step, fields are divided into read-only and writable fields (U2). To make this more user friendly, HiCuMES ships with a plug-in for the Camunda Modeler to incorporate a check box for visibility, instead of having to write down “readonly” as a validation constraint. Form fields defined in this way need to be mapped to the HiCuMES data schema (U3) using the same schema mapper that is used in step D3. Finally, the pre-defined layout of the UI mask can be altered (U4) using the HiCuMES UI editor, which generates JSON configuration files for Angular formly, the UI library used in HiCuMES together with custom CSS to also allow for company-specific colors, fonts and sizes. Customizing the user interface (UI) of the MES software [27] is especially important for the terminals on the shop floor that display information for further procedures as well as allow for reporting back data about the state of the machinery and the production process that cannot (yet) be automatically collected. This use case is sometimes called “mobile MES” [27]. The people working there are not used to working with computers and therefore require a tailored user interface that considers both physical restrictions like large touch targets for large hands as well as interaction elements that are familiar to these people.

Finally, a desirable feature of the MES is the ability to incorporate custom code without compromising the update capabilities of the standard software. Customers should be able to benefit from future updates of the base system without losing all their customizations. As long as the mechanisms described above are used, this is guaranteed because strictly speaking it is only configuration and not customization in a narrow sense. However, in practical settings it is much more realistic to assume that low code development needs to be applied instead of no code development. In HiCuMES, this is possible if service tasks within the processes are used and the code behind does not directly access internal HiCuMES classes, but rather uses the official API. The latter needs to be improved in future versions.

6. Discussion and outlook

Despite the plethora of procedure models for the introduction of I40 solutions there is a lack of concrete advice on how to perform the implementation of such solutions. This is especially severe for SMEs that seek to maintain competitive advantages by introducing a MES and introduce data-driven decision-making for their production processes. The paper presented a new procedure model that is compiled of the most helpful elements of existing models, combines them with concrete steps for introducing a MES from literature and provides further details on how to approach such an endeavor. It highlights that certain features of a MES, especially the customization capabilities, are closely related to how efficiently such a system can be introduced, by not only speeding up customization or configuration itself, but additionally generating synergies with the current state analysis in the strategic phase. To achieve that, the MES to be introduced needs graphical editors for modeling the production processes together with the data flows, interfaces to other information systems as well as customizing the user interface. A limitation of the approach is the chicken-egg problem of free choice of selecting any MES suitable for the company in contrast to the restriction to use a MES with such customization tools as described above to leverage the synergies proposed by the procedure model.

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