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Smart factory mapping and design: methodological approaches

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Abstract

Several studies show a demand for further transfer of Industry 4.0 concepts and technologies into practice. This paper describes how companies can be supported methodologically to identify individual opportunities for optimization within their future smart factories. Existing methods are screened, recombined, and enhanced to create a sufficient demand-oriented approach, based on the lean value stream mapping and design. The final approach covers a mapping phase of the current state and a design phase of a future state. It follows the general principle of process optimization prior to digitalization. Being a highly visual method, it can be used to explain the needs and the motivation for the identified improvement initiatives to all involved parties, including non-IT-specialists. This paper also presents an exemplary result and several learnings from tests with three companies with discrete manufacturing processes.

Keywords Smart factory · Industry 4.0 · Value stream · Methodology · Smart manufacturing · Maturity models

1 Introduction

The Smart Factory is one of the focus areas of Industry 4.0. It can be defined as a "factory whose degree of integration has reached a level which makes self-organizing functions possible in production and in all business processes relating to production" ([27], S. 20). Common aims in this transformation process are: increased efficiency, effectiveness, flexibility and/or adaptability ([27], S. 20).

Schuh et al. [22] created an "Industry 4.0 Maturity Index" that is meant to support companies in their Industry 4.0 transformation. At the heart of this maturity index, a model is used which consists of six different development steps, so called "value-based development levels". In this step-by-step approach the levels are: computerisation, connectivity, visibility, transparency, predictive capacitive and adaptability. The final stage of adaptability is characterized by using the data for decision making to achieve the best possible results and implementing automatic actions to achieve the desired results [22]. Transferred to the idea of a Smart Factory this final level provides an alternative definition to the previously stated Smart Factory definition. Both of these definitions imply the necessity of a high degree of digitalization in manufacturing and supporting departments.

In research the idea of a Smart Factory is already well defined, but in practice companies are struggling to keep up. In a study that applied the previously described "Industry 4.0 Maturity Index" to seventy companies, 80% of these companies were evaluated as having reached level two of the overall six levels [23]. Smaller companies in particular are being left behind. Studies show that there is a further need to demonstrate the benefits and opportunities of digitalization in order to provide further impetus for action [12, 19].

This problem formulation leads to the research question of this paper: How can companies be supported methodologically to identify individual opportunities for optimization within their future Smart Factories?

To answer the research question, a literature review of theoretical approaches was done. The most promising results were tested in three companies and optimized for application in discrete manufacturing processes. Finally, the learnings from these tests were used to create a recommended methodological approach.

2 Existing theoretical approaches

Optimization opportunities in the context of Smart Factories can be split into two major categories of approaches:

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1. The technology-oriented approaches: known technologies and other enablers like machine learning, AGVs, Cobots etc. can be evaluated regarding their applicability and the benefit they might bring in an application. Following this approach, single relevant use-cases might be identified. At first glance such an approach seems relatively simple and straightforward. But technology-oriented approaches put the assessors at risk to rather identify and focus on local optima by narrowing down their view of the overall situation, not directly ensuring that a global optimum for the daily business in the factory is found.
2. The demand-oriented approaches: this more general category of approaches is focussing on specific desirable outcomes and more openly considers the demands of the processes and sometimes even social and organizational aspects. Thus, the types of identified opportunities can be manyfold and have no narrow focus on specific technologies.

This paper focuses on the demand-oriented category of approaches. In the following sections, an overview about two major types of methods in this category is given.

2.1 Maturity models

A first and widely published method in this category is to use so called maturity models. In this context maturity is best defined as having attained a state of full development. The maturity models provide frameworks and scales to assess the completeness of having reached this full development. Well-designed maturity models should be objective (based on measurement) rather than subjective (based on evaluation) or at least target easily identifiable features as indicators and be independent of the expert level of the person that is conducting them. This makes them applicable for an objective comparison between different companies or industries, e.g., for benchmarking. Besides identifying the current maturity levels, such models can also be used to define future desired states.

Siedler et al. [24] evaluated 20 different maturity models in the context of digitalization in manufacturing companies. They found out that such models were developed for different industries or focus areas, use 3–11 maturity levels as scales and are used along 3–9 dimensions. Most of these models leave a gap between knowing the maturity level and having identified single individual projects that are needed to actually improve the assessed systems.

2.2 Methods based on lean value stream mapping and design

At first glance the impression might arise that with digitalization basically the information flow should be at focus, which might be applicable in some cases outside of manufacturing environments. But keeping the definition of a smart factory in mind, which is targeting self-organization, the manufacturing processes and service functions mandatorily need to be considered as well.

This combination leads to another demand-oriented approach: the material and information flow mapping also known as value stream mapping (VSM) within the Lean community. Following the definition of Rother and Shook: “A value stream is all the actions (both value added and non-value added) currently required to bring a product through the main flows essential to every product: (1) the production flow from raw material into the arms of the customer, and (2) the design flow from concept to launch.” ([21], S. 3) The process transparency given by a VSM can be used in a value stream design (VSD) for process-demand-oriented optimizations.

In the classic VSM approach for the production flow, the information flow is mainly focused on the order-based information flow between customer, production control and supplier, and between production control and the production processes. Regarding a Smart Factory, which is based on digitalization and connectivity, a more detailed information flow is needed.

Due to the given combination of material and information flow, an enrichment of the classic lean value stream mapping and design seems promising to create a holistic methodological approach. Several authors have already been active in this field, suggesting different types of notations.

Starting with Uckelmann [26], the enrichment of the classic VSM with Industry 4.0 relevant information was continuously discussed in literature. Uckelmann summarizes this under the term of information logistics processes. Without detailed definition of the characteristics of the enriched VSM, Uckelmann suggests adding four major process classes of cyber-physical systems (capturing/measuring, communicating and connecting, data processing, controlling) in addition to the production and logistics-oriented process boxes. Uckelmann also suggests using existing standards like the W3C Semantic Sensor Network Ontology [6] or the Sensor Web Enablement from the Open Geospatial Consortium [20] as orientation [26].

Meudt et al. [17] present a more detailed approach on the implementation of information logistics (which might be subject to informational wastes) and digital optimization possibilities into the VSM. According to the St. Gallen definition of information logistics [3] they focus on identifying waste in data generation, data transfer, data processing and data utilization. Also, a first notation and implementation into the Lean Value Stream approach is presented. The classic lean Value Stream approach is enhanced by the following main elements to form the Value Stream Method 4.0:

- enhanced data boxes which show KPIs and parameters which are produced or consumed by the corresponding process,
- acquisition interval, recording type and current actual value,
- involved storage media,
- horizontal swimlanes for each of the storage media and for each data utilization,
- simple data flow connections from the parameters and KPIs to the swimlanes,
- Kaizen Blitz notation,
- indicator that shows the direction of data flow.

The Lean Kaizen logic is also transferred to the information logistics and digital improvements. In following publications, also different steps for the application of the method for the VSM of the current state (VSM) and the VSD of the future state (VSD) are presented [8]. Additionally, the exclusive focus on the manufacturing area is extended to also administrative tasks as e.g., order creation by changing the KPIs and parameters view below the process boxes to activities and KPIs. Another publication of authors from the same research group further specifies the identification of waste in information flows [7].

Haschemi and Roessler [9] presented their smart value stream mapping (SVSM) approach, which basically adds three rates to the classic VSM notation: a vertical and horizontal integration rate, a material and information automation rate and a digitization rate. The authors suggest using SVSM in an integral approach, beginning with plant/area screenings to derive maturity levels for lean and digital manufacturing. This is followed by a medium-level SVSM and ending with deep analyses of the labour and material flow for manufacturing and the information flow for both manufacturing and administrative processes.

Lewin et al. [15] used the work of Meudt et al. [17] as a basis for a further specification of the information logistics. To address the degree of information processing they use different line types and data processing points. Technical interfaces and human–machine interfaces are indicated by additional symbols. Furthermore, indicators for data quality, measures in regard of IT security, the linkage of smart products to the data streams, transmission technologies and some minor other changes were introduced.

In a following publication some authors of that research group also described a different approach in which they split the analysis graphically into three different lanes: process, data/information and information processing. This notation framework allows to provide further insights especially into the information processing [2].

Wagner et al. [28] integrated design thinking elements into lean value stream mapping and developed means to achieve a qualitative correlation between production targets and Industry 4.0 technologies. They did not suggest changes in the notation of VSM or VSD.

Martin et al. [16] created a review and an extension of the found methods for the target group of production planners. The method shall support production planners in evaluating the potential for smart manufacturing solution (SMS) implementations in manufacturing processes, including the choice of SMS and an estimation of the impact on the process.

El Kammouni et al. [4] designed an AutomationML model of the Smart VSM introduced by Hartmann et al. [8] and Meudt et al. [18].

Wang et al. [29] made progress on automated knowledge generation out of data from a smart workshop to analyse root causes based on VSM.

Arey et al. [1] introduced two horizontal lanes, which they called "stratospheric bands". The first of these bands is the "Process KPC detection" band, which visualizes predefined "Key Performance Characteristic (KPC) shop floor relationships". As additional KPI they introduce a detection time to monitor and improve responsiveness of e.g., production quality control.

The second of these bands is the "Digital information flow" band that shows the transfer media of data which is produced or consumed by the process boxes. As data transfer media, a collection of five different types (e.g., employee, physical Kanban/FIFO, software etc.) is used in a scoring algorithm in order to evaluate an overall information transfer score.

Kihel et al. [13] assigned different Industry 4.0 technologies to specific process functions which were identified as relevant by using classic VSM.

Ferreira et al. (5) combined a hybrid simulation approach of discrete event and agent-based modelling and simulation with lean value stream mapping. They used the classic lean value stream notation.

3 Method recombination and development

Coming back to the research question stated in Sect. 1.1, the method shall support companies in the identification of individual opportunities for optimization within a future Smart Factory. By enhancing the lean value stream mapping and design method, both a certain transparency about the current state and a planning aspect in terms of the future design can be achieved. The enhanced method can be used just like traditional Lean Value Streams to identify, monitor, and optimize the material and information flow. It can support the idea of classic process optimization prior to digitalization.

In addition to the lean aspects, it shall fulfil the following purposes for supporting the Smart Factory transformation:

1. give simple to interpret transparency of the main elements of information engineering and management, i.e. the available information & its sources, the information flow in terms of inputs and outputs of information, the involved systems for processing and communication and as part of the design also the information needs ([14], S. 118),
2. be a profound basis for identifying potential in digitalization and thereby setting the starting point for project identification and roadmapping.

The target users could be from production engineering, process engineering and IT departments.

Regarding the described requirements, the approach from Hartmann et al. [8] and Meudt et al. [17] shows the best fit, although the method they describe rather has the characteristics of an overview for higher level design and decision making. Thus, some more detailed information about the information flow, the systems for processing and communication and the data processing itself would be required. This also includes transparency about the used interfaces, as mentioned by Uckelmann [26]. Lewin et al. [15] already introduced an approach for more precise insights about the information flow and interfaces that are in use. This goes hand in hand with a lack of simplicity of the overall approach.

In the following, a recombination of the existing approaches and an introduction of some additional changes will be done.

3.1 Definition of the main characteristic elements of the proposed method

Based on the previous work of Hartmann et al. [8], Lewin et al. [15], Meudt et al. [17] and Uckelmann [26] the following main elements are used in the final approach (in addition to the classic lean value stream mapping and design notation):

- enhanced data boxes which show KPIs and other data that is produced or consumed by the corresponding process box,
- acquisition interval, recording type and current actual value,
- horizontal swimlanes for each of the medias and for each data utilization,
- simple data flow connections from the KPIs and other data to the swimlanes,
- Kaizen Blitz notation.

Additionally, unobtrusive types of notations were added to indicate the following:

- technical resources and interfaces including their usage,
- involved data sources and sinks (direction of data flow indicator moved to the media lanes),
- simple comments section for additional information,
- indication of data/information processing.

Figure 1 also shows the graphical notation of the used elements.

3.2 Use in mapping of the current state

Starting with the classic lean value stream, the single process boxes need to be enriched with the additional elements.

While most of the information needed for the classic part can be found at the Gemba, details about information engineering and management usually are not directly visible. This applies in particular for the data that is collected and processed automatically. Thus, several departments will be involved to collect all the relevant information.

To get an overview of involved media, an initial media landscape can be identified which shows all involved media in the different business functions across the Smart Factory. The functional model described in the ISA 95 standard [11] can be used to get an idea about relevant business functions.

Details about information engineering and management are identified by a combination of going to the Gemba and interviewing machine operators, process leaders, persons responsible for service functions and especially from the IT department.

To be able to apply the method on an ongoing basis and to increase the acceptance of the results within the companies, their own employees should be involved in the application of the method.

3.3 Use in design approach

Keeping the general principle of process optimization prior to digitalization in mind, also for the design phase, the classic procedure for VSD is still applicable.

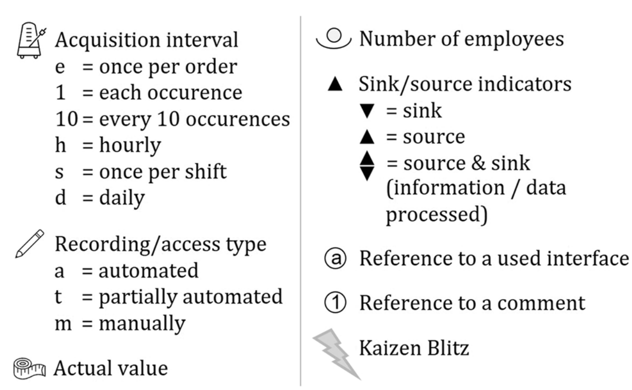


Fig. 1 Graphical notation of the main elements of the tested method

Tortorella et al. [25] collected several proposed guidelines for designing lean value streams.

Additionally, those guidelines are enhanced with the following principles for the improvement of information engineering and management and process optimization due to digitalization in general:

- avoidance of non-digital information,
- reduction/avoidance of manual processes,
- avoidance of media discontinuities,
- identification of the needed information for full availability of relevant data e.g., by checking the availability of all relevant data for the predefined KPIs,
- consideration of documentation requirements (depending on the industry)
- use of condition monitoring of relevant assets (e.g., following [10]),
- general connectivity and interoperability, both in the live data flow and the access to historical data, i.e., the avoidance of data silos in MES/ERP etc.,
- general digital measurability of process and product quality defining parameters,
- introduction of closed feedback loops for optimization and self-organization.

The last two bullet points in particular lay the foundation for data-based optimisation of the manufacturing process itself. More comprehensive changes due to digitalisation, such as adapting the business model to offer product configurators or the like, can be designed by looking at the entire value stream.

4 Test of the methodology in complex environments for discrete manufacturing

The recombined and enhanced approach was tested in three companies with discrete manufacturing processes. A detailed description of a single process box of one of these three tests will be discussed exemplary. For all three companies the same expert in the method was leading the assessments. This expert was accompanied by one to three representatives of the companies as co-assessors. Therefore, the representatives were trained in the method prior to joining the assessment process. Figure 2 shows the test process.

4.1 Test: mapping of the current state

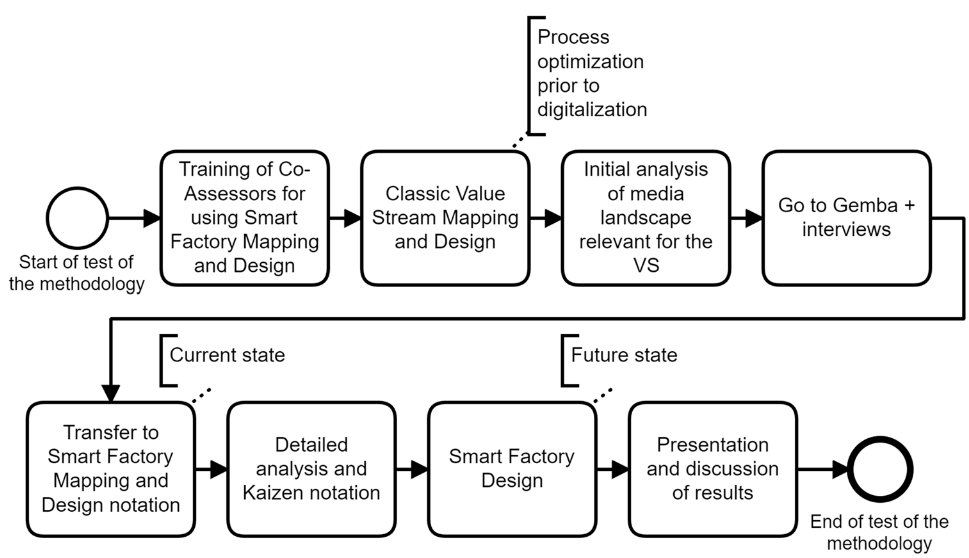
The mapping of the current state was done according to the process described in Sect. 3.2. During the tests it has proven as the best viable method to gather the relevant information by using pre-printed sheets that already have empty boxes for the media and the utilization as well as the raw data/information and the KPIs and also show the lines used for the information flow. Otherwise too much time is taken by drawing these elements by hand.

Additionally, interview questionnaires were prepared to conduct the interviews of the machine operators, process leaders, persons responsible for service functions and the IT department to raise reproducibility of the generated results.

Finishing the first process box always was the highest effort in each of the manufacturing environments, as it required to get a general overview about the involved system landscape and the general media and processes, used.

Combining all the collected information, an exemplary result for the process box "Injection Moulding" is shown in Fig. 3. In the related process, six Injection Moulding machines

Fig. 2 Process used for the tests of the methodology



were producing polymer parts for an automotive assembly. A total of 15 different media was involved, including six (three paper-based, two employees, one manual calliper) in the non-digital domain. Some of the collected data was used in five different types of utilizations. Following the notation shown in Fig. 1, the diagram is interpreted as follows: the information item “production request” is acquired daily and accessed manually. The actual value is the number “202119”. No automated interface is in use for this information item. The information is consumed by the machine operator. Besides being the knowledge of the machine operator, it is available in three different types of media: a paper-based production order, an E-Mail, and the ERP system. This information is both generated by and used in production planning. The other information items can be interpreted in the same way. Some observations of the mapping phase need to be written in the comments section, due to their complexity.

In the analysis of the current state each identified area of improvement is marked with a Kaizen Blitz and a short comment. These elements can be used as indicators to highlight improvements that should be made when designing the future state. Some examples can be found in Fig. 3.

4.2 Test: design approach

Applying the guidelines described in Sect. 3.3, the exemplary design shown in Fig. 4 was derived from the mapping of the current state. Some of the changes are:

- Increased connectivity of the technical resources leads to reduced manual transfer time, reduced transfer errors and a higher availability of data.
- The overall number of different media was reduced, especially paper-based media.
- The number of media discontinuities was reduced.
- A manufacturing dashboard gives higher transparency to the employees active in the area.
- A recipe management system is in place to avoid incorrect or employee-specific recipes.
- A manufacturing database logs process- and product-specific data for use in several service functions (e.g., maintenance department).
- Intralogistics also receives production requests now in order to proactively provide raw materials.

Also, further changes were made. All changes can be derived from Fig. 4.

5 Discussion and outlook

In all three tested companies a higher transparency of the current processes, media types and data flows was achieved. Also, this high level of transparency could successfully be used for communication with different departments, including non-IT-specialists, and for designing improvements. As exemplary shown in Figs. 3 and 4, the general number of different media and also the complexity of the data flow was much higher than shown in the previously cited papers.

Besides the increase in transparency, the identified improvements were considered highly useful by the companies. For the exemplary injection moulding process, they were estimated to direct time-savings of 30 min/shift for the shift leader, 15 min/shift for the machine operator, 15 min/incident for maintenance and additional efficiency gains of 30 min/shift for the manufacturing process. Further indirect gains were expected by the increased KPI transparency and update rate.

A general lack of connectivity was already known to the company, but the relevance of such could be pointed out more precisely, leading to a higher priority on the digitalization agenda.

It has been found that the described method is not only beneficial for use in complete value streams but is also applicable for deep dives in a single process box. Nevertheless, especially when designing future media landscapes in manufacturing, it should be avoided to concentrate on local optimization only.

For the general process improvement, the approach from Hartmann et al. [8], to add and specify the activities can also be of interest. Still, in a direct combination with the conducted method, the resulting process boxes would have an increased complexity which reduces their clarity. One approach to overcome this conflict could be to provide role-based views either with the raw data/information and KPIs or the specification of the activities. This could be subject to further development and testing.

To train the representatives of the companies, it took about one day training effort with an exemplary value stream prior to the application of the method. Still, it was helpful to have one person with more experience in application of the method accompanying the mapping and design phases. Also, the quality of the results was found to be strongly increased by providing a list containing exemplary data flows and utilizations. An exemplary excerpt of such a list can be found in Fig. 5.

6 Conclusion

In practice, to avoid digitalization ending in itself, the optimizations to be introduced and the corresponding projects should be derived from the daily business needs coming from the processes and the people being involved. Thus,

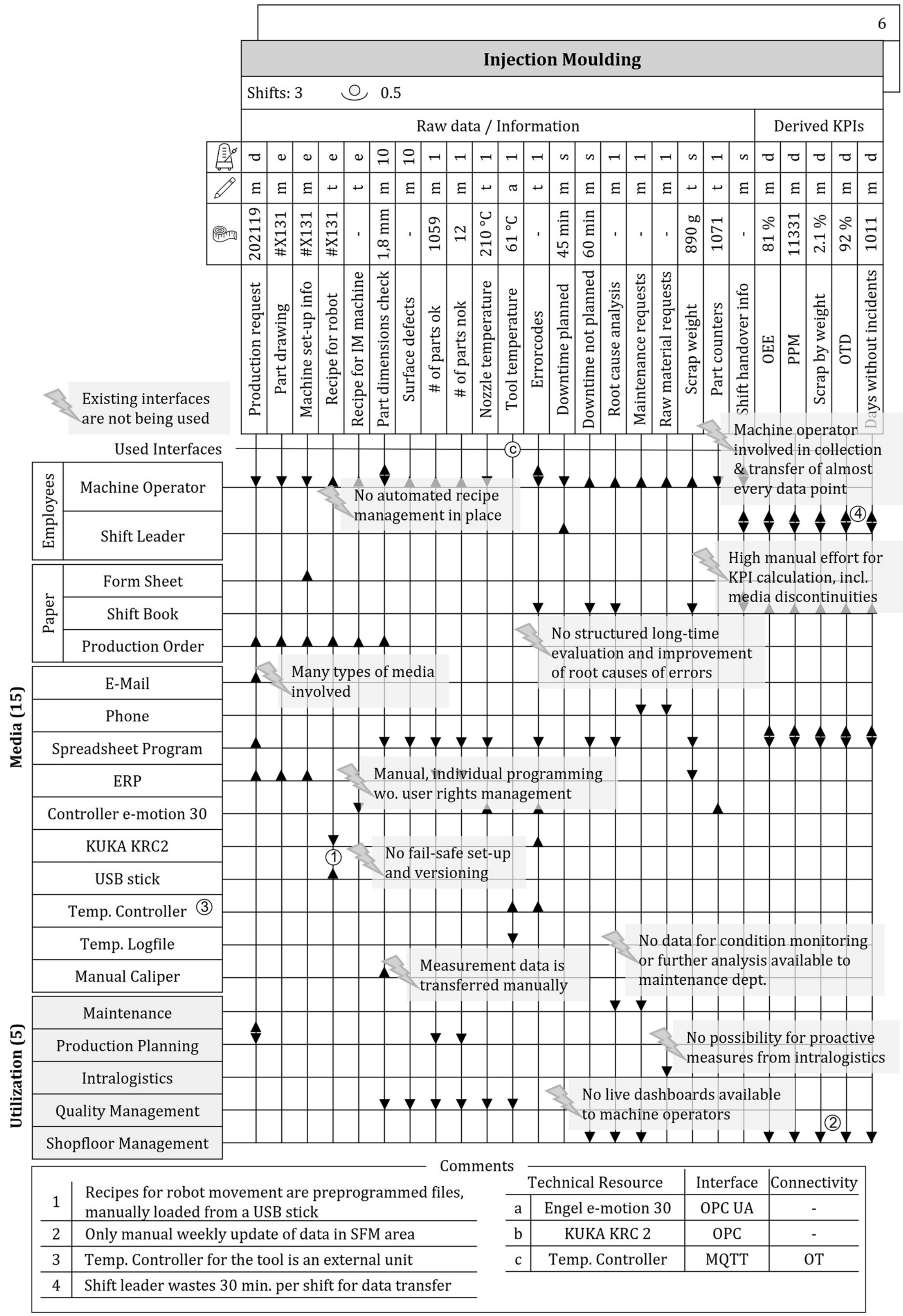


Fig. 3 Exemplary result using the enhanced method for a single process box from an automotive supplier (mapping of the current state)

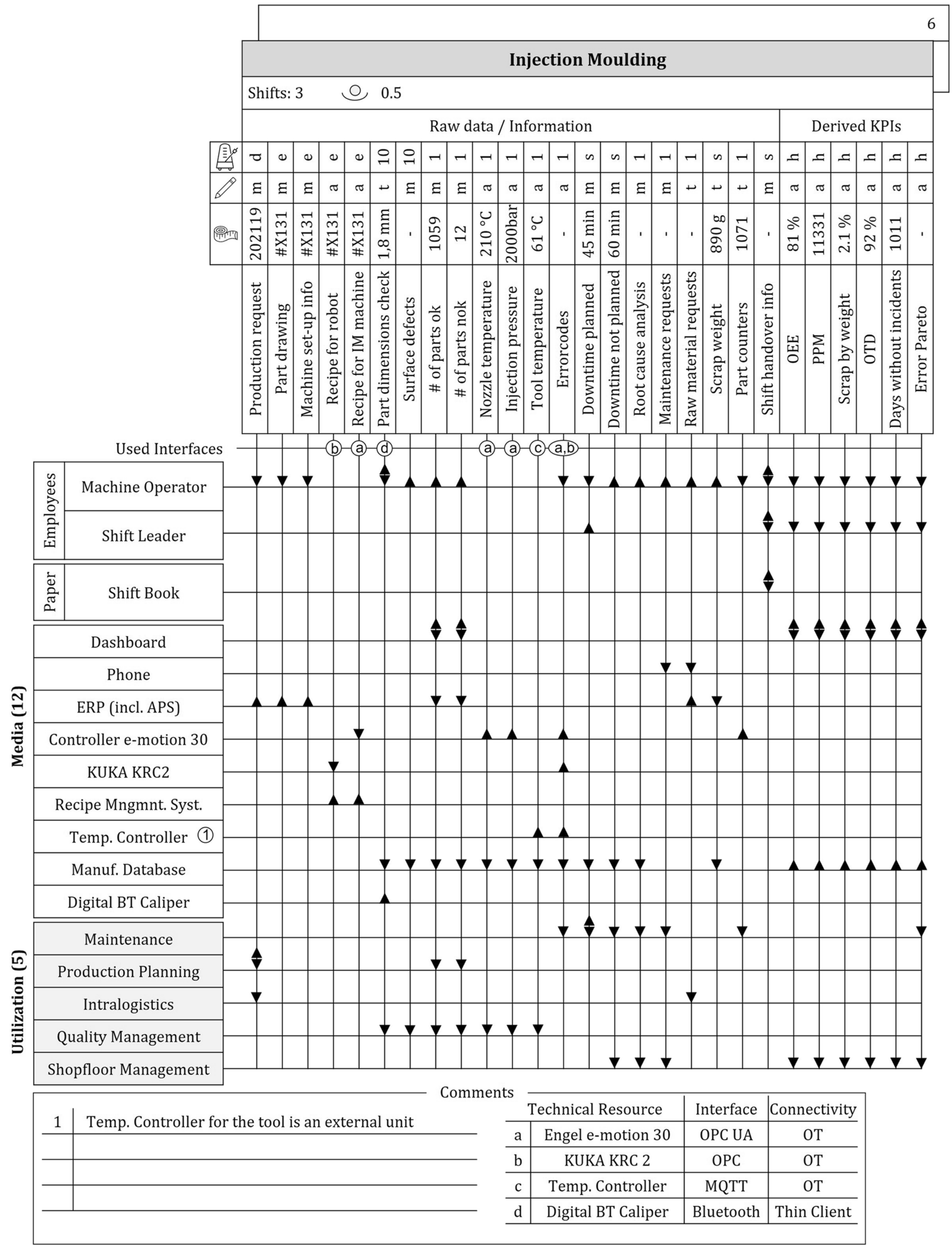


Fig. 4 Exemplary result of the design approach, using the enhanced method for a single process box from an automotive supplier

not for every single process necessarily the final smart factory level of self-organization must be achieved. Instead, even without reaching this far goal of self-organization or autonomy, several improvements like reduced unplanned downtime or increased asset utilization can be achieved underway.

To both get a detailed impression on the current state in the factory and to design the future state, the presented

KPIs, Parameters, etc.	Media
Production order	**Non digital**
Order registration	Employee
Work schedule	Phone
Material list	Production order form
Serial number	
Cycle time	**Digital**
Error codes	ERP
Set-up time	SCADA
Availability	MS Excel®
Downtime (planned)	Machine controller
Recipes	E-Mail
OEE	SQL Database

Utilization
Shopfloor Management
Maintenance department
Controlling
Quality management
Production Planning
Tool management
Process control
Operator assistance
Process simulation
Digital twin

Fig. 5 Exemplary excerpt of a list containing possible data flows, media, and utilization

method is viable. One benefit is that improvements which impact daily business can be identified. Also, it is a highly visual method that can be used to explain the needs and the motivation for the identified improvement initiatives to all involved parties, including non-IT-specialists.

The introduced changes of the method stated in Sect. 3.1 allow for a higher comprehensibility and clarity, making the content helpful and accessible to a larger community in the company. The specification of the technical resources and interfaces, including their usage, supports the identification of technological options and efforts for the optimizations. The differentiation between sinks and sources of data on the level of the single media, including the indication of data processing, is relevant for the design of the future media landscape. It supports decisions about the relevance of the involved media from the process-perspective. Replacing or removing media that processes the data can be a higher effort compared to replacing or removing media that simply stores or visualizes data.

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Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

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