A Planning Approach for an Effective Digitalization of Processes in Mature Semiconductor Production Facilities

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***Abstract*—Automation and digitalization are important measures for semiconductor manufacturers to enhance key performance indicators, and to strengthen their competitiveness. However, concrete approaches for effectively planning this digitalization of production or production-support processes are missing. Therefore, this paper introduces the Planning for Digitalization (P4D) approach. P4D aggregates general planning approaches for digitalization in production, as well as concrete tools and methods. By evaluating and categorizing their use in different situations of digitalization processes, P4D allows a situation-specific and new combination of these approaches and methods. Its goal is a comprehensive and action guiding compendium that can easily be applied. In this paper, part of P4D is exemplarily evaluated at a production site of Infineon Technologies in Dresden, Germany.**

***Keywords*—planning approach; factory optimization; lean manufacturing; digitalization; mature semiconductor fabrication facilities**

I. Introduction and Definition of Underlying Concepts

Mature semiconductor fabrication facilities following the "More-than-Moore" path face high competitive pressure regarding production times, costs, and quality, as well as short innovation cycles, and the need for fast ramp-ups of new products and technologies. Besides automation, the digitalization of manufacturing and logistics processes offers opportunities to meet these challenges by enhancing key performance indicators. Nevertheless, digitalizing production processes solely for its own sake does not guarantee satisfying effects. The transformation towards digital manufacturing procedures needs management [1] to avoid the misallocation of resources, time-consuming implementations of technologies, as well as overstrained and frustrated employees [2]. Therefore, the scope of this contribution is the development of a planning approach for semiconductor fabrication facilities on the "More-than-Moore" path to digitalize the "right" processes using the "right" technologies, and in this way, to maintain their competitiveness.

Before proceeding, a distinction has to be made between digitization, digitalization, and digital transformation as used in this work. Digitization refers to the one-to-one transformation of analogue to digital processes [3]. Digitalization, however, stands for the implementation of digital technology and includes its impact on the way of work in the company, e.g. [4]. And finally, digital transformation stands for a strategic business transformation using organizational changes as well as the implementation of digital technologies [5]. Another central term in this context is Industry 4.0. This term was first used in 2011 within the high-tech strategy of the German government. It stands for the intelligent linkage of machines and processes using ICT. It is also seen as the next evolutionary level of fabrication with implications for value creation, business models, downstream services, and work organization [6]. Similar notions in other countries are Internet of Things, Internet of Everything, Smart Factory, Smart Production, Industrial Internet [7] or Second Machine Age [8]. Another important concept accompanying Industry 4.0 is Big Data as basis for the communication of machines in a fabrication facility. However, due to uncertain borders, there is no common definition of which datasets are truly big. Big datasets in 1997 might have exceeded 100 GB, whereas nowadays the storage of such a dataset is not a problem at all [9]. Nevertheless, commonly used characteristics of Big Data are the so-called 5Vs: Volume, velocity, variety, veracity, and value [10]. Taken together, these aspects pose challenges to the used technology, and result in "datasets that could not be perceived, acquired, managed, and processed by traditional IT and software/hardware tools within a tolerable time" [11].

After this brief introduction and definition of underlying concepts, Chapter II includes the state of the art regarding existing planning approaches for digitalization and the research design of the authors. Chapter III contains a

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description of the new approach Planning for Digitalization (P4D). Chapter IV includes a first validation of the new approach by using the example of semiconductor manufacturing, before the results are discussed, and an outlook is given in the end.

II. State of the Art and Research Design

Holistic planning approaches for digitalization in manufacturing companies were already proposed by other authors. TABLE I allows a quick glance at mainly German studies that are relevant with respect to the addressed topic. For the selection of latest exemplary studies, it was important that they had at least one thing in common: They show possible procedures for digitalization projects from the beginning until the end. Each of them covers the steps of 1) stating goals, 2) assessing gaps in the current and desired state of digitalization, and 3) proposing measurements for application.

Reference [12] proposes in-depth analyses of relevant processes and compares them with best practices of Industry 4.0 applications. In this way, implementation strategies for one's own purposes shall be deducted. Therefore, the authors recommend to fill this toolbox continuously with best practices. Reference [13] provides a guideline consisting of five steps to aid small and medium-sized companies of the German mechanical engineering industry to find their own innovative business models for Industry 4.0. Focal in this approach is a so-called toolbox combining the different application levels of Industry 4.0. It is used for guiding the project team that is responsible for implementing the digitalization strategy. Reference [14] focuses on information processing in the company. It differentiates between the factors data, intelligence, and digital transformation (including human competencies) as vital aspects for a successful development towards Industry 4.0. Methods used for assessing the current readiness state and the desired one are as well workshops, complemented by interviews and reference tables for rating purposes. The acatech Industrie 4.0 Maturity Index presented in [15] uses the three steps (1) identification of current maturity state, (2) identification of capabilities requiring development, and (3) measures to assist companies in digitalizing. Reference [15] offers as well approaches for prioritizing measures and evaluating their benefits.

However, the presented approaches remain general in most parts and leave potential with regard to concrete measures. Differentiating and evaluating concrete solutions for digitalization out of a comprehensive catalogue of tools and technologies, would help managers and employees responsible for digitalization projects within the company as a manual. To overcome these weaknesses of previous studies and to enhance them, this paper aims at developing a planning approach for digitalization that includes several already existing methods for each step of the guideline. Furthermore, it aims at comparing and evaluating their use for different applications in digitalization. In doing so, special interest lies in quantifiable approaches and technologies that make investments and benefits of applying them as clear as possible to potential decision makers inside and outside the enterprise. In contrast to the aforementioned approaches that are based on readiness and maturity models, the focus of the following one lies on the manifold toolset of methods that can be used. The leading research questions are:

- Which methods are already used in existing planning approaches for digitalization and which further methods might be reasonable?
- How useful do these methods prove to be for a mature semiconductor production facility following the "More-than-Moore" path?

Besides desk research conducting literature reviews of the latest research regarding each step of the planning method, empirical evidence was collected from qualitative data via interviews and observations of workplaces at Infineon Technologies in Villach, Austria (IFAT) and Dresden, Germany (IFD). First, six semi-structured interviews at development, production and maintenance workplaces were conducted. In 2018, both executive and operations employees of each type of workplace were then interviewed. About 150 minutes of audio material was recorded, transcribed, and interpreted applying qualitative content analysis corresponding to [16]. Afterward, six days of observations [17] were conducted at a maintenance workplace at IFD lasting one shift each. In this use case the focus was especially on evaluating methods for assessing and projecting the degree of digitization of a maintenance process as one part of P4D.

TABLE 1. Studies Offering Digitialization Roadmaps for Manufacturers

Year	Reference	Scope
2014	[10]	Approach for digitizing processes using best practices in Industry 4.0 applications as referencial toolset
2016	[11]	Guideline and toolset for the German mechanical engineering industry to help developing innovative Industry 4.0 business models and products
2016	[12]	General approach focusing on information technology and processing as basis for Industry 4.0
2017	[13]	Approach including linkages between the Industry 4.0 maturity level and key figures for quantification

III. Planning for Digitalization (P4D)

In accordance with previous guidelines for conducting digitalization projects, and with respect to general planning approaches like in [18], P4D consists of the following six steps (Fig. 1):

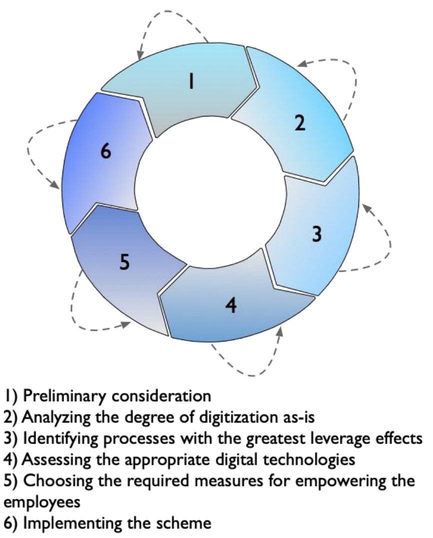

Fig 1. Recursive planning approach for digitalization projects – Planning for Digitalization (P4D).

1) Preliminary considerations,
2) Analyzing the degree of digitization as-is,
3) Identifying processes with the greatest leverage effects,
4) Assessing the appropriate digital technologies,
5) Choosing the required measures for empowering the employees, and
6) Implementing the scheme.

Each step of P4D may be repeated, if necessary. Furthermore, after finishing one digitalization project, this might be the starting point for a new one. In general, the necessity of and the will for digitalization has to be determined first. It has to state which goal is pursued by digitalizing and why, in order to justify following measures to internal and external stakeholders (step 1) [1] – ideally, a digital transformation strategy for the company already exists or id developed [5]. In steps 2) and 3) the as-is status of relevant processes has to be assessed, its degree of digitization analyzed, and projected. Afterward, reasonable technologies for digitalization are selected (step 4). If the implementation of new digital technologies necessitates measures for empowering the employees using them, step 5) proves to be relevant as well. Current competencies of the employees will be assessed, and suitable trainings and education programs for increasing them will be derived. Finally, step 6) is devoted to concretizing the results of the planning method in a plan of action before applying it. Responsibilities are defined and deadlines for implementation set.

This holistic approach of applying a digitalization project allows a multitude of methods and tools in each step that can be used as needed (Fig. 2). However, due to length restrictions, this paper focuses mainly on step 2), and partly on step 3). These steps are of interest, as there are only few methods that deal with assessing the degree of digitization of specific processes in particular. These approaches are presented, compared, distinguished, and evaluated in practice.

A. Analyzing the Degree of Digitization As-Is

General approaches to assess the readiness or maturity levels of whole companies are disregarded as there are already sufficient approaches to identify needs and possibilities towards Industry 4.0 [12–15]. In this section, it is of interest to compare methods to measure the degrees of digitization of concrete processes as objective and quantifiable as possible (TABLE II). The method of Value Stream Mapping (VSM) as a lean-management tool already includes the visualization of information flows in addition to material flows in production. However, the level of quantification of the information flows is quite abstract. Besides the number of employees being in charge of a business process, and the waiting time of new orders, no other metrics regarding the information flow are implemented. Therefore, it is foremost possible to visually identify waste, unnecessary additional work, redundant and inconsistent data storage or others, rather than by metrics [19]. In contrast, [20] focuses explicitly on the measurement of business communication. The developed categorization system of different types of information exchanges consists of ten forms of communication, from which five are considered as digital communication. This very detailed distinction between different forms of communication and the effortful calculation method allow a very precise analysis of different genres of communication within companies. However, within the digital forms of communication there are no further differentiations made in terms of quality. E.g. it is solely differentiated between digital and analog. The Value Added Heat Map (VAHM) is used for visualizing the value creation of production processes, including material and information flows. Therefore, it shows similarities to the VSM. But in addition to visually describing information flows, it offers a distinction between the different types by assigning to them levels of value added (TABLE III). Using the Degree of Digitization (*DD*) proposed in [21] with

$$DD \;=\; \left(\Sigma_{m=1}^{P} \, I_m \times VA_k \right) / \left(I_{P(\mathrm{tot})} \times VA_{\max} \right) \qquad (1)$$

where

- I_m represents the information flow "m",
- $m = 1, 2, \ldots, P$,
- $I_{P(\mathrm{tot})}$ is the amount of information flows in total of the analyzed process,
- VA_k is the degree of value added "k",
- $k = 0, 1, 2, \ldots, 5$, and
- $VA_{\max}$ is the maximum degree of value added ($k = 5$),

it is possible to quantify the contribution of each step and whole information flow processes to the value creation. Supposed, more digitization leads to more value creation, (1) can be used for assessing the degree of digitization. Furthermore, [21] suggests to highlight media discontinuities in the visualization of information flows by using different colors for identifying possible areas where information could be transmitted faultily.

As mentioned in the introduction, data play a vital role on the way to smart factories. Therefore, 3Vs of Big Data [22] seen as generalized categorizations can help further distinguishing processes and its information flows, or whole production systems by these indicators: volume, velocity, and

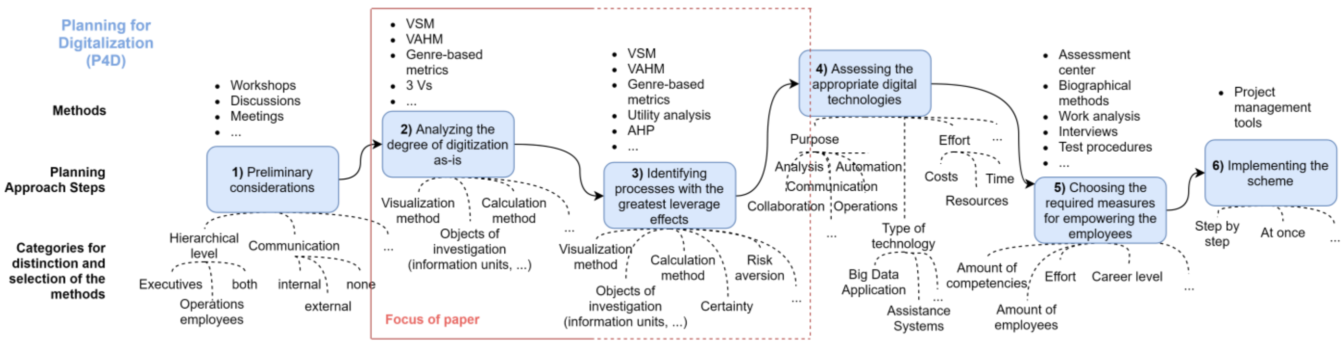

Fig. 2. Methods and categories for distinction and selection within the steps of P4D.

variety. Reference [9] proposes the following metrics for volume (2), velocity (3, 4), and variety (5) of a generic activity A for usage in big data application development:

$$Vol_A = \text{Amount of data managed by } A \text{ per incoming request} \quad (2)$$

$$VelG_A = \text{Velocity of data generation or arrival at } A = \frac{VolG_A}{TG_A} \quad (3)$$

$$VelP_A = \text{Velocity of data processing by } A = \frac{VolP_A}{TP_A} \quad (4)$$

$$Var_A = \text{Degree of structuredness of data managed by } A = \frac{Vol_A^{US}}{Vol_A} \quad (5)$$

where

- $VolG_A$ and $VolP_A$ are the volume of data arriving at A respectively the volume of data processed by A,
- TG_A and TP_A are the respective time periods of A, and
- Vol_A^{US} is the volume of unstructured data managed by A.

Derived from these characterized methods, a preliminary category system for distinction in step 2) of P4D can be set up. These approaches differ in offering visualizations and calculations of information flows. Furthermore, the presented methods differ in the objects under investigation, and the field they have been applied to, so far (TABLE II).

B. Identifying Processes with the greatest leverage effects

After having determined the degree of digitization of several relevant processes, in step 3) the processes will be prioritized. If there was only one process considered for digitalization already from the very beginning, this step proves obsolete. In this step, the beforehand used methods for assessing the current state of digitization can also be used for projecting the desired one. By doing so, weaknesses of the current processes can be seen visually – e.g. by using VSM or VAHM –, and improvements of these flaws can be calculated using the same methods as well. Presuming that the issue of being uncertain about digitizing which process first is basically a decision-making problem, it also makes sense to apply approaches from decision theory like utility analysis [23], decision trees, the analytical hierarchy process (AHP) and others. Such approaches can add more diligence to the decision-making progress, and can be especially suitable for more complicated problems. Therefore, the category framework in step 3) of P4D is extended in comparison to step 2). Possible methods for prioritization are therefore also differentiated, if they are taking certainty/uncertainty, and risk aversion into account (Fig. 2).

TABLE II. METHODS TO ASSESS THE DEGREE OF DIGITIZATION OF PROCESSES

Method	Categories			Reference
	Visualization	Calculation	Objects of Investigation	
Value Stream Mapping (VSM)	x	(x)	Material and information flows	[17]
Genre-based metrics and analysis	-	x	Business unit communication	[18]
Value Added Heat Map (VAHM)	x	x	Information flows in addition to material flows; media discontinuities	[19]
3Vs	-	x	Volume, velocity, and variety of data per generic activity	[6]

IV. P4D IN PRACTICE

To evaluate the use of P4D for semiconductor manufacturers, the aforementioned methods of the planning approach were tested at the production site of IFD. The production site at IFD follows the “More-than-Moore” path, developing large varieties of products with very short lifecycles in very short time periods. It compromises a fully automated production line for 200 mm (8 inch) wafers, as well as the world’s first front-end production line for 300 mm (12 inch) wafers. However, further development of digital technologies still yields possibilities for improvement in production and production-related processes. IFD has already gained experience in a variety of huge EU research projects concerning automation and digitalization, starting with projects like SemI40 and Productive40. Now, in iDev40 IFD and its partners are doing research on the automation and digitalization of process by integrating the human factor to enable enhanced human-centered workplaces. During an initial visit of the clean room and a workshop at IFD together with practitioners and experts, it was agreed upon analyzing the maintenance process of the transportation system inside the fabrication facilities as a starting point for a small use case for digitalization. Due to the scope of this paper, step 1) of P4D is skipped, and it is started with step 2) right away – besides, the interviews with the employees have shown, that automation and digitalization strategies are known, widely accepted, and supported by the colleagues within the company. The workers are used to the constant and sometimes rapid changes in the semiconductor manufacturing industry and therefore seeing the necessity of such a roadmap. Nevertheless, at least some employees with less complex tasks still keep their skepticisms towards digitalization as they foremost fear losing their jobs due to this development.

A. Analyzing the Degree of Digitization As-Is

Following the P4D approach, methods out of the before developed toolbox in step 2) of the planning approach were selected. For assessing the current state of digitization of the standard workflow in maintenance of the transportation system, first the approach of the VAHM [21] was used. VSM was left out due to less elaborated calculation possibilities for

TABLE III. RATING OF DIFFERENT TYPES OF INFORMATION FLOWS IN ACCORDANCE TO [12]

Degree of Value Added	Form of Information Flow
0	Missing, insufficient, incorrect or redundant information flow
1	Written information flow (e.g. via paper document, fax, email, etc.)
2	Oral or visual information flow
3	Electronic information flow in not-real-time (e.g. via spreadsheets)
4	Electronic information flow in real-time (e.g. via ERP systems)
5	Digital information flow in real-time (e.g. via Internet of Things)

information flows. The genre-based metrics and analysis were discarded as this method focuses more or less on business communication in offices. In contrast, VAHM offers both visual and more detailed calculation tools for analyzing information flows. Nevertheless, due to less material flows and the enormous area of maintenance activities – essentially across the whole production site – there was no effort to visualize the complete material flows and the facility, in the end. Instead, a process diagram of the current workflow was established. To do so, the interviews with several maintenance workers and observations at the respective workplaces were conducted. Afterward, the information flows within this process were categorized and quantified with regard to its contribution to the value creation (TABLE III). Using (1) it follows, that in its current state the standard maintenance process has got a minimum degree of digitization of 28 percent and a maximum degree of digitization of 65 percent (Fig. 3; TABLE IV). Conversely i.e. that the theoretical potential of further value added VAP_{theo} with

$$VAP_{\text{theo}} = 1 - DD \tag{6}$$

results in 72 to 35 percent within the examined process [21].

In a next step, the structuredness of the information that reaches the maintenance workers was added to the analysis as one of the 3Vs of Big Data. As the flowchart in Fig. 3 already illustrates, there is a variety of sources and media used for signaling the occurrence of errors. Using (5) in the process step of notification (Fig. 3) – and considering the notification via medium #1 separately (manually and automatically) – results in 67 percent of structuredness of the information managed by the maintenance staff.

B. *Identifying Processes with the Greatest Leverage Effects*

As shown in Fig. 3 and TABLE IV, the information flow with the lowest degree of value added is, when the maintenance staff has to prioritize the incoming error notifications (workflow node 4), and chose who is taking care of which. In some special cases, it could happen that an error notification can be received by more than only one maintenance worker at the same time. Therefore, it is possible that the information about the current activity status of the co-workers are in that special case insufficient. This can lead to two workers tackling the same problem, without knowing from one another's efforts. Therefore, the degree of value added k in this case is zero due to insufficient information flows. At the same time, in Fig. 3 can be seen that this process also happens to be kind of a bottleneck, as in any case this step is necessary. In conclusion, digitization efforts in this step will yield the greatest effects in terms of value added – this strategy is superior to increasing the value added of other information flows as compared in TABLE IV. Increasing the degree of value creation in this process step by up to 5 results in overall degrees of digitization of the maintenance process of up to 48 (minimum) respectively 90 percent (maximum). Furthermore, reducing the unstructuredness of the information flows used in the notification step will increase the uniform transportation of data, and eliminate some flaws. In conclusion, this means that for identifying promising starting points for digitalization approaches in step 3), the same methods were already used as in step 2). It was not recognizable that uncertainty or risk aversion would play a decisive role in this case. Therefore, other methods were left out.

C. *Next Steps*

The next steps 4) to 6) of the P4D are outside the scope of this paper, but will be exemplarly highlighted for further understanding. Exemplary methods and categorizations of these are also shown in Fig. 2. In this IFD use case, the purpose of possible technology to be selected in step 4) is to support the decision making respectively the prioritizing and communication process. Thus, digital technology matching

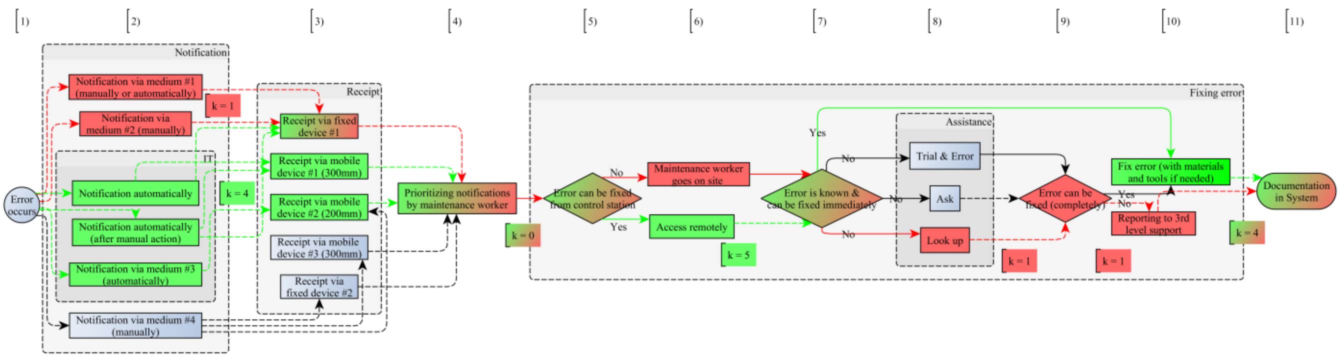

Fig. 3. Part of a standard maintenance process at IFD's transportation system including Degrees of Value Added k – overall minimum (red) and maximum (green).

TABLE IV. DEGREES OF DIGITIZATION WHEN INCREASING THE VALUE ADDED OF ONE INFORMATION FLOW EACH

Workflow node representing I_m	2)			4)	6)		8)			10)			11)	**Overall DD (minimum–maximum)**
VA_k per I_m	1	or 4	or 2	0	–	or 5	–	or 2	or 1	–	or 1	or 2	4	0.28–0.65
DD when increasing VA_k per respective I_m to 5 (c.p.) (minimum–maximum)	0.32–0.7	0.28–0.7	0.28–0.7	**0.48–0.9**	–	0.28–0.65	–	0.28–0.65	0.32–0.65	–	0.32–0.63	0.28–0.63	0.32–0.7	0.28–0.9

these categories can be e.g. IT systems that show all of the states of the machines in real-time in one place, possibly interconnected with the mobile devices of all of the maintenance staff. Furthermore, the position and status of the maintenance workers within the facility could be reasonable to see. Therefore, the maintenance staff can get standardized, interconnected, and personalized up-to-date mobile devices. In this way, they have access to the same information systems as in the control room in real-time. V.v., a dispatcher inside the control room has got a better overview of his colleagues doing what and where.

For assessing the current competencies of the workers in step 5), the observations and interviews made also a small work analysis possible, giving first impressions of some of the worker's competencies. As the planned change in technology does not include unknown hard- or software to them, there is possibly no need for further training of the employees.

The implementation roadmap (step 6) in this case consists of the presentation of the results to the managing board highlighting the benefits of the undertaking. After approval of the planned action, in a second step the affected colleagues will be presented the results to, as well. In addition, a workshop discussing the results with them should prove, if the planned measures seem reasonable, and if they are likely to be accepted by the maintenance staff. If the feedback is mainly positive, a pilot stage will be launched, implementing the technology and change gradually. The interviews have shown, that choosing employees for this stage, who are enthusiastic about the new technology, will act as a natural multiplier of their attitude among their colleagues. Nevertheless, caution is advised, if aspects were not considered that are crucial for the motivation of the employees. The observations and interviews of the maintenance workers e.g. have shown that one main positive aspect of their job is the diversity of tasks. This includes physical as well as mental activities inside the control station and on site in the facility. Installing a specific person inside the control station instead of all of the workers acting as a managing clerk, might eliminate this variety of the job. Alternatively, a rotation principle could be installed, letting the managing clerk change after a while.

V. Conclusion And Outlook

The evaluation of steps 2) and 3) of the P4D approach at the semiconductor manufacturer IFD has shown that the developed category framework for the methods in step 2) have proven helpful. Applying it, VAHM was chosen to assess the degree of digitization of a current standard maintenance process. It combines visual and more detailed calculation methods than the others. Furthermore, VAHM proved to be sufficiently flexible, as in the use case the visualization of the shop floor as well as depicting material flows was left out. Still, satisfying results could be achieved by visualizing the workflow, especially the information flows. In addition, the visualization allowed already identifying a bottleneck process for improvement (step 4), having the lowest degree of digitization. Besides, measuring the variety of the incoming information by using (5) from big data application development, helped quantifying further possibilities of improvements in terms of structuredness of information flows. All in all, conducting observations of and interviews with several shifts for assessing these work and information flows is very effortful and might be handled more efficiently. The framework for categorization, as well as the methods themselves will have to be evaluated further in practice – especially in more complex processes. Nevertheless, the presented planning approach in general aggregates existing methods and tools, and combines them for reaching the company's digitalization goals. The value of this paper therefore is the effort of collecting and filing possible methods in this context in one place. Its goal is the establishment of a compendium and manual for individual combination and use. By doing so, this work represents just the beginning, and by far not all of the thinkable and useful approaches could have yet been considered (Fig. 2).

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