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A STEPWISE IMPLEMENTATION OF THE VIRTUAL FACTORY IN MANUFACTURING INDUSTRY

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ABSTRACT

A big challenge for manufacturers today is to create a flexible and efficient production system. One way of managing this challenge is to establish a virtual factory, a virtual model of the production unit. Working smarter by using the advantages that digitalization implies enables production of personalized products at increasing speed. This paper explores how to implement such a concept by stepwise increasing the maturity of the virtual factory. Evaluated at a large-scale Swedish manufacturer, local needs and enabling technologies benchmarked at industry leaders have been identified and strategically mapped to their corresponding maturity step. This paper shows that the implementation of a virtual factory relies on standardized work procedures, ensuring its use as a decision aid throughout the company. Implementing a virtual factory in this manner will facilitate user-driven development and more accurate decision making, generating support for efficient production systems.

1 WORK SMARTER NOT HARDER

As industries grow on a global scale, companies must meet the demands of an increasingly competitive market. To satisfy customers, challenges including manufacturing of high quality products to low cost become apparent. Stimulating such innovation while maintaining cost efficiency require companies to utilize available resources and competences as efficiently and effectively as possible. To increase competitiveness in such a market climate, recent development trends in industry located in high-wage countries focus on an increased level of digitization (Schönsleben et al. 2017). This development is fueled by the potential to reduce lead time and cost as well as support decision making processes (Becker et al. 2005; Terkaj et al. 2015).

One way to provide decision-makers with facts is the implementation of a virtual factory. A virtual factory is a digital platform where data collected in production are consolidated and presented visually as relevant and precise information for the individual user, or user groups (Yang et al. 2015). Therefore acting as a foundation for data-driven decision making in process development (Terkaj et al. 2015). Furthermore, the virtual factory can help the user observe events and their effects, thus providing a holistic understanding of the production system for different stakeholders (Becker et al. 2005). Implementing a virtual factory can, therefore, leverage performance and support a transformation towards a more flexible and efficient production system. In summary, the virtual factory provides a way for basing decisions on observable facts rather than on perceptions enabling more efficient management of resources, and, thus, working smarter not harder.

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The digital twin was first mentioned in 2002 and is the concept of having a virtual environment that contains all of the information of the physical system (Grieves and Vickers 2017). A virtual factory is in this paper seen as an application of a digital twin, and has been explored by researchers since its early emergence. For instance, simulation models has been demonstrated as data analytics applications and the virtual factory was presented as the vehicle for manufacturing modelling and simulation (Jain et al. 2017). In addition, a methodology for integrating heterogeneous software tools supporting factory design has been developed (Colledani et al. 2013). Several papers provide examples of virtual tools that can be used in the virtual factory (Lobo et al. 2014; Yang et al. 2015). Even though using a virtual factory has been proven to support investments in manufacturing (Freiberg and Scholz 2015), few efforts have been focused on providing a holistic perspective on implementation (Choi et al. 2015).

This paper presents a methodology to identify needs at a case company and available technology from industry leaders. It proposes a strategic stepwise implementation of a virtual factory, tailored to match the needs at the case company, with the aim to enable decision making based on facts.

2 DEVELOPING DIGITAL PRODUCTION

Digitalization, combined with a modular production system, can facilitate manufacturing of personalized products of high quality in batch sizes of one while maintaining the cost of mass production (Lasi et al. 2014). Applied in an industrial context, digitalization forms a digital factory where the virtual factory is an important subsystem. Consequently, the virtual factory must uphold a seamless interplay between its several technologies to provide an efficient tool for production development.

2.1 Digitalization

The introduction of computers facilitated the conversion of things into bits which could be stored and sent over a network – things became digitized (Brynjolfsson and McAfee 2014). The personalized production paradigm could be seen as an extension of digitization; digitalization (Lasi et al. 2014). Digitalization is herein defined as: *”The use of digital technologies to change a business model and provide new revenue and value-producing opportunities; it is the process of moving to a digital business”* (Gartner 2018).

One crucial enabler for realizing the value that digitalization offers is the Internet of Things (IoT). This technology makes it possible to connect the entire manufacturing process, which converts factories and enterprises into smart environments often included in the agenda of Industry 4.0 (Kagermann et al. 2013). The core idea is to use emerging information technologies to facilitate the implementation of IoT and related services in order to create a flexible and efficient production system (Lasi et al. 2014).

2.2 Digital Factory

The digital factory is considered as an umbrella term, describing the model environment as well as the use of digital tools, methods, and data management systems in an enterprise (Yang et al. 2015). The technology in the digital factory serves to integrate various levels in the organization and to facilitate control of production, planning phases, system and process design as well as product development, and further facilitating collaboration and information management within an organization (Kuehn 2006). It can, therefore, be interpreted as an overlapping function between the physical system and the virtual system.

2.3 Virtual Factory

The virtual factory is considered as the model environment containing geometrical and mathematical representations of resources (Yang et al. 2015). In this paper, the virtual factory is constituted of two or more linked virtual work cells, which consist of one or more virtual machines, finally being built from virtual processes interpreting the products moving through the virtual production system. It is the back-end system, not directly seen or interacted with by the user. Instead, the user interacts indirectly with the virtual factory through modules, herein defined as tools for analyzing its data. When data are collected and fed into the virtual factory in real-time, a digital factory twin emerges. Being fully connected, it exhibits a near identical behavior to the real production unit (Schleich et al. 2017).

2.3.1 Maturity of a Virtual Factory

As digitalization projects in industry are at different levels of development, their respective level of maturity can be described (Schuh et al. 2017). Likewise can the maturity of the virtual factory's capabilities be measured. The difference in levels of functionality is utilized to define six steps of maturity, based on the framework proposed by Bjarnehed and Dotevall (2018) (Figure 1).

The first step, Digital Model, considers the establishment of a digital simulation model. It represents the current state of operations and serves as a virtual representation of the physical production unit and does not rely on real-time data. The second step, Connected Model, considers the digital model supplied with real-time production data. At this step, the virtual factory represents the production unit's current state and accurately reflects its inner workings – a digital twin is created. The third step, Diagnostic Model, considers the ability to diagnose the different operations and processes in the factory; utilizing the collected real-time data to produce up-to-date analyses. The fourth step, Prognostic Model, includes the ability to produce information as prognoses, predicting certain events and outcomes of the production unit it is representing. The remaining two steps consider an increased intelligence where the fifth step is a Descriptive Model. This step includes the ability to continuously learn from experience and suggest actions depending on different current and future states. At the final step, Autonomous Model, the virtual factory is self-governing. The model now has the ability to make decisions without human interaction; it is able to control production. Lastly, in this paper, not having established a simulation model, will be referred to as step 0.

The input data used in the simulation model must be correct and of sufficient quality to produce any useful results (Bengtsson et al. 2009). Therefore, input data management is a crucial part of the maturity of the virtual factory even though it is not depicted in the model. The virtual factory will never be more capable than the weakest part of its backbone due to the dependency on the preceding steps as well as the data used to design and run the model.

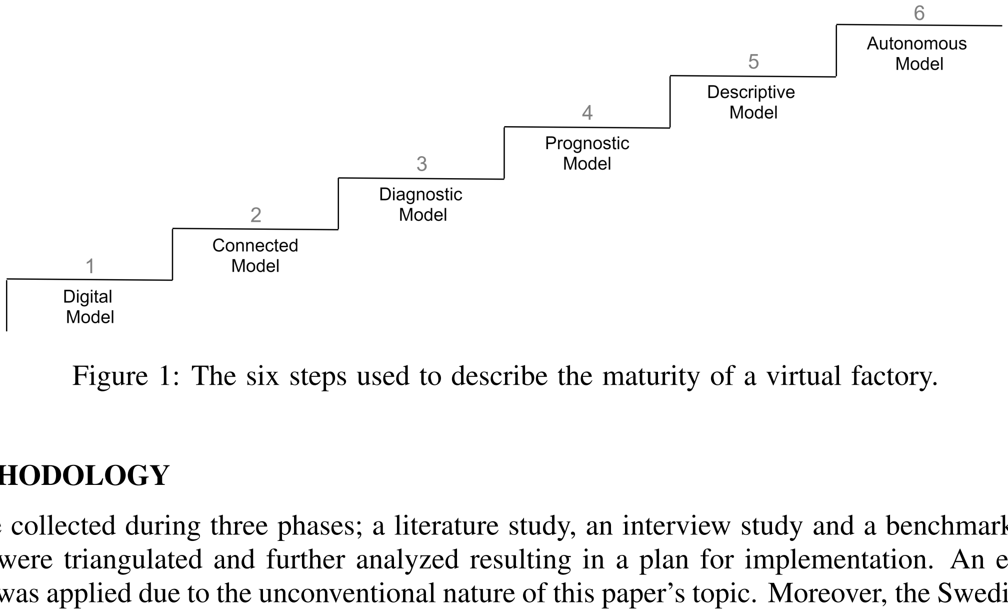

Figure 1: The six steps used to describe the maturity of a virtual factory.

3 METHODOLOGY

Data were collected during three phases; a literature study, an interview study and a benchmarking study. The data were triangulated and further analyzed resulting in a plan for implementation. An exploratory approach was applied due to the unconventional nature of this paper's topic. Moreover, the Swedish bearing manufacturer SKF Sverige AB was chosen as the case company. Its high product quality standards as well as its location in a high-wage country make it a well-suited candidate for implementation of a virtual factory (Schönsleben et al. 2017). Hereafter, SKF Sverige AB will be referred to as the case company.

3.1 Literature Review

The literature study provided initial contextual and technical information regarding the subject of virtual factories and current trends in digitalization efforts. The key topics included; virtual factories, digital twin, digital tools, discrete event simulation, verification and validation of simulation models, and input data management.

3.2 Identifying Needs

Interview sessions were designed in accordance with the proposed framework for in-depth interviews (Kvale and Brinkmann 2014). The questionnaire was based on five main sections: introduction, information, technical readiness, acceptance, and summary. This structure was created in order to facilitate review and analysis of its qualitative content. The interviews were conducted in a semi-structured manner, supported by both audio recordings and notes taken during each session. The interviews were carried out during eight weeks, each conducted with one interviewee and with a maximum duration of 45 minutes. In total 25 employees were interviewed, mainly from the department of process development, since it constituted the primary scope of the study. Additionally, interviews were conducted with employees from the departments of production technology, manufacturing development, product engineering, and factory management. The inclusion of the adjacent departments was made to define requirements of usability and organizational collaboration. The distribution of interviewees from each department was 17, 2, 1, 2, and 3 respectively.

3.2.1 Coding of Interview Data

The qualitative data from the interviews were analyzed through coding to assess the information (Bryman and Bell 2003). It was carried out as soon as possible through sprints every three interviews. Parts of the data were processed through open coding and grounded theory, and the remainder was processed through magnitude coding. Through open coding data were organized to build the foundation for identifying needs. Magnitude coding (Saldaña 2009) was utilized to construct scales of technical readiness, knowledge about the subject, and acceptance within the organization. Technical readiness was constituted of three subcategories; digitalization, simulation, and virtual factory. Each subcategory has been designed to provide insight into the topics adjacent to the concept of the virtual factory.

The range for the magnitude coding was determined to three discrete levels (-1, 0, 1), described in Table 1, for both categories and its subcategories. The subcategories for technical readiness were merged through a weighted average. The weights were distributed to reflect the adjacency to the main topic and were chosen to 0.25 for digitalization and simulation and 0.50 for virtual factory. Due to the many interpretations of the topics that exist, additional levels were not deemed to improve the accuracy of the coding.

Table 1: Description of the magnitude coding for the interviews.

Level	Technical Readiness	Acceptance
-1	No knowledge	No acceptance
0	Some knowledge	Neutral acceptance
1	Full knowledge	Full acceptance

3.3 Identifying Available Technologies

To understand which strategies and tools are available and used by other companies, a benchmarking study was performed. The benchmarking study was conducted with the main objective to find the current maturity of the company's virtual factory which provided insights to the used technology, acquired or developed, as well as organizational structure and requirements. It was performed with companies recommended by academia and field experts at the case company. The chosen companies were furthermore identified as industry leaders and could be characterized as large-scale manufacturers of high quality products or services with well-established and mature organizations located in Sweden. Three companies were identified as industry leaders and chosen as benchmarks. Company α and β are automotive manufacturers and company γ is an engineering consulting firm focusing on process, production, IT, and product development in industry.

A benchmarking session was constituted of a study visit where a meeting with a subject matter expert took place. The primary deliverable from a benchmarking session was a semi-structured interview with the subject matter experts to gain knowledge about their virtual factory and its implementation. This combined with a preview of the facilities generated a holistic foundation, which enabled comparison to the case company's needs.

3.4 Matching Available Technologies to Needs

The framework for constructing the implementation plan can be seen in Figure 2. Its structure has been made to assess all of the gathered information throughout the project and to ensure the validity of the provided solution. The strategy was founded on two perspectives; the needs expressed by stakeholders of the virtual factory at the case company, and the available technology found at industry leaders and through examination of current research. Furthermore, to ensure the ability to combine these perspectives, prerequisites of organizational maturity, technical knowledge, and acceptance were considered to facilitate a user-driven and continuous development. Finally, expressed local requirements for implementation were explored. The findings were further utilized to consolidate the implementation plan. Through this methodology, an implementation strategy was presented as well as further structured in accordance with the model of virtual factory maturity, as depicted in Figure 1.

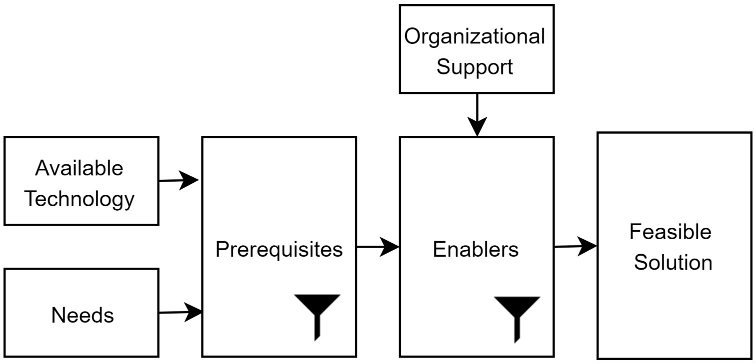

Figure 2: The developed analysis framework for delivering the implementation plan.

4 RESULTS

4.1 Needs at the Case Company

The identified needs at the case company have been divided into two subcategories; technical and organizational needs. Technical needs concern the functionality of the virtual factory, and should be interpreted as a toolbox. Organizational needs reflect the use and the implementation of the virtual factory, and, thereby, provide important insights into the case company's expectations and experience.

4.1.1 Technical Needs

In Table 2 all identified technical needs are presented, in descending order of the frequency they occurred during interviews. Altogether 29 unique needs were distinguished among stakeholders of the virtual factory. Despite some needs were expressed more frequently than others, it does not necessarily imply that they are more important. Furthermore, each identified technical need has been labeled with a capital letter which will be used later in Section 4.3.

Table 2: The identified technical needs at the case company and their respective frequency.

Expressed Need (Label)	Freq.	Expressed Need (Label)	Freq.
Simulation of production flows (A)	16	Reuseability of base model (P)	3
Visualization to educate (B)	10	Path planning and collision tests (Q)	3
What-if analysis (C)	10	Online based model (R)	3
Common information platform (D)	8	Traceability of sources of errors (S)	3
Factory layout design (E)	8	Simulating staffing in production (T)	2
Economical investment decision aid (F)	8	Work environment and ergonomics (U)	2
Resource allocation/optimization (G)	7	Integration of CAD-models (V)	1
Evaluation of available capacity (H)	7	Evaluation of product quality (W)	1
Factory layout representation (I)	7	Accurate virtual measurements (X)	1
Cost calculations for products (J)	7	Virtual FAT and SAT (Y)	1
Simulate process parameters (K)	6	Traceability of machine changes (Z)	1
Product-production feasibility (L)	4	Simulation of product assembly (AA)	1
Production logistics planning (M)	4	Optimize operator movement (AB)	1
Planning of maintenance (N)	3	NC-programming support (AC)	1
Commissioning for installation (O)	3		

4.1.2 Organizational Needs

The distribution of interviewees' acceptance and technical readiness is depicted in Figure 3, where the bubbles' area corresponds to the number of interviewees. The acceptance is very high at the case company, with the exception of one interviewee who was neutral, while the technical readiness shows a wider spread among interviewees, ranging from no knowledge to full knowledge about the topic. To conclude, acceptance for implementing and using a virtual factory is close to full and the technical readiness upholds a wide spread. Due to this, the final analysis will focus on decreasing the spread while increasing the average technical readiness.

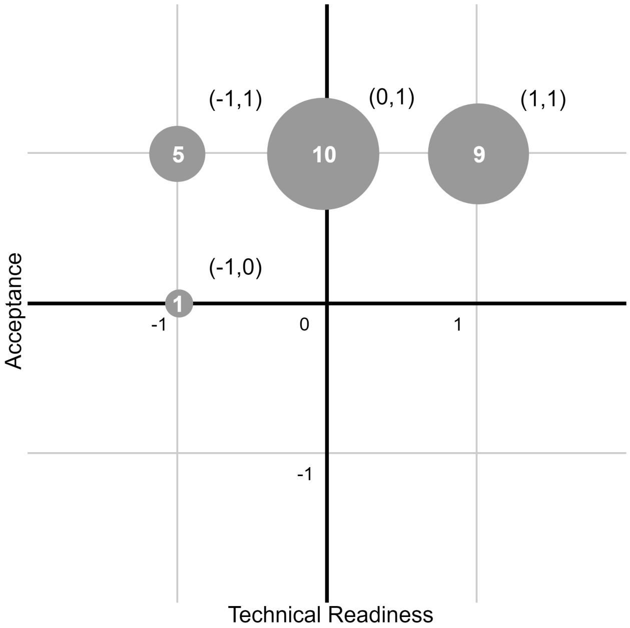

Figure 3: The distribution of acceptance and technical readiness among interviewees at the case company.

Developing pilot projects with key individuals, supported through active leadership was expressed as important. Furthermore, the need to prevent single key users was expressed in order to ensure a wider range of users. A stepwise implementation of modules and functionality was further deemed significant for enabling value-adding activities throughout the implementation. Prioritizing simplicity through standardized work procedures and striving for minimizing the amount of imposed administration was moreover seen as crucial concepts to enable a successful implementation and widespread use. In this regard, it was further added that local full-time personnel responsible for the virtual environment would be required to ease simulation and development efforts. Closely related to the ease of development, educational aspects both considering practical training and providing relevant competences for personnel were deemed important. Further, the importance of accessible in-house competences was expressed.

Specific needs regarding the system architecture and its functionality were expressed. Concerning the software infrastructure, needs to enable communication between different software systems sharing information between personnel and throughout various departments were expressed. In this regard, modularization of the simulation environment (Johansson 2006) was also expressed as important, creating different sets of tools for different users. Further should widespread use of the technology among personnel be desired, a general ease of use need to be prioritized. An online-based environment, creating ease of access and the possibility to view production environments from different locations, was also desired. Moreover, the need for proper routines to assess aspects of input data management and data quality was expressed, as well as the need for general maintainability of the system. The collected production data further require sufficient level of detail to represent the real production environment.

4.2 Available Technologies at Industry Leaders

Company α exhibited no digital simulation model of any factory, placing α at step 0 in the maturity model. Nevertheless, the company had a well-established digital toolbox for product development, assembly work, work-cell design, and similar. Some simulation of processes and flows existed but was not connected. In addition, the majority of factories owned by α had been 3D laser scanned, a technique used for rapid and accurate digitalization of spatial properties of objects or surroundings (Lindskog et al. 2012). This has provided a way for α to easily visualize factory layouts and support installation of, e.g., new machines due to the ability of making accurate measurements. α currently focuses on developing a common platform where all of the existing digital tools will be merged and build the foundation for the virtual factory, reaching for step 1, but aims at developing a Prognostic Model (step 4).

Company β exhibited a digital simulation model of the factory, placing β at step 1 in the maturity model. The current model was not connected, and was primarily used for what-if simulation in production development at process, line, supply chain, and factory level. β utilized two different simulation software systems, one commercially available and the other in-house-developed in collaboration with academia. The latter provides powerful Artificial Intelligence (AI) and Machine Learning (ML) algorithms for multi-objective optimization. AI is herein referred to as the science of making machines perform actions that would require human intelligence (Michalski et al. 1983), while ML is defined as the process of finding and describing structural patterns in data (Witten et al. 2017). The two software systems are used simultaneously, enabled by a connector, and stored online making the model accessible. Furthermore, β utilizes Value Stream Mapping (VSM), a method for mapping all actions currently required to bring a certain product through the main flow, to visualize certain simulation data in a recognizable manner. In the future model development, connectivity is the focus as well as further developing AI, which would place β on step 2.

Company γ have developed, in collaboration with the project receiver, a Prognostic Model placing them at step 4 in the maturity model. The model is a 2D representation of a highly specialized unit within the company. It is fully connected to the real factory and stored on local servers. The virtual factory depicts the theoretical output and the ideal state, and predicts maintenance actions, enabled by advanced analytics, which helps optimize the performance of the plant. γ is currently focusing on replicating the model to other units in the company, and not directly developing the model's functionality.

4.2.1 Importance of a Standardized Way of Working

To ensure that the virtual factory is used effectively, standardized work procedures carry substantial importance. Such procedures reduce the cost and time consumption associated with the establishment and continued use of the virtual factory. The amount of new technology required for the development of the virtual factory could easily hinder a holistic perspective. By establishing standardized work methods, much of the value of the virtual factory can be realized. Regarding the establishment of the virtual factory, the human must be put in the center of its design. This is exemplified at company β where a success story related to standardized work procedures was identified. By establishing 3D simulation models of its production environment, production lines have successfully been replicated over national boarders at different production plants, generating greater returns from development projects. Additionally, both company γ and β have established standardized work methods where it is mandatory to investigate the outcomes of production development projects through simulation. Through the information gained from the virtual factory simulation, the decision making processes have become based on facts, improving their quality and outcome.

Regarding creation of simulation models, it can be seen that conventional methodologies have been adapted to each company. For instance, β currently explores the possibility of establishing libraries of standardized function blocks as representations of processes within the virtual factory, to increase the speed and to reduce the competence required for developing simulation models. Furthermore, 3D laser scanning efforts as most successfully applied by α were identified to rely on work methods and mandatory re-scans for all changes made to the production environment. By continuously and frequently scanning the environment, the virtual model is ensured to be up-to-date, creating an accurate representation of the real production system.

Although standardized work methodology for simulation projects lately have become more extensive according to trends seen at industry leaders, input data management is still a complex issue. There are several methods used by industry for data collection in production, generating different levels of data quality (Skoogh et al. 2012). As applied by β, manual collection methods are utilized to keep aggregated data bases fairly up-to-date and the data, therefore, suffer from a general lack of continuity. γ had a fully connected model with greatly automated input data management, enabling continuous communication between the real factory and the virtual factory.

Finally, this study finds that educational efforts must be regarded as a part of the structured work methodology for the virtual factory establishment. The potential of the virtual factory relies on the knowledge possessed by the end user.

4.3 Implementing the Virtual Factory

The following section presents a plan for the implementation of the virtual factory considering its different levels of maturity. In Figure 4, the identified needs, as presented in Table 2, are presented in accordance to their corresponding level of required maturity. Since no present needs require the technology associated with a maturity higher than step 4, this study concludes its plan for implementation at said step to preserve user-driven development.

4.3.1 Reaching Step 1

The needs associated with the first maturity step consider utilization of the virtual factory offline. At this point it is a discrete event simulation model and thus enables fulfillment of analysis of parameters not relating to real-time production data. To facilitate development and establishment of an accurate digital model, collection of production data and product-related data are necessary in order to describe the behavior and constraints of the production unit. Depending on the desired level of detail and visualization requirements, accurate measurements of the production facility are needed. Finally, the correspondence between the virtual model and the real-world production facility it represents needs to be confirmed.

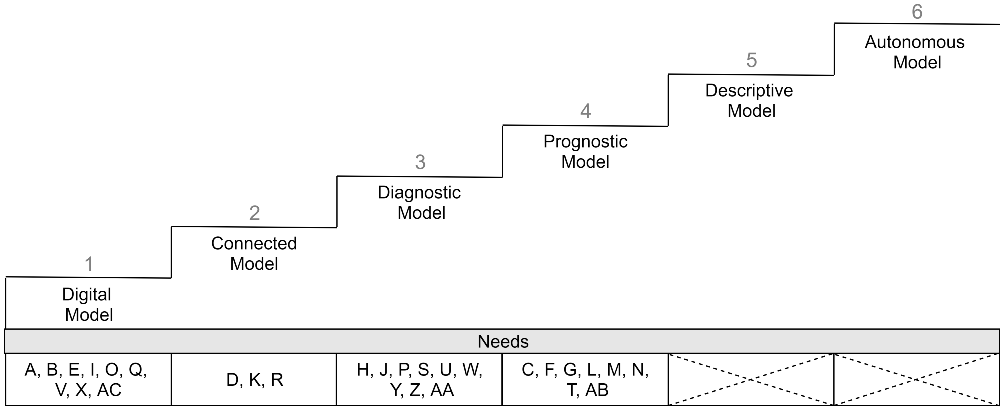

Figure 4: The identified needs mapped onto the six maturity steps of the virtual factory.

The enabling technologies identified in order to satisfy transition to the first maturity step are realized in implementing discrete event simulation software. Also implementing software for layout design and creating designated APIs to enable transfer of data between the different tools are crucial. Moreover, 3D laser scanning equipment to accurately model the production unit, process, product, and machine parameters also needs to be acquired and a verification and validation study needs to be performed.

4.3.2 Reaching Step 2

The second step, a Connected Model, relates to establishing needs regarding sharing of information, utilizing the connected platform and the ability to collect real-time data from production processes. As such, requirements regarding collection of data, connectivity, online accessible storage, as well as automatic and continuous updates of the simulation model become apparent. Enabling these requirements, production resources need to be equipped with sensors to reflect their behavior. Additionally, 5G networks or equivalent connectivity technology is required to communicate the data to an online storage for later upload to a server-based virtual factory as well as for documentation. The stored data are sorted and copied to the virtual model by an API per its request.

4.3.3 Reaching Step 3

When the virtual factory reaches step 3, a Diagnostic Model, the main functionality constitutes of a current state analysis. Thus could all identified needs, which require the ability to evaluate the present operations, be mapped onto step 3. These needs could be fulfilled by firstly developing the ability to copy the base model, enabling several users, using different interfaces, to diagnose different aspects at the same instant of time. Furthermore, the following simulation models should be developed and added onto the base model: a product cost model, a product quality model, an ergonomic simulation of operators at work stations, and a simulation of assembly of products. These models should be regarded as modules, layers on top of the base model, where the data from the virtual factory are further visualized. This puts further requirements on proper communication between different software systems and data storage for results from diagnoses.

4.3.4 Reaching Step 4

If the prior step depicted the current state of operations, this fourth step depicts the future state of operations, being a Prognostic Model. The main functionality at this step is based on the virtual factory's ability to forecast and calculate when different properties change, and can, hence, support an optimal use of resources. The identified needs that require the ability to run what-if simulations and test different scenarios were, therefore, assigned to this step. Furthermore, the ability to perform forecasts relay on proper data examination and the enabling technology is, therefore, Advanced Analytics, a technique for generating descriptive and predictive analysis. This requires that the organization acquires new skills and uses domain experts to develop accurate models. Additionally, the base model must be equipped with the ability to manage versions in order to run and save different scenarios issued by different users.

5 DISCUSSION AND FUTURE WORK

The implementation plan for realizing step 1 to 4 showed a vast mix of technologies, and to successfully merge them into an efficient common platform a comprehensive system perspective is required. The virtual factory as a simulation environment should be regarded as the original and the real factory as the copy. Despite no needs were expressed for developing the virtual factory to reach step 5 and 6, it is still important to take future development into account to apply the perspective on virtual original and real factory copy.

The development of a virtual factory requires to continuously update the scope and to find new suitable technologies, since few complete solutions exist on the market today. This is valid for the preceding steps as well. An agile mindset and development is required to implement a best practice solution. The technology benchmarks, therefore, play an important role as a to guide companies who do not yet have a virtual factory to initiate its development. Combined with the acquisition of newly required skills, active leadership, and incorporation of domain knowledge, the developed implementation plan can provide a stepping stone towards the transformation to a fully digitalized company.

The establishment of a dedicated organization and standardized work methods for the virtual factory were benchmarked as success stories. As demonstrated in the case of company β, when a complete production line was replicated from one factory to another, the co-development of ways of working with the virtual factory and its results was crucial to ensure that value was added to the organization. For the case company, this is of particular importance, since the technical readiness was identified as a prioritized objective in the implementation plan. Otherwise, the organization risks that the virtual factory becomes an isolated tool instead of being integrated in the current practice. The virtual factory needs to be regarded as a supporting function, not only a tool for process development, and, therefore, requires that employees interact with it on a frequent basis.

Few companies have identical prerequisites, e.g., technical readiness and acceptance, nor identical needs which makes this particular solution inappropriate to copy and paste. However, the methodology as such could be applied at other companies striving for developing a virtual factory. The case company is a well-established organization with mature production units and mixed age of equipment, which makes this implementation a brownfield project, with the modification of existing resources. The methodology developed in this paper is not necessarily directly applicable on greenfield projects or in a start-up setting, since the prerequisites may appear as redundant.

Future research should consider the domain-specific areas associated with the establishment of the first maturity step. Investigating the particular requirements for the implementation of each enabling technology will provide a further detailed action plan regarding its realization. Finally, pilot studies with key user groups could be initiated to establish a digital simulation model and advance its functionality. Simultaneously, greater knowledge about the topic should be established and standardized work methods be developed and evaluated throughout the company, in accordance with the proposed implementation plan.

6 CONCLUSION

This paper presents a strategy for the implementation of a virtual factory founded on a literature study, interviews with relevant stakeholders, and by benchmarking industry leaders. The strategy is organized in four consecutive steps regarding the level of maturity and enabling technologies of the virtual factory. It considers user-driven development, standardized ways of working, as well as technical readiness and acceptance. Providing a holistic perspective, a framework for further in-depth and domain-specific research has been discussed. By advancing the virtual factory's maturity stepwise and ensuring a continuous use within production and process development, this paper has facilitated a structured way to enable decision-making based on facts.

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