This paper was presented at The XXXIII ISPIM Innovation Conference "Innovating in a Digital World", held in Copenhagen, Denmark on 05 June to 08 June 2022.
Event Proceedings: LUT Scientific and Expertise Publications: ISBN 978-952-335-694-8

Supporting Industry 4.0 implementation with modelling and simulation - two SME cases

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Abstract: This article investigates the modelling and simulation that supports the implementation of Industry 4.0 through two industrial SME case studies. Our findings suggest that the importance of modelling and simulation is increasing significantly also in the SME context as the use of smart manufacturing technologies proliferate in every industry. Rather than applying all-embracing modelling and simulation tools, SMEs need lighter task-focused tools, which they can nimbly utilize and avoid big investments in modelling tools as well as competence development. Larger companies are leading the Industry 4.0 development, but to take full advantage of the benefits it promises, they need to engage their supply chains that often include SMEs. Further research on the changes Industry 4.0 brings about is needed to support the different stakeholders in the value chains better. Research is also needed in order to take advantage of the opportunities, and to respond to the challenges of this transformation.

Keywords: Industry 4.0, modelling, simulation, SME, implementation, supply chain

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1 Introduction

Manufacturing systems are becoming increasingly complex, driven by the rapid development of a broad range of technologies from sensors to information and communication technology (ICT). This development has often been termed Industry 4.0 (De Paula Ferreira et al, 2020). On the one hand, smart technologies are adopted in manufacturing equipment enabling more complex and intelligent connections between the machines, and thus, more integrated and in-depth control of the factory processes. On the other hand, factories in the supply chain become more connected, thus making the connected system much broader. This development, consisting of the increase of both the depth and the breadth of the connected manufacturing system, increases the challenges to understand and develop the operation of the system. Modelling and simulation provide tools that support the creation of this understanding (Yildiz et al, 2020). Practical challenges may arise, e.g., in planning and implementing new or updated services or components in an existing factory. There, deciding on which innovations to use in the factory is a challenge, since the effect of innovative technologies and services in the specific factory are unknown beforehand. Modelling approaches can help to understand the requirements on innovative technologies and the effect on production before applying them in reality. From the organization's perspective, modelling and simulation can provide support for increasing the acceptance of modern technology and process innovations before their implementation by using simulations as executable models with company-specific adaptions to analyse new workflows and their effect on human workers.

While modelling and simulation solutions support overcoming the above challenges, they also create problems of their own. Companies may have challenges gathering good quality data for simulations, especially when developing completely new systems. Also, they may lack capable personnel to carry out analyses and simulations, this is typical for SMEs. Also, there is always the question of what the relevant level of detail to model is and simulate, which depends significantly on the purpose and objective of the modelling task.

In this article, we investigate the challenges of using modelling and simulation in the context of Industry 4.0 implementation through industrial case studies covering two SMEs. The aim is to provide experiences and insights for company managers and development personnel in their modelling and simulations endeavours, as well as offer case study findings for academic researchers.

2 Theoretical background

While the development of manufacturing systems and technologies has progressed rapidly during the past decades, so has modelling and simulation. They have both taken advantage of the continuous increase of microchip computing power. This has enabled the modelling and simulation of ever more complex systems (Yildiz et al, 2020). However, challenges remain and some of them are not technology related. The challenges of modelling and simulation can be considered from various perspectives, e.g., phases of modelling, tools and competences of modelling, and the purpose of modelling.

The following three main phases of modelling and simulation can be identified in complex manufacturing systems context: model design, model development, and model deployment (Fowler and Rose, 2004). In the design phase, a key issue and challenge is to determine the level of detail of modelling, especially when supply chain is included in the models (Fowler and Rose, 2004; Mikkola and Jähi, 2020). In development phase the challenge is to choose the suitable modelling approach, which can significantly affect the efficiency of model building and execution times of the model (Fowler and Rose, 2004). In the deployment phase the challenge is the efficient execution of the simulation, i.e., powerful enough hardware and software (Fowler and Rose, 2004). Most interestingly, however, Fowler and Rose (2004) suggest that the most difficult challenge may be having the social acceptance in organizations for the use of simulations.

Taking a broader perspective than Fowler and Rose (2004), Mourtiz et al (2014) consider the modelling and simulation challenges in a framework, which combines both product and production lifecycle perspectives. Besides identifying tool-specific challenges related to simulation in various parts of these lifecycles, they identify general simulation challenges. According to them the simulation tools are still too dedicated, ever-increasing the complexity of products and processes demand more powerful computing, lack of data still exists, and high skills are required to work with the complex frameworks used in the design phases (Mourtiz et al, 2014). Considering the simulation challenges especially in the SME context, Yu and Zheng (2021) point out that the capital investment in acquiring the software and hiring or training a simulation competent employee are major barriers for SMEs to utilize simulation. Similarly, Schneider (2018) points out that while, on the one hand, a virtual analysis and simulation may offer significant cost savings without disturbing ongoing real-life production processes, on the other hand, “it represents a huge investment in itself, thus posing precisely the same cost–benefit considerations that it aims to solve.”

Regarding the application areas of simulation in Industry 4.0 implementations, De Paula Ferreira et al (2020) conclude that the main purpose of the simulation-based studies in Industry 4.0 “is prescription and prediction for an improved mode of operations” Applications focus on process engineering, scheduling, and production planning and control are predominant. Yu and Zheng (2021) have identified the same purposes for simulation in SME context, where simulation is mainly used to analyse and optimize existing plant structures, processes and resources, or to design and plan new plants and prcesses, where SMEs can reach direct benefit in a relatively short term. There are also reports on some SME cases showing the implementation of cyber-physical production systems and digital twins, which indicate the emergence of more long-term strategy on simulation utilization and implementation of the more advanced characteristics of Industry 4.0 (Yu and Zheng, 2021).

3 Research questions and design

The article aims to provide case study based practical insights on the role of modelling and simulation in the development and implementation of Industry 4.0 systems, especially in the SME context. The focus is mainly on the managerial and organizational perspective, considering the following questions: What kind of modelling and simulation approaches are used in the different development situations of SMEs? What kind of new requirements and challenges the application of Industry 4.0 solutions introduce to the business and operations development of SMEs? How can the Industry 4.0 implementation of SMEs be supported, especially from the modelling and simulation perspective?

Our research follows the Eisenhardt (1989) methodology and is based on two case studies. The first case comprises of a production equipment manufacturer (SME), which has developed new production technology and aims to communicate the benefits to its customer. The second case is an SME that develops automated guided vehicles (AGVs) for factory logistics. This SME aims for the optimization of AGV performance and - as in the first case - aims for simple possibilities to display the product benefits to its customers.

Both of the case studies were carried out in a joint European research and development project where researchers assisted companies with their new Industry 4.0 solutions development. The research material consists of the R&D meeting memos and deliverables produced during the course of the 3-year project, developed models, simulations and solutions, and the discussions with the companies' key personnel. The material was analysed qualitatively, reflecting and comparing the findings from both case studies with the frameworks presented in the literature, and using the following analysis elements:

- Main product offering of the company
- Product development objective
- Product development phase
- Need/Purpose for modelling and simulation
- Modelling and simulation scope
- Industry 4.0 implementation phase
- Main challenges related to modelling and simulation

4 Case descriptions

Case A

Case A company is a Finnish SME, High Metal Oy, that develops and produces stainless sheet metal products and structures. One of their product lines is dairy production equipment under the brand MKT Dairy. The company has been developing a new cheese making process taking advantage of innovative technologies such as IoT and robotics. The key idea of the new concept was that it enables the production of several diverse types of cheese on the same cheese manufacturing line much more flexibly and in smaller batches. The key aim was the ability to measure and control the production process more accurately.

The company was actively seeking customers to build the first reference installation of the new concept. Their first challenge was to convince the potential customer about the potential process performance improvements. For this, a simulation model of the cheese making process was developed with another SME that focuses on the development of simulation models (Fig 1). The main use cases identified for the first simulation implementation were: 1) Concept design configuration, 2) design evaluation from the operative perspective, and 3) efficient communication in marketing. The developed simulation solution was based on discrete event simulation with the back end system running in in a server and the front end user interface working in the web browser. The main parts of the simulation solution were design configuration, operation configuration, and results visualization.

The solution also offers future opportunities to enhanced operation and management of the new production concept. Additionally, the solution could be developed to simulation-based online digital twin in the future. As the company didn’t have the competences and tools to develop this kind of a simulation model, the development work was purchased from another SME providing modelling and simulation solutions and services.

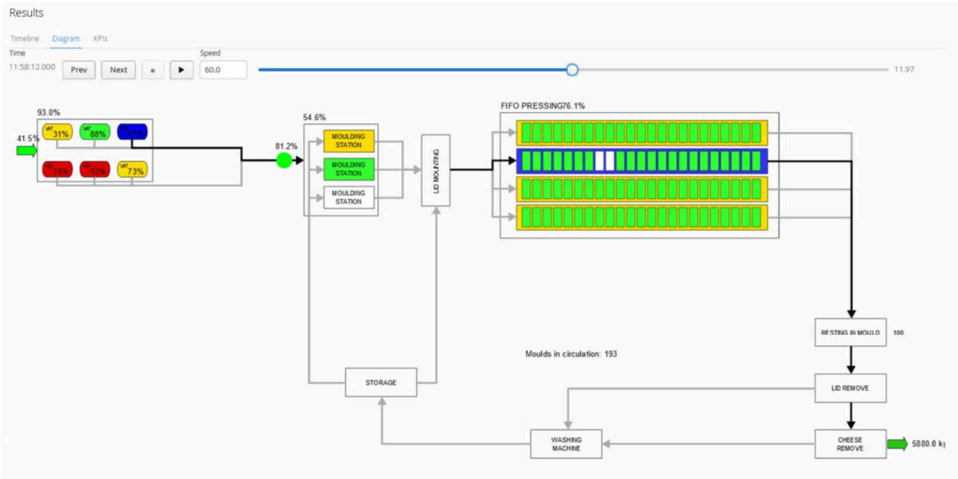

Figure 1 A screenshot of the High Metal cheese production process simulation.

Another challenge to model and analyse was the potential cybersecurity risks posed by the introduction of new digital technologies in the process control. For this analysis, the control system was modelled to a cyber-range environment (Airbus CyberRange, presented in Fig. 2), which is a dedicated modelling and analysis tool for cybersecurity development (Airbus, 2022). The Airbus CyberRange is an advanced simulation solution that allows the easy modelling of IT/OT systems composed of tens or hundreds of machines and the simulation of realistic scenarios including real cyber-attacks (Airbus, 2022). The simplified digital twin created for case A models the main industrial process systems (e.g. curdling, measuring, pressing and datalake), which communicate using mainly the Siemens-7 protocol. The monitoring of traffic in the network is handled by the gate firewall system. Using firewall capacity for additional traffic monitoring is not optimal in real environment, but was considered an acceptable compromise in resource consumption and efficiency in this demonstration environment. The misuse case defined for this analysis described the cyber actions of a malicious attacker either causing a loss of intellectual property (e.g., recipes, system configuration) or modification of the process causing the loss of product due to health concerns. Again, like in the process modelling task, the company outsourced the cybersecurity modelling and analysis work to an external service provider. These services were obtained from a research organization that was a partner in the project consortium.

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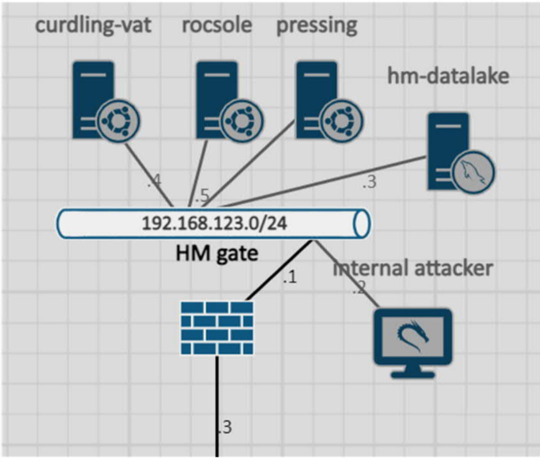

Figure 2 A screenshot of case A cybersecurity simulation model in the Airbus CyberRange tool.

The current development status of the above-mentioned modelling and simulation tools is the following. The production process simulation model has been developed and used to demonstrate the operation and performance of the new production concept. The full engagement of the potential customer is still under negotiation. The cybersecurity simulator has been set up for the demonstration in the cyber-range environment, but the actual simulations have not been carried out yet.

Case B

The second case deals with the development of automated guided vehicles (AGV) for factory-internal logistic tasks. The use case owner, ASTI Mobile Robotics GmbH, has expertise in hardware and software for logistic tasks in the automotive, e-commerce, food, pharmacy, manufacturing, logistics, aerospace, and metal industries. The company development activities are mainly focused on AGVs and software for navigation, battery management, communication, and safety. Currently, they are focusing on developing context awareness features for the robot fleet. The goal is to increase the automation grade of the fleet itself.

The use case owner is in the process of transforming new fleets from being centrally managed to a decentralized fleet management. For the realization, communication between AGVs and between AGVs and factory-internal machine execution systems (MES) is established. Instead of receiving new transport task orders from the central management unit, AGVs are now informed about open transport tasks by an MES and they negotiate on task distribution via a bidding procedure. For early analysis of fleet performance with the newly established decentralized management, a simulation of the fleet is implemented. Prospectively, this simulation should also be used for displaying new customers how the fleet could be deployed in their own factories, although the customization of the simulation is still under development. One difficulty is missing data, since information on transport needs of machines is often not known by the factory management, when the logistics are handled by employees.

The main challenge is the optimization of the newly decentralized managed fleet. One parameter for optimization is the choice of the bidding algorithm for the distribution of tasks. There are already some algorithms available, but there is no guarantee that an algorithm actually leads to desired fleet behaviour. Moreover, due to changes in the production process, bidding algorithms that might have been suitable in former situations might become insufficient. For example, an algorithm that enforces energy-saving driving modes of AGVs, might be perfect for nightly shifts with low transport demands, but might lead to empty batteries of AGVs in the middle of peaks in the number of transport tasks during daytime.

For supporting the optimization of the fleet, the architecture in Figure 3 was developed. The included key methodological elements are listed in Table 1.

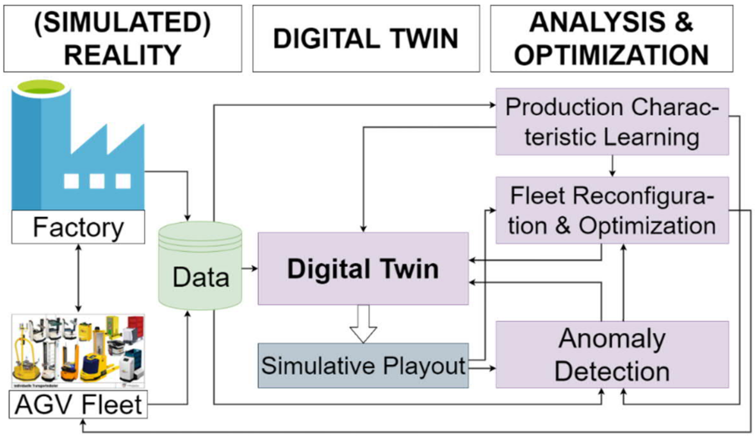

Figure 3 Modelling and simulation architecture in case B (Borchers et al. 2021).

Table 1 Key methodological elements of fleet optimization and their descriptions.

Methodological elements	*Description*
Prediction of production dynamics	The purpose of this component is to give predictions on transport tasks that lay in the near future. This information can be further used by other components for deciding the best available bidding procedure for handling the upcoming tasks and for checking if there is an anomaly in the factory that need to be taken into account. This component uses the assumption that transport task appearance follows some specific patterns, induced, e.g., by an overall production schedule or machine-specific production times. Additionally, it is assumed that the fleet of AGVs do not have direct access to factory-internal data such as production schedules. This last assumption is justified by considering the fleet of AGVs as a third-party service that should not receive confidential data.
Reconfiguration	This component provides decision support on the available bidding algorithms that should be selected for the next time. The proposed configuration can be sent to the fleet automatically. The decision is based on predictions on fleet behaviour when using different

	configurations. The predictions are won by combining a digital twin of the fleet with the prediction of production dynamics.
Anomaly detection	This component checks whether the observed data at runtime actually fits the predicted production dynamics and the predicted fleet behaviour. If this is not the case, the current configuration may not be suitable for handling the situation anymore and the anomaly detection triggers an alarm.

For refining the assumption of transport task appearance following some patterns, a machine model was created. Details of this model such as machine configurations or production recipes are not used by the prediction component, since we do consider such information as confidential. Nevertheless, the model is the basis for understanding under which circumstances the transport tasks are generated.

The digital twin (DT) is based on the provided fleet simulation. It is applied for testing the effect of different configurations without the need to actually interrupt the ongoing production. When the DT is started, it is updated to the currently observed fleet status.

As an early proof of concept, a factory model was implemented to create factory data similar to the data generated by a real factory. The model includes input warehouses, output warehouses and machines that can be modelled as individual elements. Input and output buffers, loading times, availabilities and manufacturing durations are assigned to each element. Furthermore, the internal dependencies between the elements are determined in detail.

This factory model is instantiated within a DT, to show the effects and potential benefits of the interplay between the components of the architecture in Figure 3. The DT was fed with different factory configuration and ran faster than real-time in order to assess the configurations (Eschemann et al. 2020). The best configuration was applied to the robots of the simulated reality.

To implement the prediction component of the architecture, we conducted a comparison of single output prediction methods and multi output prediction methods (Borchers et al. 2021). In the experiment we compared the statistical timing analysis, neural networks, random forests and XGBoost methods. The multi output prediction was achieved by combining classification and regression networks. The XGBoost machine was identified for making usable predictions within the factory context. With a labelled dataset over of one month the method was able to learn patterns and to predict amounts of expected transport jobs at the output of machines.

As a result, concepts have been created for implementing the individual parts of the architecture. First experiments indicate an improvement of the factorial processes by embedding the components in the overarching architecture.

5 Findings

The two case studies provide insights from practical utilization of modelling and simulation to implement Industry 4.0 solutions in the manufacturing context. Both cases illustrate especially the SME context.

Case A describes a situation where an SME has developed a new production process and a related equipment concept and intends to introduce its benefits to the customer. Case B is dealing with the development of automated guided vehicles (AGV) for factory-internal logistic tasks. The goals of this SME are to enhance the AGV fleet controllers, to take advantage of new possibilities provided by a distributed fleet management instead of a central management unit, and to be able to present the benefits of their AGVs to their customers in a simple way.

For both case studies one key modelling and simulation goal was to demonstrate the improved performance of the new manufacturing system for the potential customer. The difference is that in case A the new solution is a kind of "new-to-the-world" production concept, whereas in the case B the solution is rather an improved version of the current system. This can also be seen in the scope and detail of the modelling. Case A showcases more conceptual production system modelling and a higher-level of production equipment performance data, while case B focuses on modelling the more detailed level of automation control system and algorithms. However, case A applies more detailed technology system modelling and simulation as well in the cybersecurity analysis, but there the purpose of modelling is not to enhance production performance, but rather to analyse the security and resilience of the system.

Comparing the cases from the Industry 4.0 implementation perspective, the company in case A is in the early concept development stage of applying the new technologies in its products, while the company in case B is already in a more mature situation, designing the improvement of the already existing Industry 4.0 manufacturing systems (assuming AGVs are an instrumental part of Industry 4.0). In the modelling and simulation perspective, case B is also more advanced in Industry 4.0 application than case A in the sense that it considers using the models and simulations in operation rather than only planning and designing new processes.

Both cases provide a view on the practical modelling and simulation challenge of defining the important elements and factors, as well as the level of modelling details in a situation where there is only conceptual and design phase data available. For case A, two separate models and simulations were developed; one to demonstrate the benefits of the new process to the customer, the other to analyse the potential cybersecurity issues as the new process contained more digitized and connected technologies. This reflects the situation of the company in case. On the one hand, it had a strong desire to engage the customer to the further development and implementation of the first reference installation. On the other hand, the company had a clear need to understand the impact that modern technologies may bring from the cybersecurity perspective.

For case B, an architecture was developed that combines the technology of digital twins with methods for prediction, reconfiguration and anomaly detection. This architecture can be applied in two phases: With an additional simulation that serves as a substitute for a real factory environment, it can be used in early design phases. Replacing the simulation data by real data enables the application of the architecture in operational mode. Table 2 below provides a summary and a comparison of findings from both cases.

Table 2 Summary and comparison of the case findings.

	Case A	*Case B*
Main product offering of the company	Cheese production equipment	AGVs and their control software

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Product development objective	New, more flexible and efficient production process based on advanced digital technologies adoption	Improved performance of AGV fleet by decentralized fleet management system and increased AGV autonomy
Product development phase	Concept phase	Design/redesign phase
Need/Purpose for modelling and simulation	Convincing customer about the benefits of the new process	Analysing and proving the performance impact of the new fleet management system
	Understanding of the cybersecurity issues brought about by the new digital technologies	
Modelling and simulation scope	Production process efficiency analysis (concept design and evaluation)	AGV fleet performance analysis (control algorithm evaluation)
	Cybersecurity analysis	Digital twin
Industry 4.0 implementation phase	Early concept phase of Industry 4.0 adoption	Refinement/Improvement of existing Industry 4.0 system
Main challenges of modelling and simulation	Getting data (from customer) to make relevant simulations	Getting data (from customer) to make relevant simulations
	Lack of modelling and simulation competence in-house	
	Defining relevant level of detail for modelling	

6 Discussion and conclusions

Our findings increase the understanding about the use and role of modelling and simulation when applying Industry 4.0 solutions in SMEs. As a generic outcome, our findings suggest that the importance of modelling and simulation is increasing significantly also in the SME context as the use of smart manufacturing technologies proliferate in every industry (Yildiz et al, 2020). While being resource restricted and having limited competences, SMEs need support to take advantage of the new technologies, including modelling and simulation. This provides an opportunity for new kind of supporting service development for simulation expert companies. From the simulation technology perspective, SMEs have a need for tools, methods and solutions that are easy to apply.

Our findings emphasise the context and situation specificity when considering the Industry 4.0 modelling and simulation decisions such as choosing the modelling approach, defining the level of detail of modelling, collecting data, and integrating different models. The focus on simulation in case A was the concept and design phases of new manufacturing system development, and the operation phase use of simulation was considered only as a future development option. However, in case B, which represented a more advanced Industry 4.0 case, a simulation architecture was developed that included the Digital Twin model to enable operation phase data exchange between the AGV system and the simulation model. These kinds of different situations suggest that diverse needs require different simulation approaches and solutions that are adequate but not excessive to the problem at hand. For the SMEs, again due to their limited resources, it is essential to be able to focus modelling and simulation efforts to the relevant issues they are concerned with. This suggests that rather than applying all-embracing heavy modelling and simulation tools (Mourtzis et al, 2014), they need lighter task-focused tools, which they can nimbly utilize and avoid the potentially costly investments in modelling tools as well as competence development (Schneider, 2018). These tools should have the ability to be integrated and interoperated (Yildiz et al, 2020). These issues are something for the simulation tool developers to consider, as well as for the simulation service providers.

Industry 4.0 implementation often requires collaboration between several stakeholders (Fowler and Rose (2004), Yu and Zheng (2021)). Our findings suggest that the depth of collaboration between required stakeholders is one key factor affecting the speed of the modelling process, as well as the access to and collection of data. Building a closer and more confidential collaboration e.g., with a customer to enable data sharing is a time-consuming, reciprocal process. However, many companies, like the SME in our case A, often have some specific long-term customers with whom they can engage in more risky development projects. If modelling and simulation service providers participate in the collaboration, as we suggest being a suitable approach for many SMEs, this may significantly add to the efforts required for building mutual understanding and trust between the stakeholders in the created value network.

While the adoption of new Industry 4.0 technologies is an organizational and economical challenge for SMEs and requires new strategies and investments, the technologies develop continuously and may offer new solutions to overcome these challenges. In case B, the single components of the optimization architecture were developed to deliver a specific functionality with the focus on the use case. However, they were developed independently and represent mini services that can potentially be used outside of the architecture in further application than the primal scenario. The anomaly detection for example can be beneficial for observing other processes where the data is not normally distributed. However, due to the original holistic approach of the architecture, it is expected that companies developing, using, or planning to use AGVs and related systems can benefit from these solutions with minor work expenditure, i.e., at lower cost. Furthermore, the concept is not limited to be used in logistics, but it can also be transferred to other use cases. A condition for the transfer is that the system is accompanied with a digital twin and the behaviour of key elements of the environment is not fully known, but at least is not behaving arbitrary. This is for example the case for modern machines that are sold with a virtual representation but are operating in environments without having access to digital representations of the surrounding systems. Developers and operators of such systems can gain from the optimization architecture and from the insights given in this case study.

Our article presents only two case studies on modelling and simulation actions related to Industry 4.0 implementation. Thus, it is fairly limited for generalization purposes. Regardless of that, our findings show that SMEs can actively seek opportunities that the Industry 4.0 provides. In order to do so they need to rethink their strategies, build new competences and make brave investments to new technologies, both in the physical and virtual world. They may need to build new business relationships with companies that can support them in these developments. Larger companies are leading the Industry 4.0 development, but to take full advantage of the benefits it promises they need to engage their supply chains that often include SMEs. The ever-changing landscape of physical and cyber provides new opportunities as well as challenges for companies to organise their businesses. Further research is needed on these potentially substantial changes that the Industry 4.0 brings about in the value chains. This will also support the different stakeholders in the value chains to understand the change better, to take advantage of the opportunities, and to respond to the challenges.

Acknowledgements

This article has been produced as part of the CyberFactory#1 research project, which is funded under the ITEA3 programme (#17032). The project has received funding from the German Federal Ministry of Education and Research (BMBF; grant no 01IS18061C) and from Business Finland (grant no E!7632). We would like to thank all the project consortium members for the fruitful collaboration. Especially we would like to thank Lauri Nurminen from High Metal Oy and Christian Burghardt from ASTI Mobile Robotics GmbH for their insights and collaboration during the case studies.

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