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Identifying industrial needs for real-time simulation and digital twins

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Abstract

This chapter identifies and analyzes the industrial needs for real-time simulation and digital twinning throughout a product's lifecycle, *i.e.*, from inception; through engineering design, sourcing, and manufacturing; to operation, maintenance, service, and disposal of a manufactured product. It presents what was learned from a series of semi-structured interviews with nine manufacturing companies that are developing their digital approaches, simulation models, and toolsets for different phases of their product lifecycle. Thus, this study provides novel insights into research on product lifecycle management. The results of the study reveal that industrial needs for simulation models or digital twins still focus mainly on the product development and maintenance phases of the product lifecycle, but that virtual models to cover the entire lifecycle are still rare. Co-development, extending traditional products to the digital product-service-systems, and the increasing involvement of multiple stakeholders throughout product lifecycles all imply that there is a need to reformulate customer and innovation processes and build relevant corporate capabilities.

Keywords: Simulation, digital twin, customer needs, product lifecycle, product-service systems

2.1 Introduction

The introduction of digital tools and technologies (*e.g.,* real-time simulation) or virtual models (*e.g.,* digital twins) for enhancing business success is not enough Matching these enabling technologies to the actual needs of users and customers is equally important. This chapter identifies and analyzes current industrial needs to develop various digital approaches, *e.g.*, simulation models and digital twinning into the different phases of the product lifecycle in manufacturing companies. The digital approaches and tools are facilitators to respond to lifecycle related requirements, *e.g.*, sustainability of a product, traceability, and the reusability of data and information in manufacturing environments.

The effective use of product and lifecycle information via real-time simulation also enables faster responses to changes in customer needs and product-service related requirements. Simulation tools and digital twins can function as information carriers throughout a product lifecycle. These tools can also generate information to predict how the product will behave in its lifecycle state. Their ability to provide information based on the physics they can digitalize is their strength. Product lifecycle requirements also include service-based requirements leading to the concept of a Product-Service System (PSS). Another objective of introducing new digital approaches, such as IoT technologies, is to support customer processes to increase customer value.

Extending traditional physical products to include digital product-service systems, co-creation, and the deeper involvement of multiple stakeholders in business processes all point to the need to reform customer and innovation processes and build relevant corporate capabilities. For instance, real-time simulation technologies and tools affect new product development processes by replacing prototype testing with virtual prototype testing, which shortens new product development processes and enhances accuracy.

Recent research has strongly focused on how real-time simulation or digital twinning affect product development (*e.g.*, Alaei *et al*., 2018; Donoghue *et al*., 2019; Donoghue *et al*., 2018a). Jones *et al*. (2020) have classified research papers from the last ten years related to digital twins with respect to the product lifecycle model developed by Stark (2015). Their results reveal that research focuses mainly on the realization and support/use phases of the lifecycle. There are relatively few papers that consider digital twinning across all phases.

The study by Jones *et al*. (2020) encourages further research to understand the requirements of digital twins across the entire lifecycle, and to find out whether the existing approaches from other lifecycle phases are applicable. Further, Jones *et al*. argue that performing this research could lead to benefits, *e.g.*; reducing costs, risks, and design time; fostering innovation; and improving general reliability and decision making, especially in the imagine, define, and retire/dispose phases of the product lifecycle.

Therefore, the objective of this chapter is to collect and analyze the current needs of several industrial companies related to potential opportunities enabled by real-time simulation and digital twinning across the entire lifecycle for their product-service systems. The data for the analysis was collected by carrying out semi-structured interviews with representatives from nine manufacturing companies. The results of the study are key to enabling the digital transformation of business processes and the successful implementation of real-time simulation and digital twin approaches across the entire lifecycle of product-service systems.

The rest of this chapter in structured as follows. The next section reviews related research on real-time simulation, digital twins, and product lifecycle management. It also presents the research approach and data collection methods followed by a discussion of the interview results. The final section offers conclusions and suggests further research directions.

2.2 Real-time simulation and digital twins over the product lifecycle

2.2.1 Real-time simulation and digital twins

In use for the past three decades, *real-time simulation* is not new. The challenge has been developing simulation models that produce sufficiently accurate results. Real-time simulation is a technology that enables the development and use of simulation environments to model the real-world behaviors of a product solution within its operating environment in real-time. This can be, for example, an aircraft operating in its simulated mission environment beginning with pre-flight checks and ending with the aircraft parking in its hangar upon mission completion.

For this model to have value, it must be capable of simulating real-world physics as accurately as possible. The objective of real-time simulation is to produce a precise model of a complex system and its operating environment that represents the system's physical behavior defined by physics equations that describe the system and the operating environment. (de Jalon *et al*., 1994). Simulation tools have been used widely for decades in the planning and design phases of electrical system development, and they have played a critical role in the successful development of a huge number of applications, *e.g.*, from the layout of transmission lines in large scale power systems to the optimization of motor drives in transportation (Bélanger *et al*., 2010). According to Guillaud *et al*. (2015), digital real-time simulations can be used to develop models and design new concepts or devices for various applications, prototyping and its implementations, and teaching and training.

The concept of *Digital Twins* has been in the scope of Product Lifecycle Management for about two decades, but the language used to describe the digital twin has evolved over the years (Grieves, 2006) as technology has advanced. The digital twin originated in 2002 when the digital twin concept was presented at the first time by Dr. Michael Grieves from the University of Michigan. Grieves (2019) sees the digital twin as a model connected to its real-world counterpart so that the digital twin and its real-world counterpart form a connected dual system that are copies of one another. The connection between system elements can be either one-way or two-way, where data or information flows back and forth. The flow of information can come from a real-time simulation model and its simulation environment where the operational parameters can be compared to the real-world counterpart.

2.2.2 Product-Service System and Product Lifecycle Management

Extending traditional physical products into services has led to the concept of the *product-service system.* Baines *et al*. (2007) define a PSS as an integrated combination of products and services where products are tangible and services intangible. A PSS is a special case of servitization where a manufacturing company offers value to the market with the inclusion of services defined around the core products. This can offer a unique solution for the customer that builds value that is difficult to copy. Typically, manufacturing companies are product based, and they use servitization to offer complimentary services over the product lifecycle.

Product Lifecycle Management (PLM) is a systematic approach to managing and developing products and product-related information (Sääksvuori & Immonen, 2013). Grieves (2006) defines PLM as an information-driven methodology that integrates people, processes/practices, and technologies throughout a product's entire life including its development, manufacture, deployment, maintenance, removal, and final disposal. Different authors describe the product lifecycle phases using various terms and categories. Kiritsis (2011) categorizes the product lifecycle process into the following three main phases.

1. Beginning of Life (BOL) includes conceptualization, definition, and realization processes.
2. Middle of Life (MOL) includes usage, service, and maintenance processes.
3. End of Life (EOL) includes reuse of the product with refurbishing, reuse of components with disassembly and refurbishing, material reclamation with and without disassembly, material reclamation with disassembly, and disposal with or without incineration.

According to Terzi *et al*. (2010), BOL includes design and manufacturing. Design comprises product, process, and plant design and includes several sub-actions, such as analyzing requirements, defining concepts, doing more detailed design, developing prototypes, and performing tests. Further, MOL includes distribution (external logistic), use, and support (in terms of repair and maintenance). Finally, EOL is where products are retired, *i.e.*, reverse logistics targeting recycling (disassembly, remanufacture, reuse, etc.) or disposal.

Stark (2006) has introduced two viewpoints for the product lifecycle: the manufacturer's view and the user's view. From the manufacturer's viewpoint, a product's lifecycle lasts from the idea of the product via its production, realization, support and services to its retirement. For users, a product has a "life" from the moment they acquire it and start using it to the moment they stop using it or dispose of it. These two viewpoints have congruent steps, but especially the last two steps are different and not chronologically related; a user may stop using the product, but the manufacturer still produces the product and related services. On the other hand, the manufacturer may retire the product well before the user disposes of it.

Donoghue *et al*. (2018b) have identified in their study that companies can also have a PLM framework that includes three lifecycle phases and the interaction between the different product layers, which need to be managed with the different core business processes. This PLM framework is illustrated in Figure 2.1. These three lifecycle phases are 1) product lifecycle 1, which focuses on the existing product portfolio and developing new product-service systems based on the markets requirements (outside-in), 2) product lifecycle 2, which focuses on sell and deliver processes, and 3) product lifecycle 3, which focuses on maintaining the installed base and operations. There is a marketing process between product lifecycle 1 and 2, which focuses mainly on product and services marketing (inside-out) to increase market awareness of the existing products and services to the existing and new customers.

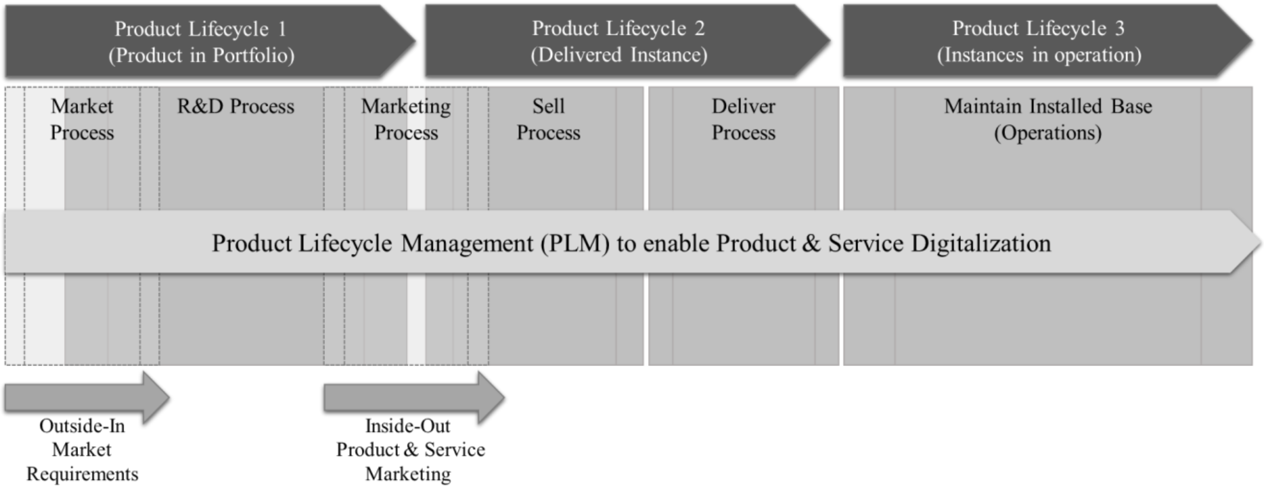


Figure 2.1. Product lifecycle management framework (modified from Donoghue *et al*. 2018b)

The development of shared virtual space has radically changed the way we use information to manage products and their lifecycles (Grieves, 2006; Tao *et al*., 2019). The premise that each product consists of two systems was introduced first time in the beginning of the 21st century (Grieves & Vickers, 2017). The two systems include the physical system, which has always existed, and a new virtual system (the digital twin), which contains all product information.

In 2006, Grieves presented an Information Mirroring Model (IM Model) that comprises a physical space, a virtual space, the linkages between these two spaces, and a virtual simulation space. The IM Model not only enabled the capture of information during the product lifecycle, but it also made it possible to simulate various product actions that would be costly or even destructive to carry out in real life. Grieves later expanded the digital twin concept via the introduction of the *Digital Twin Prototype, Digital Twin Instance, Digital Twin Aggregate*, and *Digital Twin Environment.* Together, these enable the application of a data-driven approach throughout the entire lifecycle of a product (Grieves & Vickers, 2017; Grieves, 2019).

Even though digital twinning has recently attracted much attention in both academia and companies, the concept and its industrial applications need consolidation (Jones *et al*., 2020). For example, Tao *et al*. (2019) argue that the convergence of a physical product and the virtual space is still usually absent in many companies. Jones *et al*. (2020) state that establishing the requirements and realizing the benefits of digital twin solutions across the product lifecycle is still quite challenging and should be researched in different industrial contexts. Further research to understand the needs of digital twins throughout the entire lifecycle should be encouraged.

2.3 Methodology

In this chapter, the research methodology is qualitative. The examination focuses on activities occurring in the work environment and attempts to make sense of or interpret phenomena in terms of the understanding of the workers (Denzin & Lincoln, 2005). Theoretical and empirical knowledge is combined via case studies (Yin, 2013). Yin (2013) defines a case study as an empirical inquiry that investigates a contemporary phenomenon within its real-life contexts, especially when the boundaries between phenomenon and context are not clear.

The data collection method comprises semi-structured interviews with nine manufacturing companies and the data was collected between October 2017 and March 2018. The number of interviewees from the companies varied from two to seven. These were group interviews, and there were two interviewers present at each session. The interviews were documented in written format, and the key results of the interviews were summarized into separate documents and sent to each company for review and further comment. Detailed information about the interview participants is summarized in Table 2.1.

Table 2.1. Information of the data collection process

Company	Main products and services	Interviewees	Interview date
Alfa	Forestry and material handling technology and solutions	2	10 October 2017
Beeta	Elevators, escalators, automatic building doors, monitoring, access and destination control systems	4	23 October 2017
Gamma	Material handling solutions, attachments and expert services	2	12 October 2017
Delta	Tractor manufacturer	4	22 September 2017
Epsilon	Hydraulic cylinders and solutions, motion control, and related services	1	23 October 2017
Zeeta	Machinery, systems and technology for the production of plywood and veneer	2	27 October 2017
Eeta	Drive technologies and solutions	11	8 January 2018
Theeta	Trucks, automatic truck systems and related services	3	20 March 2018
Ioota	Tools and tooling systems for industrial metal cutting, stainless steels	7	21 December 2017

The objective was to identify and analyze the current needs of industrial companies related to the potential opportunities of real-time simulation across the entire lifecycle of their product-service systems. In addition, viewpoints were collected related to digital twinning. The interview questions were divided into four different subject areas as follows.

1. Digitalization in business and product processes
2. The role and possibilities of simulation and digital twins
3. The key benefits and functionalities of simulation
4. Company architecture and simulation; processes, data, systems and tools

The focus of the study was to analyze the interview results related to the digitalization of business and product processes and the role and possibilities of real-time simulation and digital twins. First, the starting point for each company was discussed, especially addressing the implementation status for real-time simulation and digital twinning in their product processes, *i.e.*, in different phases of the product lifecycle. Second, interviewee expectations and their ideas about the possibilities offered by the simulation tools or digital twins were collected and discussed focusing on the needs of the company and the nature of the benefits these technologies could bring to the product lifecycle. The collected data was analyzed by reviewing the interview summaries to collect all industrial needs related to real-time simulation and digital twins. These needs were grouped together based on the lifecycle phase they represent.

2.4 Results – identified industrial needs for real-time simulation and digital twins

The results of the study revealed several industrial needs and suggested possibilities related to the digitalization of product processes and the utilization of real-time simulation tools or virtual tools and technologies such as digital twinning or virtual- and augmented-reality technologies. The following paragraphs present the main results based on the product lifecycle management framework presented earlier in the related research section (see Figure 2.1). The interview results about identified industrial needs are divided into three phases following the structure of the PLM framework:

1) Needs related to product lifecycle phase one - Product in Portfolio (Figure 2.2),
2) Needs related to product lifecycle phase two - Delivered Instance (Figure 2.3), and
3) Needs related to product lifecycle phase three - Instances in operation (Figure 2.4)

In product lifecycle phase one (Figure 2.2), companies had mainly focused on the R&D process phase for industrial needs. Interviewees indicated they had already utilized real-time simulations or other digital tools to support and accelerate their R&D processes. Virtual testing was highlighted as a key requirement to receive user and customer feedback as early as possible and to test virtual prototypes, machine implements, automatic functions and software. Further, the need to virtually test several machines and virtually simulate its environment was also mentioned. However, it was emphasized that real-time simulation models or digital twins should be developed as accurately as possible so the most relevant data could be obtained from customers and end users.

The results also indicated that these companies have realized the value that simulation brings to their marketing processes. Interestingly, the interviewees did not separate marketing activities into the two different processes the PLM framework suggests, *i.e.*, outside-in and inside-out marketing. The collected needs were divided into outside-in market requirements and inside-out product and service requirements. Utilizing simulation tools was seen as important to marketing to determine customer needs before kicking off a new product development project and to collect feedback from the developed product-service systems after completion of the R&D process. Further, enhancing the user experience with augmented reality (AR) and virtual reality (VR) technologies was mentioned as a way to further improve marketing. Interviewees suggested that a tool to measure user experience was also necessary. In addition, the possibilities of AR/VR technologies in enabling customers to test modular parts of a product were highlighted.

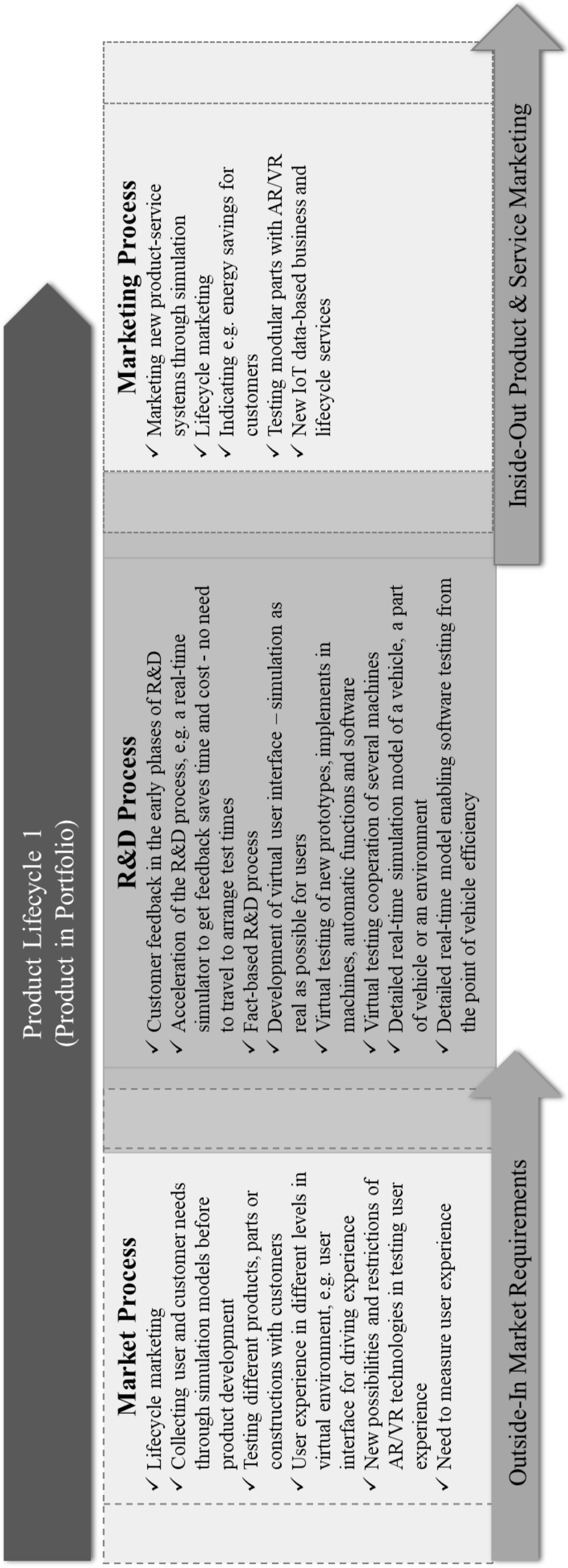


Figure 2.2. Industrial needs for Product Lifecycle 1 – Product in Portfolio

In the product lifecycle phase two (Figure 2.3), industrial needs were divided into sell and deliver processes. However, the interviewees brought up that marketing and sales processes are usually seen as one entity, and the needs are therefore difficult to distinguish from each other. Simulation tools and virtual models were considered important additions to the sales processes, where they could be used to further increase sales by promoting more service business. Simulation tools were also seen as beneficial for supporting the customer buy decisions during product showcasing, because they make it possible for the customer to “see, test, and feel” the final product. Moreover, virtual modeling was seen to support pre-order services, where information and feedback about customers can be collected as early as possible before their final buy decision.

The usage of simulation tools and digital twins in education and training was mentioned as one of the main needs in the deliver process. Simulation tools could enhance the training process of new product-service systems at customer sites. Especially, there was a growing interest in testing AR or VR technologies for training. In addition, the interviewees mentioned that these virtual models could also be utilized for the digitalization and visualization of project management practices. Interview results, however, revealed there were relatively few ideas on how to apply simulation tools to improve the delivery process. For example, the interviewees did not mention any industrial needs related to manufacturing processes or production.

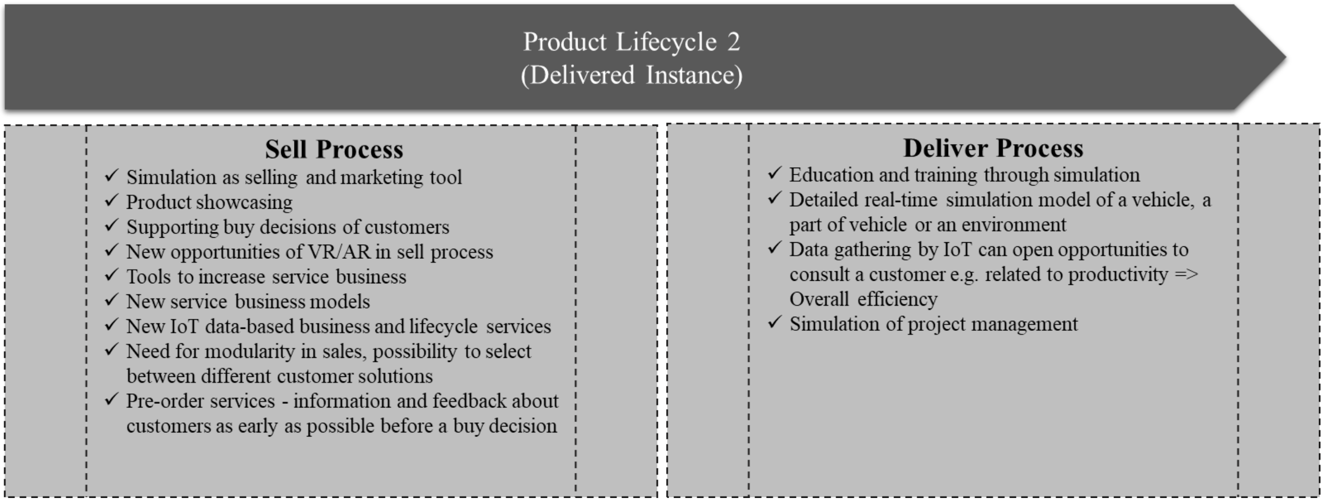
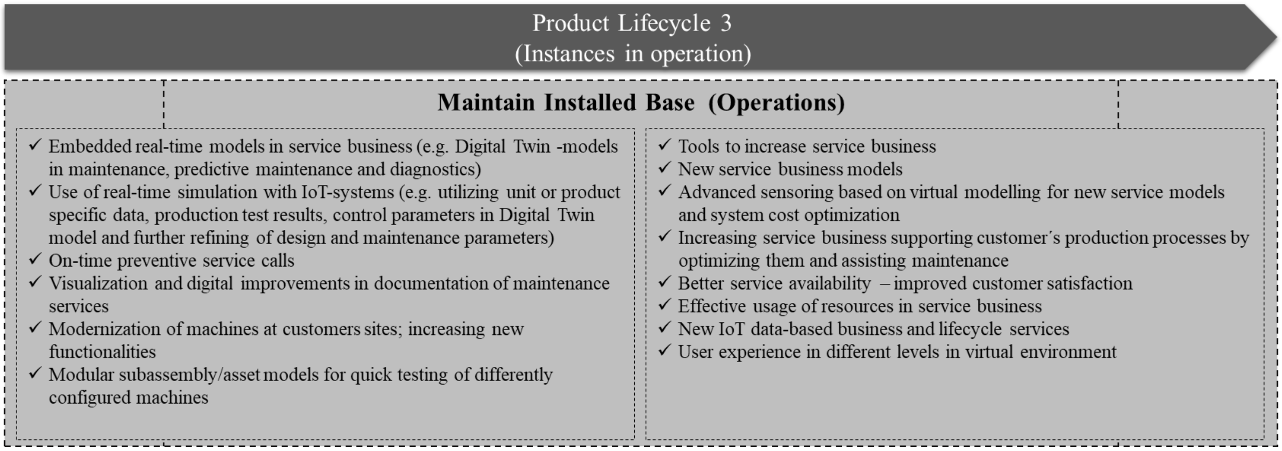


Figure 2.3. Industrial needs for Product Lifecycle 2 – Delivered Instance

In product lifecycle phase three (Figure 2.4), the industrial needs focused on operation instances, *i.e.*, maintenance and service businesses. The use of real-time simulation with IoT-systems adds new possibilities for utilizing unit or product specific data, production test results, or control parameters in the digital twin model and further refines design and maintenance parameters. Interviewees also suggested that real-time models such as the digital twin are needed in predictive maintenance and diagnostics, *e.g.*, on-time preventive service calls. Further, the use of simulation tools to enhance the visualization of maintenance services was mentioned. Developing an online shop for maintenance services to ensure better service availability is an example. Also, by optimizing customer production processes and assisting in maintenance, the virtual tools were seen as important to building the service business.



Product Lifecycle 3
(Instances in operation)

Maintain Installed Base (Operations)

- ✓ Embedded real-time models in service business (e.g. Digital Twin -models in maintenance, predictive maintenance and diagnostics)
- ✓ Use of real-time simulation with IoT-systems (e.g. utilizing unit or product specific data, production test results, control parameters in Digital Twin model and further refining of design and maintenance parameters)
- ✓ On-time preventive service calls
- ✓ Visualization and digital improvements in documentation of maintenance services
- ✓ Modernization of machines at customers sites; increasing new functionalities
- ✓ Modular subassembly/asset models for quick testing of differently configured machines

- ✓ Tools to increase service business
- ✓ New service business models
- ✓ Advanced sensoring based on virtual modelling for new service models and system cost optimization
- ✓ Increasing service business supporting customer´s production processes by optimizing them and assisting maintenance
- ✓ Better service availability – improved customer satisfaction
- ✓ Effective usage of resources in service business
- ✓ New IoT data-based business and lifecycle services
- ✓ User experience in different levels in virtual environment

Figure 2.4. Industrial needs for Product Lifecycle 3 – Instances in operation

The interviewees brought up several times the need to explore the potential of digital tools and technologies (*e.g.*, real-time simulation), or virtual models (*e.g.*, digital twins) to increase their service businesses and to develop both suitable and sustainable business models to achieve a competitive market advantage. The additional services for customers could be provided in each phase of a product’s lifecycle, but the need for more holistic services was also highlighted. The willingness to provide entire lifecycle services to support customer business processes is an example.

2.5 Conclusions

Based on the empirical results, Product Lifecycle 1 is the phase where real-time simulation solutions have already been utilized widely by industrial companies, especially in R&D processes, but also to support marketing activities before and after product development. With the fast development of digital twin solutions, companies are beginning to accelerate existing R&D activities, gather increasing amounts of customer data before and after the product development, and improve marketing processes and tools.

In the second product lifecycle phase, Product Lifecycle 2, identified needs were scarcer and mainly related to the sales of a product/solution rather than to its installation. Company needs were identified, *e.g.*, in promoting further sales, supporting buying decisions of the customers, and training processes at customer sites.

In the Product Lifecycle 3, the identified needs related mainly to improving maintenance and monitoring services. A need to explore new service business opportunities made available by the increasing amount of IoT data, for example, was also expressed.

The empirical results support the previous findings from the recent literature (*e.g.*, Jones *et al.*, 2020) that digital twins that cover the entire lifecycle are still rare. One remarkable reason for this may be that digital twin solutions are still under development in many companies; their utilization has become general in R&D processes, and increasingly, these solutions are integrated into instances that are in the early phases of operation. It will take time until these products and processes are at the end of their relatively long lifecycles. Therefore, the necessity of real-time simulation or digital twinning at product lifecycle end may not yet be clear. Moreover, many manufacturing companies are still taking early steps in their servitization, and product-service systems and related service business capabilities are still developing.

In manufacturing companies, product development is still often product-centric, and the role of services is complementary. Congruently, product lifecycle management and real-time simulation solutions have traditionally concentrated on physical products. As companies are transitioning towards co-development of product-service offerings across the entire product lifecycle, the need for digital twins to support lifecycle services is expected to grow, as also revealed by the empirical research.

However, digitalization may still take time in many manufacturing companies. One of the main concerns is associated with data ownership, *i.e.*, who owns the data and how and by who the data can be used. Often the up to date information about the installed base is with the customer, and the information that the manufacturer needs is spread over multiple back-end systems (*e.g.*, PLM, ERM, and MES). This makes it challenging to maintain a relevant digital twin and carry out meaningful real-time simulation later in the product lifecycle. Certain companies in the study have emphasized collecting good install base information for services, but the information is not connected to real-time simulation models.

One of the challenges faced by all the companies surveyed is data security and how to comply with the different data security requirements that customers and authorities are imposing, which complicates the application of digital twinning and real-time simulation models that represent customer instances. As the amount of data increases in companies and in the business ecosystems, the pressure or opportunity to utilize digital twins will increase also. This scenario also opens even more opportunities to take advantage of real-time simulation in business operations.

Customer needs are not divided or spread over the PLM lifecycle phases presented in this chapter. The needs determined here are typically internal to the companies surveyed, and they do not include the customer view directly. An example of this is the marketing activities done before and after delivery that could result in a continuous marketing lifecycle that supports customer engagement throughout the product lifecycle. Customer needs are still collected in a way that reflects the manufacturers’ view of the product lifecycle, which represents an inside-out view of the market.

Interestingly, based on the survey results, there is a gap between real-time simulation and delivery in PLM lifecycle phase 2. Although this gap was not examined thoroughly, some initial conclusions can be offered. Real-time simulation has only seen limited implementation directed at research and development functions. There have been no production implementations. However, opportunities available to the manufacturing engineering of new products and service are obvious. The current lack of production implementations might indicate that manufacturing engineering has been outsourced to partners and suppliers, and these partners and suppliers did not participate in the survey. This is an area where real-time simulation could offer benefits and should be investigated in more detail in the future research.

The concepts of digital twins and real-time simulation are not established in the companies surveyed. Many of the companies involved have invested in real-time simulation, but the business benefits that it brings were difficult for decision makers to understand. The most common statement was "why should the company invest in real-time simulation". In general, demonstrating the benefits seems to present a challenge. This is probably because in most cases the focus of real-time simulation has been on product development alone. This study encourages decision makers and business managers to consider the potential of digital tools and virtual models throughout the entire lifecycle of product-service systems to build relevant corporate capabilities for achieving competitive advantage in the marketplace.

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