International Journal of Production Research

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tprs20

Enabling collaboration on digital platforms: a study of digital twins

Wiebke Reim, Ebba Andersson & Kajsa Eckerwall

To cite this article: Wiebke Reim, Ebba Andersson & Kajsa Eckerwall (2023) Enabling collaboration on digital platforms: a study of digital twins, International Journal of Production Research, 61:12, 3926-3942, DOI: 10.1080/00207543.2022.2116499

To link to this article: https://doi.org/10.1080/00207543.2022.2116499

INTERNATIONAL JOURNAL OF PRODUCTION RESEARCH
2023, VOL. 61, NO. 12, 3926–3942
https://doi.org/10.1080/00207543.2022.2116499

Taylor & Francis
Taylor & Francis Group

OPEN ACCESS Check for updates

Enabling collaboration on digital platforms: a study of digital twins

Wiebke Reim, Ebba Andersson and Kajsa Eckerwall

Entrepreneurship and Innovation, Luleå University of Technology, Luleå, Sweden

ABSTRACT
Digital platforms are transforming almost every industry today and are expected to revolutionize future value creation. Digital platforms require collaboration, but this is challenging especially in the manufacturing industry where sensitive data need shared and high investments are required. Therefore, the purpose of this study is to enhance the understanding of how to successfully collaborate on digital platforms in the manufacturing industry by developing a contingency framework. The study is an explorative single case study of a digital platform. More specifically, the study examined the development process of a digital twin platform created by a large high-technological company and its collaborative actors. The results are based on 21 semi-structured interviews and reveals that actors on digital platforms can face five types of challenges that hinder a successful collaboration: disadvantages of dependency, uncertainty regarding data management, varying customer needs, insufficient work methods, and unsuitable payment models. The analysis also reveals four strategies that can be used to address the challenges: transparency strategy, incentive model strategy, servitization strategy, and control strategy. Moreover, these findings are summarized in a contingency framework that explains which types of challenges that can be addressed with which strategies based on the specific prerequisites of each collaboration.

ARTICLE HISTORY
Received 26 June 2021
Accepted 2 August 2022

KEYWORDS
Digital platform; digital twin; manufacturing industry; collaboration; challenges; digital servitization; digital transformation

1. Introduction

Digital platforms are transforming almost every industry today (de Reuver, Sørensen, and Basole 2018), and are expected to revolutionize future value creation as they enable companies to become more digitalized (Müller 2019). The advanced technologies used on digital platforms have opened enormous opportunities for product and process optimization as it allows companies to apply an analytic approach and to operate more predictively (Kritzinger et al. 2018). More specifically, technologies that connect the physical and virtual world will be crucial for companies to operate efficiently enough, and companies that fail to enable and exploit the opportunities of these technologies risk to be outcompeted (Landolfi et al. 2018; Leminen et al. 2015; Zheng et al. 2019). In addition, digital platforms lay a foundation for new interactions and collaborative approaches, which is expected to accelerate innovation and fundamentally change how manufacturing companies operate (Müller 2019). Digital platforms can be defined as a collection of technical elements (software and hardware) and associated organizational processes that mediate between different user groups (de Reuver, Sørensen, and Basole 2018; Gawer 2014). Gawer (2014) further propose that digital platforms can be divided depending on organizational context where the level of openness is a central aspect. An internal platform is considered to be closed as it only allows users from a single company, while an industry platform is at the core of a network of companies and thereby completely open to external parties. Supply-chain platforms are described as a type in-between that is partially open to external parties, depending on the preference of the platform owner.

A technology which has received much attention in later years are platforms used to create digital twins, i.e. exact virtual replica of products, processes, and the performance of these (Biesinger et al. 2018; Wang, Lee, and Angelica 2020). As digital twins has been at the top of the Hype Cycle for emerging technologies, it is expected to be one of the most important technologies over the coming years (Gartner 2018). The platform is similar to a supply-chain platform as several external parties collaborate, but their access to the platform is regulated by the platform owner. Digital twins are developed to exactly reflect all dimensions of reality which allows companies to virtually explore and commission production lines before physically building them (Avventuroso, Silvestri, and Pedrazzoli 2017; Kritzinger et al. 2018). However, in current practice, there is limited value in the extensive level of details that an exact replica would mean. Instead, digital

CONTACT Wiebke Reim wiebke.reim@ltu.se Entrepreneurship and Innovation, Luleå University of Technology, Luleå SE-97187, Sweden

twins vary in detail depending on the specific customer needs. With its many application areas, digital twins have extensive possibilities to, for example, reduce new products time to market, time and cost of commissioning, as well as lowering downtime due to a more predictive approach but there is limited knowledge about to organize the usage of a digital platform such as digital twins (Kritzinger et al. 2018).

Despite the promising opportunities, the adoption of such platforms is challenging. As the virtual models require detailed data which in many cases is owned by an external party, collaboration is vital for the simulation platform's function and value. In the case of the digital twin, information is needed from actors across the supply-chain (Avventuroso, Silvestri, and Pedrazzoli 2017; Zheng, Lu, and Kiritsis 2021) which, in comparison with an internal platform, makes the process much more uncertain. For example, external parties' willingness to share sensitive data is a serious issue that may occur (Müller 2019; Singh et al. 2018). If, for example, a manufacturing company is to create a digital twin of their production, they need detailed information of all machines at their site. However, a machine builder might not want to share the specific details of their machine as they consider it to make them vulnerable. Thereby the digital twin does not reflect the reality which causes its value to reduce. Thus, the collaboration between the involved parties is crucial to obtain the benefits of simulation platforms and more research in this area is needed (Ardanza et al. 2019; Landolfi et al. 2018).

Even though most companies realize that external collaboration will be essential, companies have difficulties establishing these relationships (Li et al. 2021; Müller 2019). As previously mentioned, data-sharing is one major issue and additionally, the ownership of specific data is often unclear, and some companies consider it risky to become dependent on other companies (Constantinides, Henfridsson, and Parker 2018; Müller 2019; Singh et al. 2018). The collaboration is further complicated by the fact that digital platforms often involve large investments which need to be compensated by the obtained value. However, in the case of digital twins, the value is dependent on the participation of all concerned actors and will reduce if not all join the collaboration. Consequently, it is difficult for a few actors to initiate the digital platform collaboration if they cannot motivate the entire supply-chain to join. Simultaneously, the manufacturing sector is facing intense pressure to adopt digitalization to stay competitive, where digital platforms is a key to success (Landolfi et al. 2018). Therefore, it is important to understand how companies can find ways to motivate and manage digital platform collaboration.

While previous literature has studied digital platforms in various contexts (Müller 2019), most studies focus on the underlying technologies and the challenges in the development of these rather than managerial aspects (e.g. Schluse et al. 2018; Zheng et al. 2018). Some researchers (e.g. Constantinides, Henfridsson, and Parker 2018; Müller 2019; Singh et al. 2018), have performed foundational studies within the area, nonetheless, a comprehensive study of collaboration challenges is absent but very important. Consequently, even less attention has been paid to how possible challenges can be managed. Furthermore, as each collaboration has its unique set of challenges and prerequisites, a one-fits-all solution will likely not be applicable. Therefore, there is a research gap of in-depth and qualitative studies on how to manage collaboration challenges on digital platforms. The novelty of the field in combination with the increasing vitality of industrial digitalization makes digital platform collaboration essential to study and understand the mechanisms behind.

To this background, this study aims to enhance the understanding of how to successfully collaborate on digital platforms in the manufacturing industry by developing a contingency framework. This will extend the digital platform literature with knowledge on digital platforms by providing a management perspective on challenges when collaborating on digital platforms and how these challenges can be managed, which previous studies have paid limited attention to (Müller 2019). For practitioners, the findings will enable manufacturing companies to successfully implement and operate digital platforms, and ultimately allow them to stay competitive. To fulfill the purpose, this study will provide an in-depth case study of how companies in the manufacturing industry collaborate around the platform type digital twin. By analyzing the collected data, a framework for identification of appropriate methods to manage the challenges of specific collaborations will be provided.

2. Theoretical background

2.1. The digital platform concept

The literature provides numerous platform types with various definitions and characteristics. To help navigate through the literature field, Gawer (2014) divide the digital platform discussion into two perspectives, economics, and engineering design. Within the economics perspective, digital platforms are considered to constitute markets where the platform facilitate exchange between actors who would not otherwise have been able to transact with each other. An example of this kind of platform is Uber, since the platform connects drivers with travelers, and enables the transaction between the two groups. More suitable for this study, the engineering design perspective views digital platforms as a collection of technical elements (software and hardware) and associated organizational processes and mediate between different user groups (de Reuver, Sørensen, and Basole 2018; Gawer 2014; Hahn 2020; Henfridsson and Bygstad 2013). A fundamental idea is that the platform comprises modules which allows complex systems to be broken down into manageable components which are connected through interfaces.

A number of characteristics can be identified which help to distinguish platforms from each other, which have been summarized in Table 1. Gawer (2014) classifies platforms into three organizational categories; internal platform, supply-chain platform, and industry platform, where supply-chain and industry platform are external. By definition, each platform type has a different level of analysis. For example, the internal platform only allows a single company as the unit of analysis, while the industry platform allows an entire industry ecosystem to be studied. The unit of analysis is closely linked to the degree of openness since an internal platform is completely closed to external actors while an industry platform allows external actors to access and process information on the platform (Thomas, Autio, and Gann 2014). The platform openness does not only affect actors' access to information, naturally, it also influences innovation capabilities as an increasing number of participators means a larger number of perspectives and, in turn, stronger innovation capabilities (de Reuver, Sørensen, and Basole 2018; Gawer 2014). Moreover, how the platform is controlled, for example by hierarchical structure or contracts, is another interesting feature.

In existing literature, articles that study internal platforms (e.g. Schluse et al. 2018; Zheng et al. 2018), put the emphasis of the discussion on the underlying technologies. On the other hand, studies that look at industry platforms pay less attention to technologies and more to the arrangements of the network (de Reuver, Sørensen, and Basole 2018). Given that internal platforms are completely closed to external users, while the basis for industry platforms is external collaboration, the focus of the discussions is not surprising. However, when considering supply-chain platforms both perspectives are important to consider. According to the definition by Gawer (2014), supply-chain platforms are partially open to external actors, and therefore the collaboration between the actors is significant to the value created on the platform. However, existing literature on supply-chain platforms mostly discusses underlying technology (e.g. Vachálek et al. 2017), even though actor relationships clearly are of great importance. This becomes clear when examining digital twins which has received much attention within the manufacturing industry in later years. Several authors, for example Avventuroso, Silvestri, and Pedrazzoli (2017) and Schluse et al. (2018), reviews digital twins and its possibilities in detail, but do not explain the relationship of the involved actors. In line with digitalization, the relationships between the actors will, however, become increasingly important and more research is needed.

2.2. Digital twins

2.2.1. Definition and function

The digital twin can be described as an exact representation of a product, machine or process. In the literature, the digital twin is described as a one-to-one virtual replica of technical asset (e.g. machine, component, or process) that contains models of its data (e.g. geometry, structure), its functionality (e.g. data processing, behavior), and its communication interfaces (Schluse et al. 2018; Wang and Wang 2019). However, by practitioners, this description is considered a utopia as an exact model would require parameters that are not possible or desired to include. For every added detail, the cost increases, and depending on the area of usage, it is not certain that the obtained value increases with it. Therefore, digital twins can also be viewed as a virtual representation that contains the desired level of details of the simulated entity (Avventuroso, Silvestri, and Pedrazzoli 2017; Luo et al. 2021).

Digital twins can be seen as one type of digital platform where several actors share their data to replicate the physical asset. In the context of manufacturing, usually the number of users is limited and strictly regulated (Liu

Table 1. Overview of the platform types and their characteristics.

	Internal platform	Supply-chain platform	Industry platform
Level of analysis	Company	Supply-chain	Industry ecosystem
Degree of openness	Closed interfaces	Selectively open and closed interfaces	Open interfaces
Accessible innovation capabilities	Company capabilities	Supply-chain capabilities	Unlimited number of external sources
Control mechanisms	Managerial hierarchy	Contracts between supply-chain companies	Ecosystem governance
Literature	Dobrescu, Merezeanu, and Mocanu (2019); Gawer and Cusumano (2013); Gawer (2014)	Gawer (2014); Vachálek et al. (2017)	de Reuver, Sørensen, and Basole (2018); Eloranta et al. (2016); Gawer and Cusumano (2013); Gawer (2014)

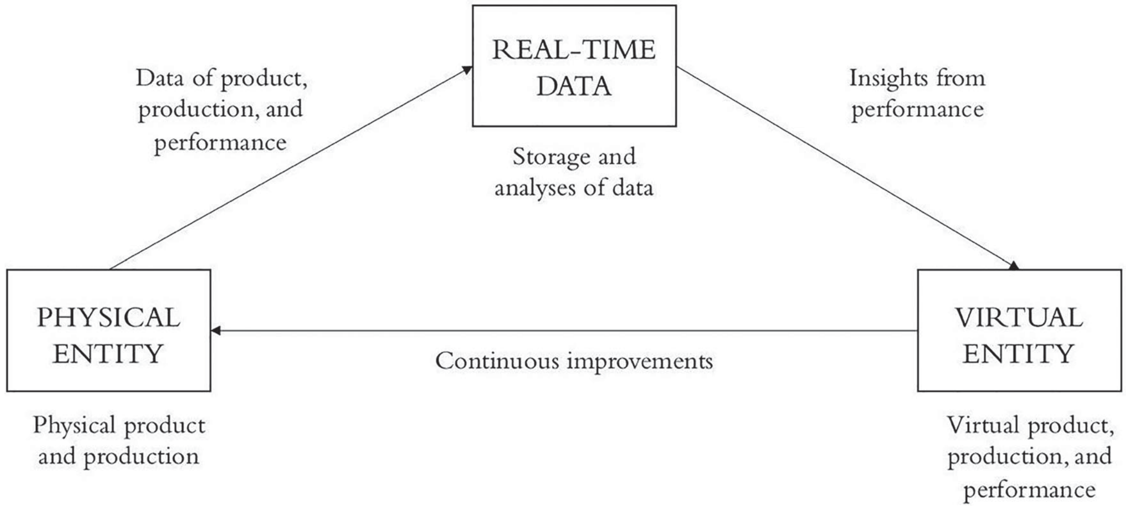

Figure 1. The structure of digital twins.

et al. 2021; Suuronen et al. 2022). The digital twin consists of three main parts; the physical entity, the virtual entity, and the data and information flow that connects the two products (Avventuroso, Silvestri, and Pedrazzoli 2017; Zheng et al. 2018), which can be seen in Figure 1. As the virtual entity is fundamentally based on data generated by the physical entity, the flow of data is a central aspect to consider. According to Kritzinger et al. (2018), digital twins can be categorized into three subcategories based on their level of data integration. In the first category, any changes made in the physical entity does not affect the virtual entity and vice versa. Therefore, the flow of data must be addressed manually. In the second category, an automated one-way data flow exists, which means that changes in the physical entity automatically alters the virtual entity, but not reversed. The final category is a full-scale digital twin where the data flow is completely automated, and changes in both the physical and virtual entity induce changes in the corresponding entity. However, as the full-scale digital twin is extremely complex, it is not yet a widespread concept. Currently, many companies are struggling to create the first category of digital twin and to make it a viable representation of reality (Madni, Madni, and Lucero 2019).

Even though some technological challenges remain, digital twins have great potential. Since the digital twin constitutes a digital factory environment, companies can virtually optimize their products and production processes before testing them physically (Huang, Wang, and Yan 2022; Vachálek et al. 2017). This approach reduces the time of introducing new products, as well as the time and cost of commissioning (Lee and Park 2014; Vachálek et al. 2017). The digital twin also enables more predictive work methods as it can perform advanced analyses (Avventuroso, Silvestri, and Pedrazzoli 2017). Another important feature is the possibility to share a visualization of the same digital twin to stakeholders who do not share the same location (Avventuroso, Silvestri, and Pedrazzoli 2017). However, there is a research gap on the collaboration around digital twins specifically as well as on digital platforms.

2.2.2. *Actors collaborating around digital twins*

Previous literature fails to discuss the involved actors of supply-chain platforms, using existing literature on service-oriented manufacturing and cloud-manufacturing (Moghaddam and Nof 2018). Digital twins are advanced constructs that require close collaboration of the involved actors. Commonly, agreement-based strategic alliances are formed with trusted actors to avoid conflicts of interests among the actors (Yaqub et al. 2020). In the case of digital twins, the actors can be generalized to involve four main types (Kress, Pflaum, and Löwen 2016). An overview of how the actors collaborate around digital twins is presented in Figure 2.

The first type of actor is the *end-customer*, e.g. the manufacturing company where the production line is situated and the actor who utilizes the production line. To manufacture products, the end-customer needs to purchase machines from a *machine builder,* which has the role to construct and deliver machines. As production lines can be complex, it is not uncommon that the end-customer purchases machines from several different machine builders. Once the machines are in place, they need to be interconnected in order for the production to function automatically without human interference at each step of the production process, which is the role of the *integrator.* The end-customer purchases the integration from the integrator which thereby becomes a

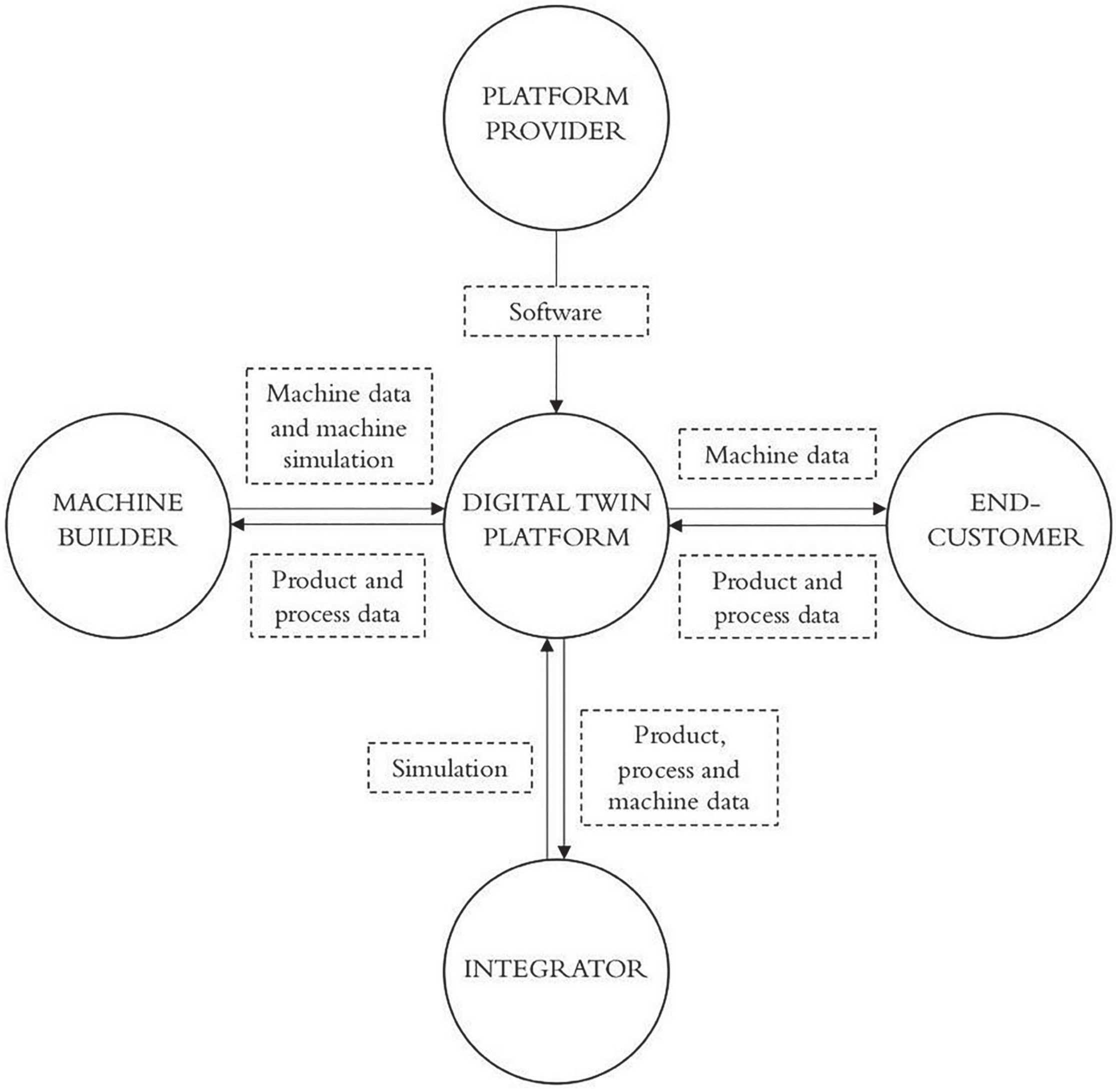

Figure 2. Overview of the collaboration around digital twins.

vital part of the commissioning process. In some cases, a company can act as both the machine builder and the integrator, or switch between the two roles in different collaborations. Lastly, as digital twins are a digital platform, the additional role of *platform provider* becomes involved (Andreassen et al. 2018). The platform provider supplies the platform and software used to create digital twins. As all of the other three types of actors collaborate to construct a production line, they can all utilize digital twins, and can thereby all be customers to the platform company. To enable the desired optimization from digital twins, data needs to be transferred between the involved actors. However, digital twins have not been used yet to their potential and the challenges of collaboration is a main hinder and more understanding and knowledge about how to manage collaborations is needed.

2.3. Managing collaboration challenges on digital platforms

Collaboration on digital platforms is discussed in previous literature, however, the collaborations are mostly studied from the aspect of uncertain economic outcome (Gawer 2014; Waurzyniak 2017). When the collaboration is studied in terms of networks of actors which is most applicable for industry platforms, several authors highlight challenges of the collaboration (e.g.; Eloranta et al. 2016; Gawer and Cusumano 2013; Smedlund and Faghankhani 2015; de Reuver, Sorensen, and Basole 2018). For example, Moura and Hutchison (2016) and Gibson et al. (2012) point out the importance of being aware of legal issues related to data movement and storage. However, the network view is often not suitable when studying platforms in the manufacturing industry as the actors often are bound by contractual agreements similar to supply-chain platforms. As a consequence, the collaboration challenges described from a network view are not applicable.

Even though they are few, studies regarding collaboration challenges on digital platforms have increased over recent years where Constantinides, Henfridsson, and Parker (2018) and Müller (2019) have found data management to be a challenge. Constantinides, Henfridsson, and Parker (2018) argue that this challenge is related to difficulties in specifying the ownership of data that is generated by physical products. Regarding digital twins specifically, the majority of previous literature exclusively highlight challenges related to technical development. For example, Mourtzis, Doukas, and Bernidaki (2014) argue that the integration and interoperability of systems is a major difficulty. Mourtzis, Doukas, and Bernidaki (2014) also argue that these technologies are expensive and complex which complicates the usage of digital twins. Likewise, Singh et al. (2018) point out that the technological complexity requires major development costs and thereby is harmful to the digital twins' cost-effectiveness.

In digital manufacturing, information sharing across the value chain bring tangible benefits but may be one of the biggest challenges as it is derived from company policies, and the mindset about data ownership (Reim et al. 2022; Singh et al. 2018). Mourtzis, Doukas, and Bernidaki (2014) point out the confusion regarding the optimum number of partners and duration of partnership regarding digital twins. When it comes to platform collaboration, aside from platform related challenges, the relationships of the collaboration itself must also be considered. Oliveira and Lumineau (2019) specify opportunism as an issue in alliances which refers to one party exploiting the other by seeking their self-interest, for example by intentional acts of misleading, disguise, and confuse. Additionally, Jiang (2011) discuss how alliances can make one party overly dependent on the other. This is harmful in long-term perspective since the company loses control over future decisions and development.

As new technologies require industrial companies to adopt digital platforms and the collaboration that comes with it, ways of managing the required collaborations on the platforms must be studied. Previous platform literature tends to focus on management of the network that surrounds industry platforms. For example, Van Alstyne, Parker, and Choudary (2016) argue that managing the network is central for success, and to do so, platform providers need to create a design that enables the right kind of interaction that strengthens the network. However, in similarity with collaboration challenges, management methods which address networks of industry platforms are not applicable when studying other types of digital platforms as they do not have surrounding networks. Given that the platform literature fails to study management of other platform types, literature that studies the collaboration between companies without platforms can be used for guidance.

In the field of product-service systems (PSS), Reim, Rönnberg Sjödin, and Parida (2018) argue that either monitoring, in terms of control and governance, or trust can be applied to avoid adverse customer behavior. Due to the similarities of the relationship structure, this can also be applied to collaboration on digital platforms in the manufacturing industry (Zheng et al. 2018; Zheng et al. 2020). Regarding control, Oliveira and Lumineau (2019) and Paik (2005) discuss how contracts with clearly defined roles and responsibilities can be used to reduce opportunism and conflicts. Bai, Sheng, and Li (2016) state that even though contractual control can decrease conflicts, exclusively applying legal enforcement can increase both conflicts and opportunism. Wuyts and Geyskens (2005) mean that when managing collaborative relationships, a social perspective must be considered as well, whereas social ties and dynamics have a direct effect on the effectiveness of contractual agreements. Both Paik (2005) and Blomqvist, Hurmelinna, and Seppänen (2005) add to this by arguing that mutual trust is crucial since only a partial view of the reality can be obtained if contracts are studied without any aspect of trust. Reim, Rönnberg Sjödin, and Parida (2018) also emphasize that trust between collaborative parties is significant in order to maintain a long-term customer relationship. However, there is a research gap concerning literature on managing collaboration on digital platforms.

3. Method

To fulfill the research purpose of enhancing the knowledge of how to collaborate on digital platforms, an explorative research approach was applied. A qualitative approach enabled us to progressively develop the understanding of the studied area (Saunders, Lewis, and Thornhill 2009). Moreover, since the study aimed to gain a deeper understanding of how to successfully collaborate around digital platforms, a single case study was performed (David and Sutton 2011; Saunders, Lewis, and Thornhill 2009). This was well suited since it enabled us to gain a more in-depth understanding of a specific digital platform and its surrounding actors which is necessary to understand collaboration in the context of digital platforms and would be difficult with another research design.

For this study a digital twin was selected, which is a typical digital platform in the manufacturing industry. More specifically, the case that this study relies on is the collaboration of a single platform provider and its collaborative actors. This platform provider is a large global high-technological company that produces technical and digital solutions for a wide range of industries. Its collaborative actors, often smaller companies, include both end-customers, integrators, and machine builders, either working with digital twins sporadically or on a daily basis. At the time of the study, the platform provider was considered to be at the forefront in the industry of digital twins.

Interviews were conducted to create an in-depth understanding of the studied area. A semi-structured format was used to ensure that relevant topics were discussed simultaneously as additional questions could be asked to not miss out on valuable information (Saunders, Lewis, and Thornhill 2009). The interviews followed a pre-constructed interview guide asking questions about e.g. the experience of collaborating on digital platforms, its challenges and how to manage them. The questions were formulated based on the findings in the literature. However, as the research progressed and as the respondents gave new insights, the interview guide was adapted in order to stay relevant. In total, 21 semi-structured interviews were conducted with respondents at the eight different companies involved in the study, all of which were recorded and transcribed. The companies were selected based on their progress in the development process of digital twins and to ensure that all four types of actors were represented. Moreover, specific respondents were selected based on their knowledge of the studied area as well as recommendations throughout the data collection. The two final interviews were conducted with the purpose of verifying and confirming the preliminary result. During the interviews, the initial findings were presented and discussed to ensure that data had been correctly interpreted and to assess the practical relevance of the findings. The respondents were selected based on recommendations of the previous respondents and additional interviews were conducted until saturation was reached.

The collected data was analyzed in line with a thematical analysis presented by Braun and Clarke (2006). The purpose of the method is to identify, analyze and label patterns within the collected data. This was a suitable method for this study as it enabled us to identify key similarities of a large set of data in a flexible way, and thereby extend the existing literature. When analyzing the collected data, we followed Braun and Clarke's (2006) process of a thematical analysis consisting of five steps: (1) Familiarizing with data, (2) Generating initial codes, (3) Searching for sub-themes and themes, (4) Reviewing sub-themes and themes, and (5) Defining sub-themes and themes. The used process of analysis was not linear of simply moving from one phase to the next. Instead, a more recursive process was applied where we moved back and forth between the steps when needed. Moreover, the analysis was developed over time which ensured that no important details were overlooked. The final thematic maps can be seen in Figure 3 and Figure 4.

4. Analysis and findings

The findings of this study are divided into two categories; collaboration challenges and collaboration strategies. Collaboration challenges refer to complications that may arise in the collaboration and hinder the work with digital twins. Collaboration strategies refer to management methods that can be applied to overcome the challenges. Each category is discussed separately below. Moreover, the challenges and strategizes are matched together in a contingency framework that explains which types of challenges that can be managed with which strategies, based on the specific prerequisites of each collaboration.

4.1. Collaboration challenges

The empirical analysis indicates five types of challenges when collaborating around digital twins in the manufacturing industry: disadvantage of dependency, uncertainty regarding data management, varying customer needs, insufficient work methods, and unsuitable payment models. A thematical map with an overview of the findings is presented in Figure 3. Each of these types of challenge is discussed separately in the following sections.

4.1.1. Disadvantages of dependency

The respondents expressed an uncertainty regarding the disadvantages of being highly dependent on other actors. The challenge type refers to how individual actors can experience a decreasing influence of their situation as they engage in digital twin collaboration. More specifically, the challenge regarding disadvantages of dependency can be divided into two sub-themes: (1) need for multiple software creates dependence on platform provider due to desired synergy, and (2) small actors must adjust to the standards set by large actors.

To be able to work with digital twins, the actors must apply different software with different functions. These programs can be provided by different platform companies but in order to successfully utilize digital twins, the programs must integrate with each other seamlessly. This complicates the possibilities to collaborate with

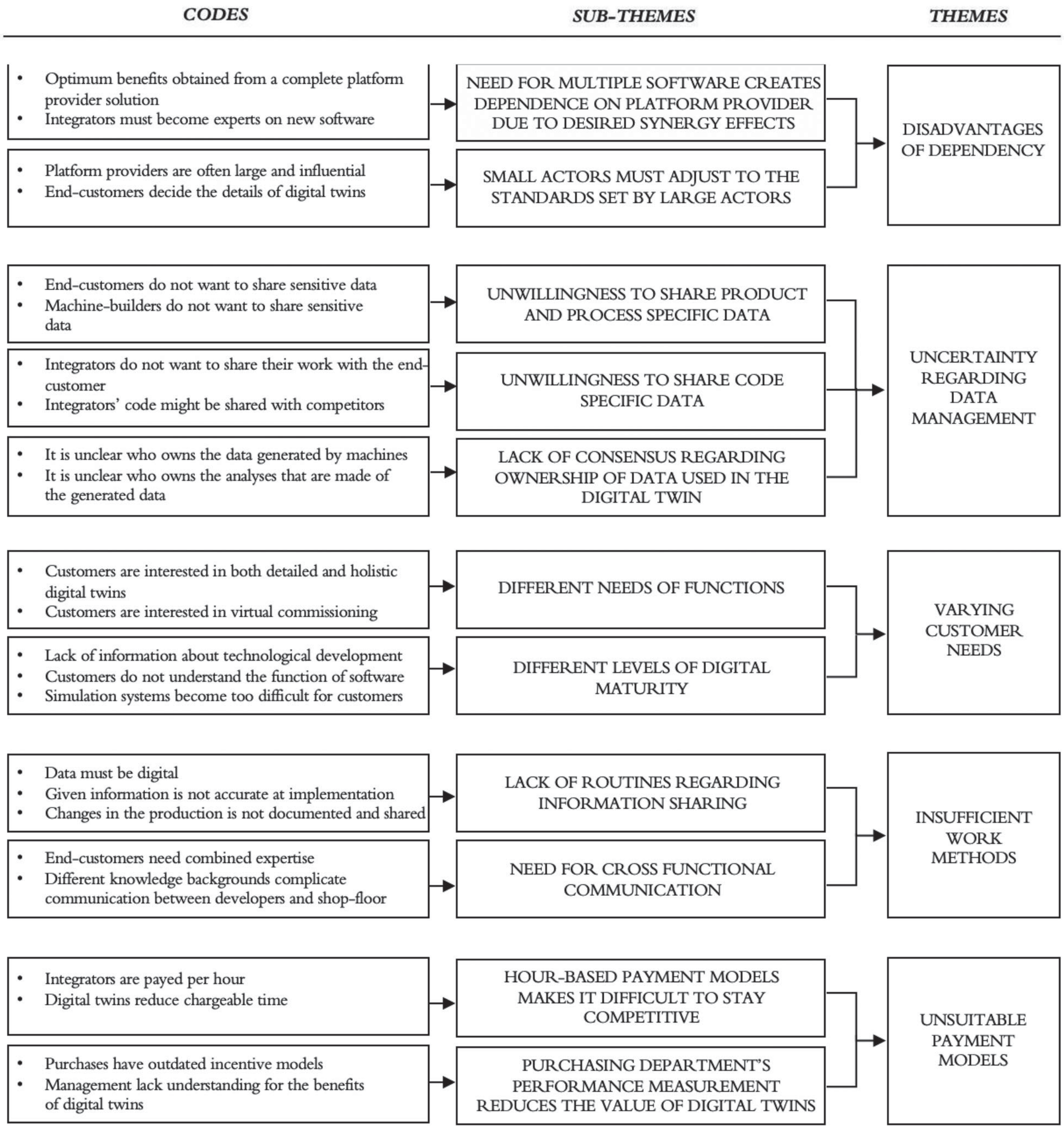

Figure 3. Thematic map of collaboration challenges.

different actors as the seamlessness depends on which platform provider each party uses. Additionally, if several platforms providers are involved, the responsibility becomes unclear if an interface does not work. Consequently, the need for multiple software creates a challenge regarding the actors' *dependence on the platform provider due to desired synergy effects*. Even though some respondents claim that their platform solution allows customers to seamlessly integrate different software programs, it has been found that the most optimized solution is created when using software from one single provider which another respondent expressed clearly is a challenge: '… one complete Alpha solution will give optimized benefits, but simultaneously one has backed the customer into a corner that they can never get out of, and they do not like that.'

Moreover, the respondents expressed that *smaller actors must adjust to the standards set by larger actors* as another challenge that creates undesired dependency within the collaboration. Applying digital twins to their full extent is not possible without the participation of all actors. However, it is clear that the power-balance

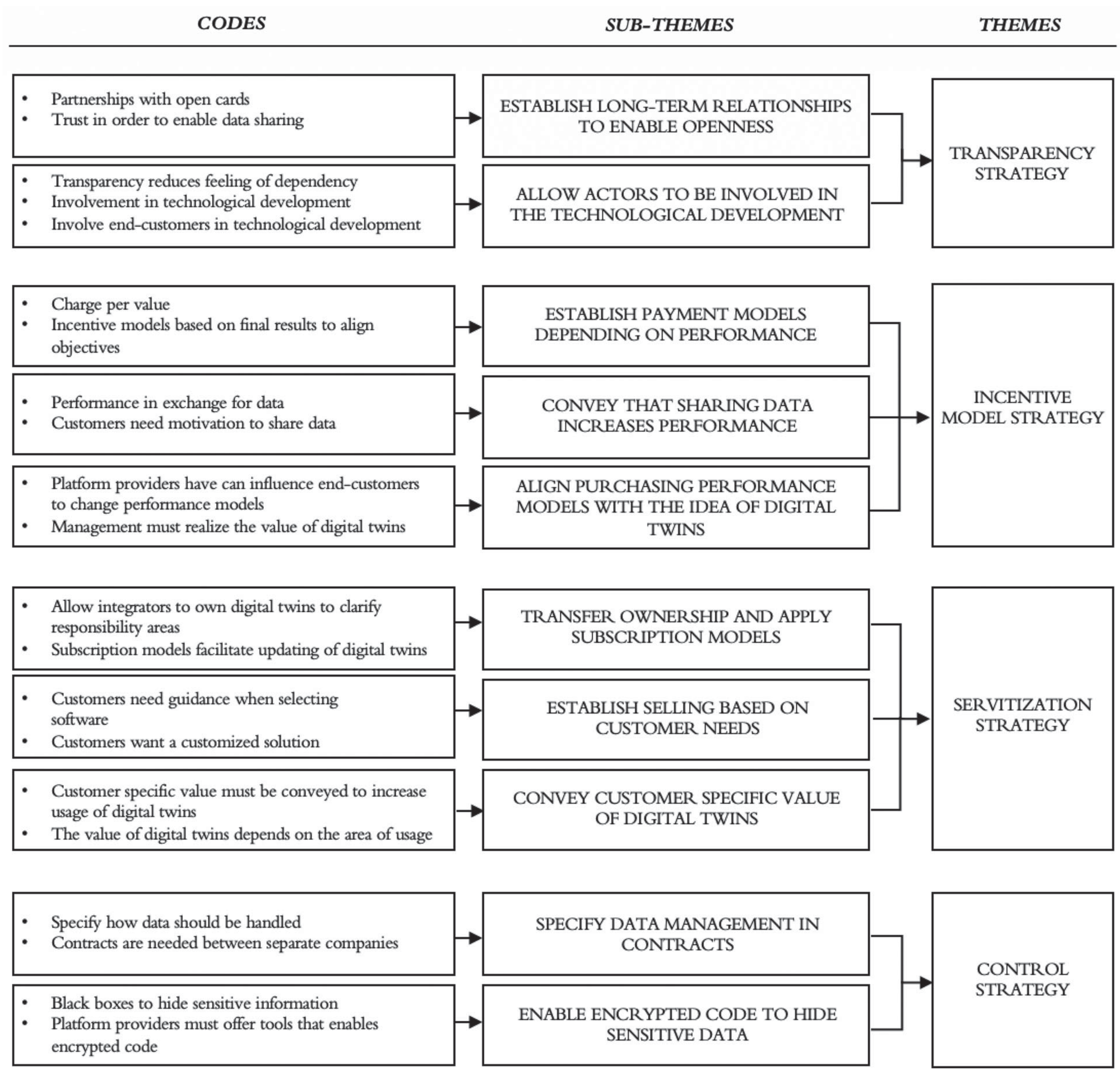

Figure 4. Thematic map of collaboration strategies.

between the actors differs as the actors' size vary as a respondent stated:

> If Zeta is a strong end-customer and Alpha a strong supplier of software, then the integrators become most dependent and do not have any other choice but to follow a certain standard.

As expressed by the respondent, the platform provider and the end-customer tend to be large companies in relation to integrators and machine builders. The difference in size allows the larger companies to set the terms for the collaboration which the smaller companies have to adjust to. Consequently, if one of the larger actors wants to change something in the agreement, the smaller companies must agree to this regardless of its impact.

4.1.2. Uncertainty regarding data management

The findings indicate that there is an uncertainty regarding how to handle data when collaborating between several companies. Since data is fundamental to construct digital twins, the handling of data is crucial. However, the findings showed that uncertainty arises both regarding how companies share data, and who owns specific data, which complicates and hinders the work with digital twins. It was found that three major areas within data management were particularly challenging: (1) unwillingness to share product and process specific data, (2) unwillingness to share code specific data, and (3) lack of consensus regarding ownership of data used in the digital twin.

In line with digitalization, the manufacturing industry is increasingly producing data about both products and processes. This data is needed in order to create digital twins and further, even more data is generated when applying digital twins as code is developed and analyses are made. However, the respondents clearly expressed that there is an *unwillingness to share both product and process specific data, but also code specific data*. Regarding product and process specific data, end-customers and machine builders mean that they are afraid that their data will be shared to competitors are thereby, their company-specific secrets will be revealed. Digital twins do not minimize these concerns as it requires detailed information about both products and processes in order to fully be utilized.

Code specific data is something that increases as the usage of digital twins increases. Integrators that create code are not willing to risk that their code is shared with other integrators and thereby, they are careful about giving the code to end-customers or any other actor. The respondent further explained:

> If we hand over our digital twin to a customer and then they go to one of our competitors and say: look what Delta has done, this works great. Can you do the same? … The code cannot be completely transparent to the customer.

As the respondent indicates, if the integrator share code that is open, the customer might share this with another supplier, who essentially can copy the work.

The third part of the uncertainty regarding data management is related to a *lack of consensus regarding ownership of data used in the digital twin*. The problem arises as data is handled more openly among the collaborating parties. If for example, the machine builder allows the end-customer to take part of their sensitive data and the end-customer creates a substantial benefit from the data, the ownership becomes unclear. In this case, one can argue that the end-customer is obliged to share the benefit with the machine builder, but on the other hand, one can also view the machine builder's consent as them renouncing their rights to the data. As a respondent phrased it: 'One can create a certain value from the information, but who owns it?'.

4.1.3. Varying customer needs

A third type of challenge that the analysis revealed was that the customers have considerably varying needs when it comes to digital twins. The differences make it difficult for platform providers to understand each customer's situation, and consequently, it becomes challenging to deliver an optimal solution. This becomes problematic since many platform providers historically have delivered standardized products and are not used adapting their offer according to customer-specific needs. It was found that the challenge could be divided into two sub-themes: (1) different need of functions, and (2) different levels of digital maturity.

The software portfolio that the platform provider offers for creating digital twins is large and continuously developed, which means that all employees at the platform provider are unable to learn all the functions and applications. Thereby, the employees are only focused on selling the products that they know about, regardless of *customer-specific needs of functions*. Moreover, due to the novelty of digital twins and its used techniques, some respondents expressed that they perceive that providers want to sell the newest programs regardless of what programs the customer needs and has since before.

It was also found that there are *different levels of digital maturity* between the collaborative actors which naturally complicates the collaboration. The differences mean that what are useful products for some customers, are far too advanced for others. The respondents mean that the development of digital twins almost exclusively is done in-house by the platform provider, without any information to the other actors involved. As a result, some respondents expressed that they perceive the closed approach to extend the differences in digital maturity. A respondent explained:

> Alpha says that they have been trying internally to get people to understand what this is for several years which means that we are several years behind and if they have internal problems with getting people to understand what digital twins are, imagine our difficulties with this then

This results in a situation of unbalanced digital maturity which hampers the chance of successful collaboration around digital twins.

4.1.4. Insufficient work methods

The analysis indicated that the work methods are insufficient in order to successfully use digital twins. The challenge type refers to how the end-customer needs certain work methods to maintain the digital twin and keep it updated according to the current state of the production. More concrete, there are two parts regarding work methods that need to be considered: (1) lack of routines regarding documentation and information sharing of physical changes in the production and (2) need for cross-functional communication.

For a digital twin to stay relevant, its data need to be updated in line with the physical version. However, a problem related to this is the *lack of routines regarding documentation and information sharing of physical changes in the production*. The ideal technique used for digital twins enables automated updates in the virtual environment when changes are made in the physical environment and vice versa, but this is not yet developed. Therefore, changes in the production have to be documented in order for the digital twin to stay relevant which the respondents pointed out is a major problem in today's manufacturing world. A respondent explained the problematic scenario: 'CAD models are often not updated according to physical changes and suddenly, the digital twin is not a twin anymore since it does not match the reality.'

Lack of documentation does not only affect the desired usage of digital twins, it also creates a need for additional work which one of the respondents pointed out: 'When we work at our customers, the first thing we have to do is to see that everything is correct which is a bit embarrassing'. However, it is a situation hard to manage since this is not only in the hands of the actors discussed in this study, additional actors as for example electricians and mechanics are partly involved in this challenge as they make some of the changes.

To successfully digitalize the manufacturing industry, the need for *cross-functional communication* will increase. Communication is not only necessary externally between the collaborative actors, but it is also crucial to communicate internally between functions at each actor. For example, as one respondent explained: 'We want to hire people with IT-knowledge in but if one does not understand the production and have no sense for what type of data one is optimizing, then you come to conclusions with very strange solutions that are not applicable in this context'. Naturally, if the internal cross-functional collaboration does not work, the external collaboration will be affected since the needed outcome from each actor is lacking.

4.1.5. Unsuitable payment models

The findings also show a challenge regarding the suitability of the current payment models when working with digital twins. The challenge type refers to how the current payment models make it unbeneficial for certain actors to work with digital twins and therefore hinders the establishment of digital twins. More specifically, the challenge can be divided into two sub-themes: (1) hour-based payment models make it difficult to stay competitive when using digital twins and (2) purchasing department's performance measurement reduces the value of digital twins.

Since the digital twin is a relatively novel concept and therefore not fully established on the market, a suitable payment model has not yet been developed. However, it is clear to say that today's *hour-based payment model makes it difficult to stay competitive when using digital twins*. The difficulties arise since utilizing digital twins is a more expensive method but in order to stay competitive, the price cannot be increased even if the method is more efficient which reduces the payment period.

Another aspect of unsuitable payment models is that today's *performance measurement for purchasing departments reduces the value of digital twins*. Purchases are often paid based on incentive models that encourage them to bargain down prices as much as possible. However, the idea of digital twins is to deliver a specific value which is lowered down when the price is barging down, as one respondent stated: '… they drive down prices as much as possible and thereby, are lowering the given value which could be that one can start a production much earlier and can produce much more than planned'. Basically, the payment models for purchasing departments hamper the possibility for companies to collaborate successfully around digital twins.

4.2. Collaboration strategies

The empirical analysis indicates that four management strategies can be used to overcome the collaboration challenges around digital twins in the manufacturing industry: transparency strategy, incentive model strategy, servitization strategy, and control strategy. A thematical map with an overview of the findings is illustrated in Figure 4 Each of the collaboration strategies is discussed separately in the following sections.

4.2.1. Transparency strategy

The findings show that transparency plays an important role when it comes to a successful collaboration around digital twins. Since digital twins require companies to share more information externally than previously, several respondents emphasize that the parties need to apply more transparent work methods towards each other to build essential trust. The transparency strategy involves two parts that are both crucial in order to work transparently: (1) establish long-term relationships to enable openness and (2) allow actors to be involved in the technological development.

The transparency strategy has high potential to meet certain challenges when used appropriately. The first part of the strategy involves *establishing long-term relationships that enable openness* between the collaborative parties. This strategy addresses challenges related to uncertainty regarding data management since data is more likely to be shared within a relationship where the parties consider each other as partners, rather than customer and supplier. However, these partnerships are based on trust and need to be developed over time which means that it is important to successively build such partnerships. As one respondent stated: 'It is possible to share data through trust if we really trust a customer and have a good partnership, and it is important to build such partnership early'.

Besides establish long-term relationships, the transparency strategy also includes *allowing actors to be involved in the technological development*. By applying an open approach to development, the platform provider can reduce the gaps in the actor's digital maturity. Moreover, involvement and openness within the collaboration have the potential to reduce the negative feeling of dependency as it increases the customer's possibility to influence the situation. Additionally, by including the customers' views, the platform provider can obtain substantial benefits as one respondent pointed out: 'If we are let in more, the agreement will become even better, and they will get input from us an end-customer which will help them to create better products'.

4.2.2. Incentive model strategy

Implementing incentive models has been found as a promising strategy when it comes to successful collaboration around digital twins. The strategy refers to how systems can be designed to motivate actors to behave in a way that is beneficial for the digital twin collaboration. More specifically, three different types of incentive models should be applied: (1) establish payment models depending on performance, (2) convey that sharing data increases performance, and (3) align purchasing performance models with the idea of digital twins.

A suitable payment model for the digital twin is to *establish payment models depending on performance*, which perfectly addresses the challenge of unsuitable payment models. For example, it can be an incentive model in which all parties agree on a certain goal and if the result is better than that, all parties share the profit. On the other hand, if the result is worse than expected, all actors will be affected by the loss. Another example is if one is to deliver a result better than expected, then that part gets a percentage of the improvement.

Besides a payment model based on incentives, it is also important to establish a model that *conveys that sharing data increases performance*. It is important to offer proper benefits to the customer if they are willing to share their data. In this way, challenges regarding willingness to sharing both product, process and code specific data can be reduced. One respondent explained: 'We try to work with performance guarantees, we promise a certain level of performance if the customer is open about sharing their data'. By doing so, the company motivates the customer to behave in a way that will be favorable for the digital twin collaboration.

Lastly, it has been found that purchasers' performance measurements are often based on how much they can barge down prices which in turn, affects the value given from digital twins. Therefore, *aligning purchasing performance models with the idea of digital twins* is also an important action to take in order to capture the full value of digital twins, and to overcome challenges related to unsuitable payment models specifically related to purchasing's performance measurements. However, in order to do this, higher management must be involved and understand the potential of digital twins. Moreover, collaboration is necessary as some actors have better possibilities in influencing higher management. As pointed out by a respondent: 'We believe that we need to go further up the organization and show the benefits of digital twins to senior managers. But we need help from Alpha since they have much better contacts higher up in organizations and boards than us'. Hence, large actors as the platform providers are more likely to influence the end-customer to change their purchasing performance models than smaller actors as the integrator.

4.2.3. Servitization strategy

The findings also indicate that a servitization strategy is suitable to ensure a successful collaboration around digital twins. The strategy refers to how the digital twin should be considered a service rather than a product and that the offerings of digital twins should be customized according to specific customer needs. The strategy includes two sub-themes: (1) transfer ownership and apply subscription models, and (2) establish selling based on customer needs, which were found suitable to ensure a successful collaboration around digital twins.

Several respondents mentioned that the logic of digital twins is to deliver a service rather than a product, and by doing so, companies are able to *transfer ownership and apply subscription models*. One respondent gave an example of transferring the ownership of the digital twin from the end-customer to the integrator who then offers it as a service to the end-customer. In this way, a suitable payment model is created and also, the ownership situation becomes clearer. Moreover, this will ensure that the digital twin is owned by a party that knows how to keep it updated. Also, as a respondent pointed out:

> I absolutely believe that you need to introduce this as a service. That is the way we need to go because then we will have a common interest in keeping the digital twin alive.

By creating the common interest in keeping the digital twin updated, the chance that information will be shared from the end-customer about changes in the physical version increases. In turn, this addresses challenges related to insufficient work methods and ultimately, increases the chances for a successful collaboration.

Another part of the servitization strategy is to *establish selling based on customer needs* which, as indicated by the name, perfectly addresses challenges related to varying customer needs. This strategy mostly concerns the platform providers' offerings, as one respondent stated:

> I believe that Alpha has to be clearer about the intended customer of their various tools and be better at leading their customers rather than introducing them to a jungle of things that they have to look through themselves.

The collaboration between the platform provider and their customers will become better if the customer feels that the software they use is the most suitable for their needs. This may require a better collaboration internally at the platform provider company since today, some customers perceive that programs are sold based on a seller's specific knowledge or based on the newest technologies, rather than the specific customer's needs. However, to convince the end-customer that the value of digital twins exceeds the costs can be challenging. One respondent, therefore, suggested that the integrator and the platform provider must work together since the platform provider often has better contacts at the end-customer company. By making efforts from two different sources, possibilities to show the value increases.

4.2.4. Control strategy

Lastly, control has been found as a potential strategy to overcome challenges that occur when collaborating around digital twins. By control strategy, we mean actions that regulate or hinder certain behavior of a collaborative party. The control strategy includes the two sub-themes: (1) specify data management in contracts, and (2) enable encrypted code to hide sensitive data.

The respondents described that regardless how good the partnership is between the collaborative parties, some kind of *contract that specifies data management* is needed to overcome challenges related to both insufficient work methods and uncertainty regarding data management. A respondent explained: '… it is part of a partnership to include contracts that clarify what information one is willing to share and what one can do with that information'.

Even if trust between the parties is the desired way of collaborating, some kind of contract is needed that describes the standards of the collaboration and the consequences if it is not followed, especially in the beginning of a partnership.

The other part of the collaboration strategy is to *enable encrypted code to hide sensitive data* which is a method that is already applied when creating simulation models today and should be further continued. As one of the respondents stated: 'Encrypted code could be a way of collaborating without revealing any business secrets'. Therefore, this strategy is, to some extent, suitable to meet challenges related to uncertainty regarding data management. However, the level of details needed to create a digital twin goes beyond the level needed when only creating a simulation model. Therefore, encrypted code is not a method that can be used to hide all data that one prefers not to share because this will affect the value of the digital twin. None of the challenges are addressed perfectly with a control strategy. The fundamental reason for this is the fact that digital twins are under development which increases the risk for unforeseen situations that are not specified in contracts and therefore, cannot be managed with contracts.

4.3. Contingency framework for successful collaboration on digital platforms in the manufacturing industry

Since the digital twin is a typical digital platform, the findings provide insights into what challenges that occur when collaborating on digital platforms and moreover, an understanding of how these challenges can be addressed. However, the findings also indicate that there is no optimal strategy for all challenges. Instead, certain strategies meet certain challenges more effectively, which argues for a contingency assessment. The suitability of different strategies primary depends on what stage the specific actors are in regarding the development process of a digital platform. To show these insights, a framework that matchmakes each challenge with the different strategies was developed and presented in Figure 5. The number of stars (∗) indicate how well a certain strategy addresses each challenge. The decision about the number of stars is This assessment was made based on the discussion in section 4.2, Collaboration Strategies data and validated by the respondents afterwards.

However, when collaborating on digital platforms, the actors typically face more than one challenge, which means that several strategies must be combined to achieve the best outcome. The findings indicate that when combining different strategies, synergy effects can be created in terms of how well the selected strategies cope with a specific challenge or a set of challenges. For example, the incentive model strategy clarifies the benefits of sharing data and thereby creates a willingness to share data which reduces uncertainty regarding data management. However, uncertainty regarding data management also benefits from a servitization strategy that clarifies the ownership of data. None of these strategies address uncertainty regarding data management perfectly, but together the challenge can be solved. Consequently, synergy effects between the incentive model

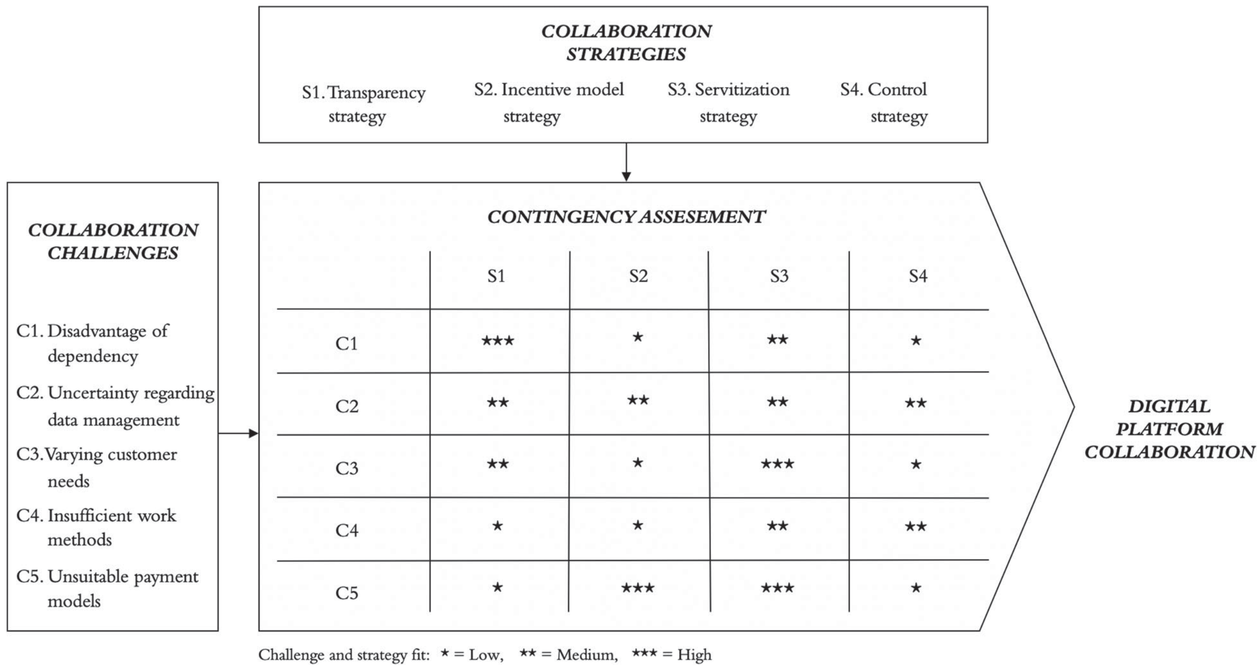

Figure 5. Contingency framework for successful collaboration on digital platforms in the manufacturing industry.

strategy and the servitization strategy are created to address uncertainty regarding data management.

Worth considering is also that applying a strategy to address a specific challenge may increase the risk of other challenges. For example, applying a servitization strategy increases the dependency between actors as well as the need of sharing data externally since the ownership of the digital platform is transferred to another actor. However, applying a transparency strategy that promotes long-term relationships is a great complement to the servitization strategy as it increases the chance of data-sharing and minimizes the risk of negative feelings of dependency. Therefore, every set of actors around a digital platform needs to develop its own unique collaboration strategy to meet its specific challenges. The presented framework can be used as a guideline to help managers handle collaboration around digital platforms in the manufacturing industry.

5. Conclusion

This study has enhanced the understanding of collaboration on digital platforms by developing a contingency framework that specifies how specific challenges can be managed. This knowledge is of importance since manufacturing companies are increasingly embracing digital platforms as a mean to survive the digitalization era (Leminen et al. 2015), where well-functioning collaboration is fundamental to success (Landolfi et al. 2018). Our research thus contributes with important implications for both managers within the manufacturing industry as well as to the literature on digital platforms.

5.1. Theoretical contributions

Our study provides theoretical contributions in three areas. Firstly, while prior literature extensively discusses digital platforms, scarce attention has been paid to digital platforms in a manufacturing context. By examining digital twins, which is one of the most important digital platforms in the manufacturing industry (Biesinger et al. 2018; Kritzinger et al. 2018), we contribute with insights of the importance of digital platforms in the manufacturing industry. The scarce literature that discusses digital platforms in a manufacturing context has tended to focus on the technical functions of the platforms (e.g. Schluse et al. 2018; Zheng et al. 2018). By applying a management perspective, we have extended the platform discussion and shed light on important aspects to consider other than the technical. These insights are especially valuable since manufacturing companies' adoption of digital platforms will intensify over the coming years (Müller 2019), and studies such as this are valuable to design digital platforms appropriately from the start.

Secondly, even though there are occasional studies that examine challenges when collaborating around digital platforms in a manufacturing environment (e.g. Constantinides, Henfridsson, and Parker 2018; Müller 2019; Singh et al. 2018), we have greatly extended this literature by identifying five challenges, namely 1) disadvantage of dependency, 2) uncertainty regarding data management, 3) varying customer needs, 4) insufficient work methods, and 5) unsuitable payment models. Through our mapping of collaboration challenges, we have identified several challenges that have not been previously discussed. Thereby, we have extended the knowledge of the platform collaboration and provided the current literature with a comprehensive overview of the challenges.

Thirdly, prior research fails to discuss how collaboration on digital platforms within the manufacturing industry should be managed (de Reuver, Sørensen, and Basole 2018). We identified four collaboration strategies (transparency strategy, incentive model strategy, servitization strategy, and control strategy) that companies can apply to manage collaboration on digital platforms. In addition, by connecting specific challenges to the collaboration strategies we developed a contingency framework, which contributes to the literature by providing valuable insights into how collaborations on digital platforms can be managed.

5.2. Practical contributions

As digital platforms are a vital part of industrial companies' digitalization, which in turn is crucial for their future competitiveness (Landolfi et al. 2018), our study provides meaningful implications for managers within the industry. We have provided three main implications that are relevant to managers. Firstly, we have shown that collaboration is central to obtain the full benefits of digital platforms, which means that managers can not only consider their own company when adopting digital platforms. It is critical that companies also take their collaboration partners into consideration and develop a strategy for each individual collaboration.

Secondly, we have shown which complications that may arise in the collaboration, which allows managers to act preventively when engaging in digital platform collaboration. By applying a proactive approach, managers can reduce the risk of failure, as well as the risk of unforeseen costs and inefficiency due to inadequate collaboration. Lastly, we have provided managers with the tools to enable successful collaboration and additionally, we have given valuable insights into how the enablement requires an assessment of the prerequisites of each collaboration. In doing so, we have equipped managers with the tools they need to successfully adopt digital platforms and sustain their competitiveness.

5.3. Limitations and further research

The study has some limitations as well as possibilities for future research. Firstly, even though our findings rest on empirical data from eight different companies, the study is limited to a single case-study where one platform type in a specific context is examined. To validate the findings and strengthen the generalizability of the findings, future research could examine the collaboration around other types of platforms in the same context as this study. Alternatively, future research can examine collaboration around the same platform in other contexts. Preferably, both suggestions should be attended to in future studies.

Secondly, the establishment of digital platforms in the manufacturing industry is in an early stage (Müller 2019), and consequently also our case study. This means that the raw data is partially hypothetical, where the respondents have reasoned around digital twins based on their current understanding and experience of them. Therefore, we believe that as digital platforms become more established, future research could gather empirical evidence where the study examines which challenges companies have faced and how they have managed them. Blockchain technology can be an important enable to reduce uncertainty in digital platforms.

Thirdly, the study was conducted solely with companies in Sweden. This means that the findings were completely based on the prerequisites of the Swedish manufacturing industry. As conditions may differ between countries, it is possible that the occurrence of collaboration challenges as well as the suitability of collaboration strategies may vary. Therefore, we recommend that future research perform similar studies in other geographical areas. By doing so, the generalization of the findings can be further supported.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

Due to the nature of this research, participants of this study did not agree for their data to be shared publicly, so supporting data is not available.

Notes on contributors

Wiebke Reim is associated senior lecturer in Entrepreneurship and Innovation at Luleå University of Technology, Sweden. Wiebke's research is mainly focused on business models for Product-service-systems, digitalisation and circular economy.

Ebba Andersson has a master's degree in industrial engineering and management from Luleå University of Technology, Sweden with a major in innovation and strategic business development. She is currently working as an enterprise sales executive at Siemens Digital Industries Software.

Kajsa Eckerwall has a master's degree in industrial engineering and management from Luleå University of Technology, Sweden with a major in innovation and strategic business development. She is currently working as a Service delivery manager at Fujitsu Sweden.

References

Andreassen, T. W., L. Lervik-Olsen, H. Snyder, A. C. Van Riel, J. C. Sweeney, and Y. Van Vaerenbergh. 2018. "Business Model Innovation and Value-Creation: The Triadic way." *Journal of Service Management* 29 (5): 883–906.
Ardanza, A., A. Moreno, Á Segura, M. de la Cruz, and D. Aguinaga. 2019. "Sustainable and Flexible Industrial Human Machine Interfaces to Support Adaptable Applications in the Industry 4.0 Paradigm." *International Journal of Production Research* 57 (12): 4045–4059.
Avventuroso, G., M. Silvestri, and P. Pedrazzoli. 2017. "A Networked Production System to Implement Virtual Enterprise and Product Lifecycle Information Loops." *IFAC-PapersOnLine* 50 (1): 7964–7969.
Bai, X., S. Sheng, and J. J. Li. 2016. "Contract Governance and Buyer–Supplier Conflict: The Moderating Role of Institutions." *Journal of Operations Management* 41: 12–24.
Biesinger, F., D. Meike, B. Kraß, and M. Weyrich. 2018. "A Case Study for a Digital Twin of Body-in-White Production Systems." In *2018 IEEE 23rd International Conference on Emerging Technologies and Factory Automation (ETFA) (Vol. 1, pp. 19–26)*. IEEE.
Blomqvist, K., P. Hurmelinna, and R. Seppänen. 2005. "Playing the Collaboration Game Right—Balancing Trust and Contracting." *Technovation* 25 (5): 497–504.
Braun, V., and V. Clarke. 2006. "Using Thematic Analysis in Psychology." *Qualitative Research in Psychology* 3 (2): 77–101.
Constantinides, P., O. Henfridsson, and G. G. Parker. 2018. "Introduction—Platforms and Infrastructures in the Digital age." *Information Systems Research* 29 (2): 253–263.
David, M., and C. D. Sutton. 2011. *Samhällsvetenskaplig metod* (Vol. 1). Lund: Studentlitteratur.
de Reuver, M., C. Sørensen, and R. C. Basole. 2018. "The Digital Platform: A Research Agenda." *Journal of Information Technology* 33 (2): 124–135.
Dobrescu, R., D. Merezeanu, and S. Mocanu. 2019. "Process Simulation Platform for Virtual Manufacturing Systems Evaluation." *Computers in Industry* 104: 131–140.
Eloranta, V., L. Orkoneva, E. Hakanen, and T. Turunen. 2016. "Using Platforms to Pursue Strategic Opportunities in Service-Driven Manufacturing." *Service Science* 8 (3): 344–357.
Gartner, K. 2018. "5 Trends Emerge in The Gartner Hype Cycle for Emerging Technologies", 2018.
Gawer, A. 2014. "Bridging Differing Perspectives on Technological Platforms: Toward an Integrative Framework." *Research Policy* 43 (7): 1239–1249.
Gawer, A., and M. A. Cusumano. 2013. "Industry Platforms and Ecosystem Innovation." *Journal of Product Innovation Management* 31 (3): 417–433.
Gibson, J., R. Rondeau, D. Eveleigh, and Q. Tan. 2012. "Benefits and Challenges of Three Cloud Computing Service Models." In *2012 Fourth International Conference on Computational Aspects of Social Networks (CASoN)* (pp. 198–205).
Hahn, G. J. 2020. "Industry 4.0: A Supply Chain Innovation Perspective." *International Journal of Production Research* 58 (5): 1425–1441.
Henfridsson, O., and B. Bygstad. 2013. "The Generative Mechanisms of Digital Infrastructure Evolution." *MIS Quarterly* 37 (3): 907–931.
Huang, S., G. Wang, and Y. Yan. 2022. "Building Blocks for Digital Twin of Reconfigurable Machine Tools from Design Perspective." *International Journal of Production Research* 60 (3): 942–956.
Jiang, X. 2011. "Theoretical Perspectives of Strategic Alliances: A Literature Review and an Integrative Framework." *International Journal of Information Technology and Management* 10 (2/3/4): 272–295.
Kress, P., A. Pflaum, and U. Löwen. 2016. "Ecosystems in the Manufacturing Industry." In *Emerging Technologies and Factory Automation (ETFA), 2016 IEEE 21st International Conference on* (pp. 1–4).
Kritzinger, W., M. Karner, G. Traar, J. Henjes, and W. Sihn. 2018. "Digital Twin in Manufacturing: A Categorical Literature Review and Classification." *IFAC-PapersOnLine* 51 (11): 1016–1022.
Landolfi, G., A. Barni, S. Menato, F. A. Cavadini, D. Rovere, and G. Dal Maso. 2018, May. "Design of a Multi-Sided Platform Supporting CPS Deployment in the Automation Market." In *2018 IEEE Industrial Cyber-Physical Systems (ICPS)* (pp. 684–689).
Lee, C. G., and S. C. Park. 2014. "Survey on the Virtual Commissioning of Manufacturing Systems." *Journal of Computational Design and Engineering* 1 (3): 213–222.
Leminen, S., M. Rajahonka, M. Westerlund, and R. Wendelin. 2015. "The Future of the Internet of Things: Toward Heterarchical Ecosystems and Service Business Models." *Journal of Business & Industrial Marketing* 33 (6): 749–767.
Li, M., Y. Fu, Q. Chen, and T. Qu. 2021. "Blockchain-enabled Digital Twin Collaboration Platform for Heterogeneous Socialized Manufacturing Resource Management." *International Journal of Production Research*, 1–21 (in press).
Liu, X., Y. Jiang, Z. Wang, R. Y. Zhong, H. H. Cheung, and G. Q. Huang. 2021. "imseStudio: Blockchain-Enabled Secure Digital Twin Platform for Service Manufacturing." *International Journal of Production Research*, 1–20 (in press).
Luo, D., Z. Guan, C. He, Y. Gong, and L. Yue. 2021. "Data-driven Cloud Simulation Architecture for Automated Flexible Production Lines: Application in Real Smart Factories." *International Journal of Production Research*, 1–23 (in press).
Madni, A. M., C. C. Madni, and S. D. Lucero. 2019. "Leveraging Digital Twin Technology in Model-Based Systems Engineering." *Systems* 7 (1): 7.

Moghaddam, M., and S. Y. Nof. 2018. "Collaborative Service-Component Integration in Cloud Manufacturing." *International Journal of Production Research* 56 (1-2): 677–691.

Moura, J., and D. Hutchison. 2016. "Review and Analysis of Networking Challenges in Cloud Computing." *Journal of Network and Computer Applications* 60: 113–129.

Mourtzis, D., M. Doukas, and D. Bernidaki. 2014. "Simulation in Manufacturing: Review and Challenges." *Procedia CIRP* 25: 213–229.

Müller, J. M. 2019. "Antecedents to Digital Platform Usage in Industry 4.0 by Established Manufacturers." *Sustainability* 11 (4): 1121.

Oliveira, N., and F. Lumineau. 2019. "The Dark Side of Interorganizational Relationships: An Integrative Review and Research Agenda." *Journal of Management* 45 (1): 231–261.

Paik, Y. 2005. "Risk Management of Strategic Alliances and Acquisitions Between Western MNCs and Companies in Central Europe." *Thunderbird International Business Review* 47 (4): 489–511.

Reim, W., D. Rönnberg Sjödin, and V. Parida. 2018. "Mitigating Adverse Customer Behaviour for Product-Service System Provision: An Agency Theory Perspective." *Industrial Marketing Management* 74: 150–161.

Reim, W., P. Yli-Viitala, J. Arrasvuori, and V. Parida. 2022. "Tackling Business Model Challenges in SME Internationalization Through Digitalization." *Journal of Innovation & Knowledge* 7 (3): 100199.

Saunders, M., P. Lewis, and A. Thornhill. 2009. *Research Methods for Business Students* (5th ed.). Edinburgh: Pearson Education Limited.

Schluse, M., M. Priggemeyer, L. Atorf, and J. Rossmann. 2018. "Experimentable Digital Twins—Streamlining Simulation-Based Systems Engineering for Industry 4.0." *Transactions on Industrial Informatics* 14 (4): 1722–1731.

Singh, S., E. Shehab, N. Higgins, K. Fowler, T. Tomiyama, and C. Fowler. 2018. "*Challenges of Digital Twin in High Value Manufacturing* (No. 2018-01-1928)." SAE Technical Paper.

Smedlund, A., and H. Faghankhani. 2015. "Platform Orchestration for Efficiency, Development, and Innovation." In *System Sciences (HICSS), 2015 48th Hawaii International Conference on* (pp. 1380–1388).

Suuronen, S., J. Ukko, R. Eskola, R. S. Semken, and H. Rantanen. 2022. "A Systematic Literature Review for Digital Business Ecosystems in the Manufacturing Industry: Prerequisites, Challenges, and Benefits." *CIRP Journal of Manufacturing Science and Technology* 37: 414–426.

Thomas, L. D., E. Autio, and D. M. Gann. 2014. "Architectural Leverage: Putting Platforms in Context." *Academy of Management Perspectives* 28 (2): 198–219.

Vachálek, J., L. Bartalský, O. Rovný, D. Šišmišová, M. Morháč, and M. Lokšík. 2017. "The Digital Twin of an Industrial Production Line Within the Industry 4.0 Concept." In *2017 21st International Conference on Process Control (PC)* (pp. 258–262). IEEE.

Van Alstyne, M. W., G. G. Parker, and S. P. Choudary. 2016. "Pipelines, Platforms, and the new Rules of Strategy." *Harvard Business Review* 94 (4): 54–62.

Wang, K. J., Y. H. Lee, and S. Angelica. 2020. "Digital Twin Design for Real-Time Monitoring–a Case Study of die Cutting Machine." *International Journal of Production Research* 2020: 1–15.

Wang, X. V., and L. Wang. 2019. "Digital Twin-Based WEEE Recycling, Recovery and Remanufacturing in the Background of Industry 4.0." *K* 57 (12): 3892–3902.

Waurzyniak, P. 2017. "PLM's Digital Twins Offer Virtual View of Manufacturing." *Manufacturing Engineering* 158 (4): 67–73.

Wuyts, S., and I. Geyskens. 2005. "The Formation of Buyer—Supplier Relationships: Detailed Contract Drafting and Close Partner Selection." *Journal of Marketing* 69 (4): 103–117.

Yaqub, M. Z., M. Srećković, G. Cliquet, G. Hendrikse, and J. Windsperger. 2020. "Network Innovation Versus Innovation Through Networks." *Industrial Marketing Management* 90: 79–89.

Zheng, P., T. J. Lin, C. H. Chen, and X. Xu. 2018. "A Systematic Design Approach for Service Innovation of Smart Product-Service Systems." *Journal of Cleaner Production* 201: 657–667.

Zheng, X., J. Lu, and D. Kiritsis. 2021. "The Emergence of Cognitive Digital Twin: Vision, Challenges and Opportunities." *International Journal of Production Research*, 1–23 (in press).

Zheng, P., Z. Wang, C. H. Chen, and L. P. Khoo. 2019. "A Survey of Smart Product-Service Systems: Key Aspects, Challenges and Future Perspectives." *Advanced Engineering Informatics* 42: 100973.

Zheng, C., Z. Wang, X. Qin, B. Eynard, P. Hehenberger, J. Li, J. Bai, and Z. Yicha 2020. "Integrated Design for Product–Service Systems: A Focus on Multi-Disciplinary Interface." *International Journal of Production Research* 59 (19): 5884–5902.