Digital Twin Ecosystems: Potential Stakeholders and Their Requirements

Reshani Liyanage[1], Nirnaya Tripathi[2], Tero Päivärinta[2], and Yueqiang Xu[2]

University of Oulu, Finland
[1]reshaniliyanage1@yahoo.com
[2]firstname.lastname@oulu.fi

Abstract
Context: As industries are heading for digital transformation through Industry 4.0, the concept of Digital Twin (DT) - a software for digital transformation, has become popular. Many industries use DT for its advantages, such as predictive maintenance and real-time remote monitoring. Within DT domain, an emerging topic is the concept of an ecosystem—a digital platform that would create value for different stakeholders in an ecosystem of DT-driven products and services. However, current empirical research on Digital Twin Ecosystems (DTEs) is still in its infancy, with a limited amount of knowledge on potential stakeholders and their requirements.
Objective/Methodology: Thus, the objective of this research was to explore potential stakeholders and their requirements. The research employed an empirical research methodology in which semi-structured interviews were conducted with DT professionals for data collection.
Results: Data analysis of the study revealed 13 potential stakeholders who were categorized as primary (manufacturers, suppliers, subcontractors, and intelligent robots), secondary (maintenance service providers, platform integration service providers, tech companies, etc.), and tertiary (research organizations, third-party value-added service providers, cyber security firms, etc.). This study also presents the different requirements of these stakeholders in detail.
Contribution: The study contributes to both research and industry by identifying possible stakeholders and their requirements. It contributes to the literature by adding new knowledge on DTEs and fills a research gap while contributing industry by providing ample knowledge to the industry's practitioners that is useful in the development and maintenance of a healthy DTE.

Keywords: Digital Twin, Ecosystems, Stakeholders, Industry 4.0

1 Introduction

In today's highly competitive industrial environment, industries are seeking digital transformation through Industry 4.0, which offers a competitive edge for organizations by improving processes and products through embracing new technologies [1]. In this aspect, DTs which act as a software for digital transformation have become a promising and emerging area of technological focus through which industries can gain a number of benefits, such as foreseeing problems in the development processes and the ability to give early warnings [2]. The initial concept of DT was brought to attention by Michel Grieves in 2002 [3] and, later, the term “digital twin" was put forward by NASA in their integrated technology roadmap [4]. DT was defined in [5] as;

> “a multi-physical, multi-scale, and probabilistic simulation model of a complex product. It uses updated sensors and physical models to mirror physical life in the digital world and vice versa” [5].

Due to DTs’ vast number of advantages, such as developing novel prospects and designing enhanced devices and products by means of digital representations[6], its applications can be seen in number of areas, including manufacturing, healthcare, industrial Internet of Things (IoT) environments, automobiles, retail, smart cities, etc. Another critical advantage of DTs is that they can integrate information from multiple sources and scales in real time from physical entities and then create a living model of the physical entity that can be used for predictive maintenance [7]. To cater these benefits, it uses a number of emerging technologies, such as artificial intelligence, deep learning, machine learning, and other trends, such as the IoT and big data [6].

Furthermore, to boost the improvement of the product and service development processes and to identify and develop novel product-service systems (PSS), the concept of the DT ecosystem (DTE) has been put forward [8]. In the same study, the authors stated that the DTE is a digital platform based on DTs that would help in product design and lifecycle management by creating value through an ecosystem of twin-driven products and services. The authors in [8] defined the DTE as:

> “an interconnected multiple instances of a digital twin or different digital twins that have been arranged into value networks using the different enabling technologies for digital twins”. [8]

Further, this concept would lead industries to achieve real-time prediction and repeated and continuous optimization of the different parameters in a system by providing intelligent optimization instructions [9]. Thus, an ecosystem will enable stakeholders to collaborate and exchange digital artifacts, which will be done in a dynamic way and generate mutual benefit [10].

1.1 Problem Statement and Research Objectives

The empirical research work in this area still needs a lot of improvement [11]; most of this research is focused on the application of DTs in various industries and the use of different technologies in developing DT applications. However, the literature on DTEs is still in its infancy. In particular, there are only a few studies that focus on stakeholders and their requirements from the perspective of DTEs. Still, the study of stakeholders and their requirements is important in developing a healthy DTE while generating value through collaboration. In this stance, this research aims to conduct an empirical study with the research objective of identifying potential stakeholders and their requirements in the DTE.

The paper is divided into the following chapters. Chapter 2 discusses the background literature, and Chapter 3 describes the empirical study. The results, discussion, and conclusion are presented in subsequent chapters.

2 Background Literature

2.1 Industry 4.0 and Digital Twins

Given the increasingly competitive nature and the need to recreate value in global industrial networks, Industry 4.0 (I4.0) has recently become a buzzword in both academia and practice [12]. While Industry 3.0 is more about the digital transformation of industrial facilities, I4.0 signifies that it is more data-oriented, with a higher degree of focus given to large amounts of data generated in industrial processes and communications between machines. In I4.0, the focus is on processing this data to generate useful information that could be used in industrial environments [13]. I4.0 is a revolution that unleashes a number of benefits for industries in the process of digital transformation. These include the reduction of costs, improved quality of products, increased scalability, and achieving a higher level of flexibility in production facilities. Further, this new paradigm also enables organizations to respond to defects and deviations in a faster and more effective way so that the product or production improvements are self-adjusting [12]. These benefits of I4.0 are derived using modern technologies, such as the IoT, Artificial Intelligence, Cyber Physical Systems (CPS), DTs, cloud computing, and big data, etc. [14]. CPS is significant for achieving virtualization. On top of this, DTs add a greater value by providing real-time monitoring capabilities of these real-world systems, and thus play an important role in the context of I4.0, allowing smart products and manufacturing systems to provide a more competitive advantage to the industries [14].

2.2 Digital Twin Definitions

DTs are an emerging area of research, and many previous studies have presented different definitions for DT. Table 1 shows some prominent definitions that were put forward in previous literature.

Table 1: Definitions of Digital Twins Identified from the Literature

Study	Definition
[3]	"a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level"

[5]	"a multi-physical, multi-scale, and probabilistic simulation model of a complex product. It uses updated sensors and physical models to mirror physical life in the digital world and vice versa"
[11]	"An integrated system that can simulate, monitor, calculate, regulate, and control the system status and process. It has the characteristics of individualization, high efficiency and highly quasi-real"

Based on the above table, it can be seen that the definition for DT has evolved over time and different studies have their own ways of defining a DT. Despite these differences in definition, these definitions also represent some common features that define a DT. As such, in simple terms, a DT can be defined as a full digital representation (virtual counterpart) of a physical system or a product (physical counterpart) in which the virtual counterpart and physical counterpart are connected to each other in real time to transfer data from the physical counterpart to the digital counterpart, and vice versa. Going forward in this research, the authors will use this definition of DT.

2.3 Digital Twin Ecosystems (DTE)

An ecosystem is composed of different facilities and parties and includes the data generated by each party in the ecosystem [8]. When analyzing the literature on DTEs, it can be seen that there is another definition for DT ecosystems than the definition mentioned in the introduction above. In these studies, the authors considered a DTE to be an environment that includes a single DT, its sensors, the technologies used, and the users [15, 16]. Thus, going forward in this research, the authors will consider the definition proposed by [8] for DTE: an interconnected multiple instances of a digital twin or different digital twins that are connected to each other using different technologies to form a value network. This concept could lead industries to achieve real-time prediction and repeated and continuous optimization of the different parameters in a system within the ecosystem. Furthermore, this could enable advanced risk warnings, fault detection, and the provision of intelligent optimization instructions for different categories of workers, such as system operators, maintenance workers, etc. [9].

The different stakeholders in this ecosystem have different objectives, and their decision-making criteria can differ [17]. Additionally, the same study mentions that the decisions and behaviors of one stakeholder affect the other, and this ultimately affects the evolution and decline of the ecosystem. Thus, the identification of potential stakeholders and their requirements provides valuable insights for the management of stakeholders within DTEs.

3 Empirical Study

In this study, two research questions were framed to achieve the study objectives, as mentioned in Section 1.1. To answer the research questions, an empirical approach was used, which is a qualitative research methodology in which semi-structured interviews were conducted to collect the empirical data. In software engineering, interviews, questionnaires, and observations are different ways of carrying out this type of empirical study [18].

3.1 Research Questions (RQs)

RQ1: Who are the potential stakeholders that will be involved in the digital twin ecosystem?

RQ2: What are the requirements of these stakeholders for involvement in this digital twin ecosystem?

3.2 Empirical data collection

Interviewees were selected through our industrial research project Oxilate (https://itea4.org/project/oxilate.html), in which they are working together to develop DT solutions. This project is aimed at developing DTs that will be used by these companies. For example, companies C2, C3, and C5 are working in a DTE, and the other companies are planning to expand to the DTE level. The general information for the interviewees in this research is shown in Table 2. To ensure anonymity, interviewees are referred to as I, while companies are referred to as C. Initially, in this research, an interview script was developed that included a set of warm-up, general (DT utilization specific), future-oriented (on DTE), follow-up, and wrap-up questions. The interview timing was set to one hour, and all the interviews were conducted and recorded online using MS Teams. These recordings were then transcribed to obtain the data.

Table 2: Information about the Interviewees

Interviewee (I) / Company (C)/ Location	**Interviewee Experience Related to DT**
I1 / C1 / Belgium	Working in the company for 1.5 years as a machine learning research engineer. Mainly worked in contributing to different machine-learning-related projects and solutions used in development of DT.
I2 / C1 / Belgium	Research manager working on developing simulation software, test software, and hardware used in different industries, such as automobile, aerospace, etc. He also had experience in developing various product and performance DTs developed in the company.
I3 / C2 / Turkey	A software engineer, working in the company for about 1.5 years in the research and development department. The interviewee had been working on different DT projects in the automotive and food sectors.
I4 / C2 / Turkey	Software engineer working to develop DTs for a factory in the automotive sector and a food factory.
I5 / C3 / Turkey	Consultant with more than 10 years of experience in the IT field and currently trying to guide digital transformation and consulting with the software company, which is creating DT software for an automotive company.

I6 / C4 / Finland	Working as a research director in one of the major software development and automation companies in Finland and has built prototypes related to digital twins.
I7 / C5 / Finland	A senior data scientist working in a Finnish technology company for more than three years. Has been engaged in producing data-oriented solutions in which the data is analyzed to provide solutions based on data from DTs to optimize and make the process more efficient, more reliable, and to spot the possible anomalies and problems beforehand.
I8 / C6 / Finland	Has been in a company that developed software as well as provided consultancy services for industries and public sector organizations focusing on the medical sector since 2008. Experience in developing DT systems in the automotive industry for testing autonomous vehicles.

As per Table 2, almost all the interviewees had experience and knowledge regarding DTs. Furthermore, the participants were from different companies in three geographic locations that engaged in the development of DTs at different levels. This selection of study participants ensured that the collected empirical data aligned with the research objectives.

3.3 Data Analysis Procedure(s)

Before the extraction of data from the interviews, the audio files were transcribed. After this, data were extracted into a spreadsheet for data analysis and then manually coded. The authors reviewed the extracted data several times to identify all possible codes for the study. In this study, an inductive coding approach was used, where the codes and themes were generated from the extracted data itself [19]. This approach was used to identify all possible codes that existed in the extracted data. Later, these codes were aggregated into the main themes of stakeholders and requirements. The aim was to structure the extracted data so that they could be adopted in reporting the state-of-the-art research results of the study.

3.4 Study Validity

The validity and reliability of the research results can be assessed according to four main criteria for evaluating the quality of research design proposed in [20]. The evaluation criteria consist of construct validity, internal validity, external validity, and reliability.

- Construct validity: To establish construct validity in this study, an interview script was designed and developed to reflect the RQs. Further, this research collected data from eight different semi-structured interviews with eight different participants who had experience with DT, such that it added insights from different points of view. Any inaccuracies in the data caused by the influence of interviewers have been minimized by conducting several interviews. Therefore, some threats to construct validity were minimized in the study.

- Internal validity: This is not directly related to this study, since this research does not focus on identifying causal relationships.
- External validity: The study presents a generic but versatile look at different stakeholders who would be there when moving to the DTE level as well as their requirements from different perspectives. Since the study comprises an empirical study with different interviews from different companies, this reduces the possible opportunities for the bias in results that would have been present if the research were focused on one interview or one company. Thus, the results of the study cannot be applied in all contexts, as the interviewees were from different industries and locations.
- Reliability: To achieve reliability, this empirical study has described the research process and how the data has been analyzed to answer the RQs. However, there is a possibility that another researcher might identify different results, as the data gathered from semi-structured interviews can change depending on the interaction between the interviewer and interviewees, the situation, and the accumulated knowledge of the interviewee at the time. As such, there is a possibility that the results from the empirical study could be changed if repeated.

4 Results

4.1 Identified Potential Stakeholders in DTEs (Answer to RQ1)

Based on the data gathered from the semi-structed interviews, a number of different potential stakeholders were identified (as shown in Table 3 below) who could be involved in the DTE by providing their various services. Table 3 also shows the different roles played by these stakeholders in the DTE.

Table 3: Stakeholders and Their Roles within the Ecosystem

Identified Stakeholder	Role
Intelligent robots	React based on the feedback from the DT. This feedback could be about possible deviations/abnormalities in the processes or any other instructions. This enables real-time responses to these deviations in the systems in the DTE.
Manufacturers (develops products and services)	Use DT within the organization to monitor products and processes, and for communication with external parties such as suppliers, subcontractors, etc., for sharing related information withing the DTE.
Physical asset suppliers such as manufacturers of intelligent robots/machines	Develop intelligent robots/machines used by the manufacturer's companies within the DTE.
Subcontractors	Conduct subcontract work from other partners such as manufacturers, and use DTs to share information with the related party.

Platform integration service providers	Integrate different DT systems and equipment of different stakeholders within the DTE and enable them to share data and work together.
Third-party value-added service providers (AI engineers, data scientists, developers)	Use big data generated within the DTE and perform analytics to gain more knowledge that will give a competitive advantage, direct improvements of processes and systems, and generate new business models used by the stakeholders in the ecosystem.
External maintenance service providers	Provide maintenance for the physical systems/machines used by the manufacturer based on the feedback in intelligent instructions by data generated from DTs.
Suppliers	Provide raw materials to manufacturers and use DT for sharing related information on supplies.
Cyber security companies	Monitor the DT systems to ensure that the ecosystem is not vulnerable to cyber-attacks and take necessary remedial actions in the case of cyber-attacks.
Tech companies	Develop DTs to be used by different ecosystem participants.
Consultancy firms	Provide consultations for manufacturer/supplier for product, process, and service improvements based on information from the DTs.
Research organizations	Conduct research and collect data for studies that will impact improvements and development of the DTE research area.
Government, legal authorities	Government authorities, such as legal and regulatory authorities, can engage in the ecosystem by setting up standards, deriving policies, etc., that govern the ecosystem as well as the use of data from the DTE for providing services.

4.2 Stakeholder Requirements in the DTE (Answer to RQ2)

Based on the analysis of data from the interviews, the following requirements of the stakeholders can be identified, as shown in Table 4. These different requirements of the stakeholders would lead and direct them to use the DTs within the ecosystem, and also for them to engage in this ecosystem. Furthermore, understanding stakeholder roles will make it easy to understand stakeholder requirements, as shown in Table 4.

Table 4: Stakeholders and Their Requirements

Stakeholders	Requirements for Engaging in DTE
Manufacturers	• To gain information on processes and system defects and respond to them in real time while ensuring and monitoring processes are operating under required conditions • To enable real-time coordination with other partners • To gain information and insights to create new products and services through the use of data from DTs • To gain information on processes and systems to make them more efficient through the analysis of DT data
Suppliers	• To identify supply needs in real time, and gain and share information on quantity and quality of supplies using DTs

Subcontractor	• To gain and share information on subcontract work and share information on predesign models, actual work, etc., among the parties in a real-time and dynamic manner
Intelligent robots	• To gain real-time and beforehand information of processes/products regarding the deviations/abnormalities that need to be responded to in real time so that the systems work properly with minimum issues and downtime • To gain instruction on necessary actions in situations of deviations in physical systems
Tech companies that develop DTs (might not use DTs)	• To gain information about products, processes, and systems of DT use for system development • Quick access to data for system maintenance
Maintenance service providers of physical systems	• To gain necessary information and access for monitoring the health of machines and real-time response to any issues • To have real-time access to information to identify upcoming maintenance requirements and provide predictive maintenance • To gain information for making future improvements and upgrades in machines through data analysis
Platform integration service providers (might not use DTs)	• To gain information about different systems and equipment used by stakeholders that needs to be integrated
Consultancy companies	• To gain information to provide insights for products, processes, and service improvements and create more value to their partner.
Physical asset suppliers for manufacturer	• To obtain information and monitor the health of the machines/robots in real time through the use of DTs • To gain information for making improvements/upgrades to these physical assets, such as machinery/ robots for better performance
Cyber security firms (might not use DTs)	• To gain security-related information and monitor the vulnerability of the systems to cyber-attacks and improve the safety of the system and its data • To gain information about cyberattacks for taking remedial actions and ensuring system safety
Third-party value-added service providers	• To obtain big data within the DTE to perform analytics, from which ecosystem participants gain competitive advantage.
Research organizations (do not use DTs)	• To collect data for research that impacts the improvement and development of DTEs
Government authorities (might not use DTs)	• To have easy and quick access for the information required for activities such as taxation, development laws and standards on services provided in the ecosystem and to enable ecosystem governance

5 Discussion

5.1 Potential Stakeholder Mapping in DTE

This study identifies 13 different stakeholder groups that can be classified as primary, secondary, and tertiary stakeholders based on the level at which they are operating within the ecosystem, as shown in Figure 1.

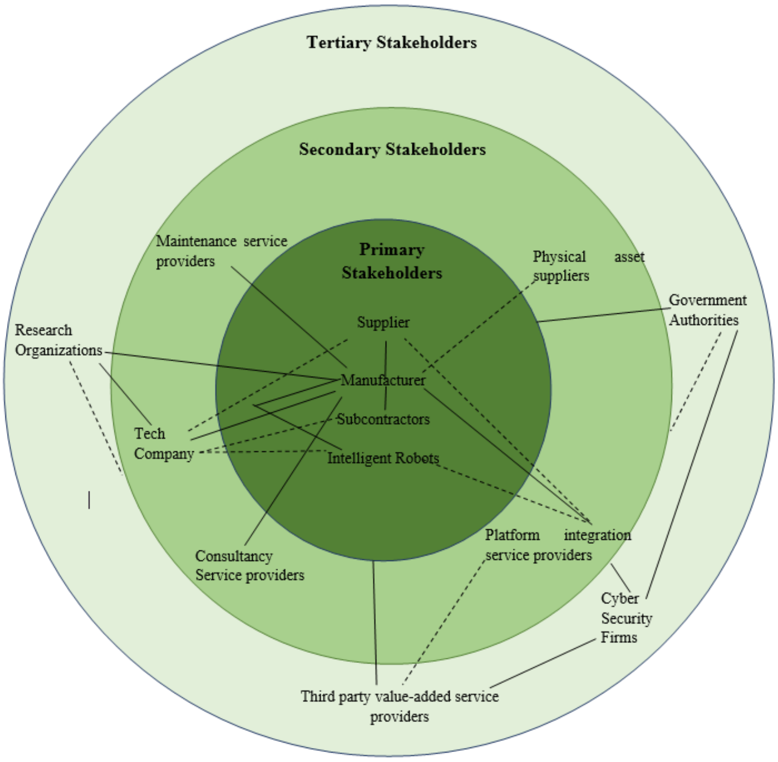

Figure 1: Stakeholder Mapping and Their Interactions Within the Ecosystem

- Primary stakeholders: In the diagram (Figure 1), there are primary stakeholders in the center who engage in the value chain level of the organization (such as manufacturers, suppliers, subcontractors) and internal stakeholders (such as intelligent robots).
- Secondary stakeholders: Secondary stakeholders include maintenance service providers, platform integration service providers, tech companies, physical asset providers, and consultancy service providers. These stakeholders provide different services to the primary stakeholders that support and enhance the provision of the services by the primary stakeholders.

- Tertiary stakeholders: The most external to the primary stakeholders are the tertiary stakeholders, who interact with different stakeholders within the ecosystem at different levels with different levels of interest from the participants. Also, these stakeholders would use data from the overall ecosystem. These stakeholders include third-party value-added service providers, cyber security firms, government authorities, and research organizations.
- Relationships between stakeholders: Figure 1 also shows the interactions among the different stakeholders. The direct straight lines show the primary interactions among the stakeholders, while the dashed lines show the possible secondary interactions among the stakeholders. When developing and managing healthy DT ecosystem, it is important identify these interactions carefully and facilitate them. This would eventually lead to satisfy most of the stakeholder requirements identified above. For example, maintenance service provider who is a secondary stakeholder is interacting with the manufacturer. From table 4 it is clear that the intention of this interaction to share the information on health of physical systems and provide intelligent maintenance feedback on system maintenance. For this it is important that the maintenance service providers to have real time information transmission to facilitate their services. Thus, by identifying these interactions and requirements of the stakeholders, organizations could identify other infrastructure requirements and challenges they would need to face when developing these DTEs.
- Stakeholders' motivations: Through data analysis, it is evident that different stakeholders engaged in the ecosystem have different interests in terms of their requirements. Although their main requirement was to seek information, this information was used to derive some capabilities within the ecosystem, such as having efficient and flexible processes that are more resilient, providing better offerings to the customer, reacting to defects and deviations faster, providing predictive maintenance, conducting better research, and deriving better policies by governments.

5.2 Implications for Research

Previous literature on the context of DTEs identified stakeholders such as suppliers and subcontractors [21, 10]. Further, previous research also identified stakeholders such as government organizations, research organizations, and external analytic service providers that could be considered new stakeholders at the ecosystem level [22, 21, 23]. However, in this empirical research, the authors were able to identify another seven significant potential stakeholders in the ecosystems level of DTs, who were not specified in the previous literature. These stakeholders include intelligent robots, external maintenance service providers, physical asset suppliers (such as suppliers of robots and machinery), tech companies developing DTs, consultancy service providers, platform integration service providers, and cyber security firms. Further, the study presents the different requirements of these stakeholders and their roles and interactions with each other in the ecosystem.

Apart from the identification of the potential stakeholders, this study contributes to the literature on DTEs by identifying and describing in detail the stakeholder requirements as well as the interactions and relationships that can be inferred through these interactions. Previous literature hardly discusses these in the context of DTEs, which makes this study significant in terms of the literature on DTEs and stakeholders. This knowledge can be used by researchers in their future studies on DTEs.

5.3 Implications for Practice

In any ecosystem, the co-creation of value depends on the stakeholders engaging in it.. Thus the identification of possible stakeholders through this study helps organizations decide which stakeholders should be get involved in the ecosystem to generate the highest possible value, based on the different services they provide. For example:

- Intelligent robots can be used in future smart manufacturing environments to streamline the manufacturing process to operate much faster and with higher accuracy [24].
- Artificial intelligence-based robots can be used to improve manufacturing processes by providing enhanced monitoring and auto-correction of the processes in the manufacturing environment. As such, these intelligent robots will be capable of self-configuring, self-adjusting, and self-optimizing through data from DTs [25]. Thus, they will make manufacturing processes more resilient.
- Platform integration service providers could enable systems and applications from different stakeholders to integrate easily. Thus, these service providers could provide standard protocols, application programming interfaces (APIs), and automated tools in this stance [26].
- Physical asset suppliers—such as manufacturers of machinery and robots, are also an integral part of this ecosystem that will enable the improvement of manufacturing systems and processes by providing efficient and adaptive machinery and robots that will improve manufacturing processes within these organizations.

As such, it can be seen that these stakeholders within the DTE provide a number of services to the ecosystem partners in the digital transformation of their systems, processes, and organizations. This study will help companies understand how these stakeholders contribute to deliver value in the ecosystem by playing different roles. This will also help the companies understand how the different stakeholders will interact with each other and their relationships. For example, as shown in Figure 1, manufacturers interact with many stakeholders, such as suppliers, intelligent robots, subcontractors, platform integration service providers, etc., while maintenance service providers interact with manufacturers. Furthermore, the stakeholders in this ecosystem have different requirements, as discussed in this study, and their decision-making criteria can be different from each other. The decisions and behavior of one stakeholder affect another, and this ultimately affects the evolution and decline of the ecosystem. Thus, this knowledge about stakeholder requirements, interactions, and relationships will help manage these stakeholders properly within the ecosystem.

Through this study, industries and practitioners benefit by enabling them to gain ample knowledge that helps in the design and development of a healthy DTE while satisfying stakeholder needs. Companies could use this study to identify the different possible stakeholders within a DTE, and the study enables the understanding of what the roles and requirements of these stakeholders are, and how these stakeholders interact with each other—through which their relationships can be understood. As a whole, this study will ease the process of digital transformation while giving fruitful results for organizations are intending to develop DTEs or are already a part of such DTE.

6 Conclusion

The focused area of research in this study (DTEs) is still in its infancy; only a few studies are available in this domain. The objective of this research was to generate new knowledge and fill this research gap in DTEs with regard to the identification of possible stakeholders and their requirements to provide a broader view of this ecosystem. As such, the authors conducted an empirical study to answer the research questions. After a comprehensive analysis and synthesis of the data, the following results were achieved from the study.

- Identification of 13 possible stakeholders within the DTE, in which the study identified seven new stakeholders other than those mentioned in the existing literature. These new stakeholders are intelligent robots, maintenance service providers, consultancy service providers, physical asset suppliers, platform integration service providers, tech companies and cyber security firms.
- Further, this study has analyzed and discussed the different requirements of these stakeholders in detail, which will generate valuable insights and contribute knowledge to the existing literature and well as the industry.

6.1 Study Limitations and Future Work

The study may have the following limitations owing to the nature of the study and its participants.

The interviews were designed as semi-structured, with open-ended questions so that there were no specific answers to these questions. Thus, the focus of each participant may change. Since the ecosystem perspective of DTs is not quite familiar to the all the participants, there is a possibility that the participants misunderstood the questions and that they also provided answers based on imagination due to a lack of experience with DTEs. Hence, there is always the possibility that the answers they provided could be subjective and biased, depending on their knowledge and experience. The interviews were conducted in English. As such, some Finnish participants had issues articulating their ideas in English. This may have had some impact on expressing ideas, which would, in turn, impact the quality of the data gathered from interviews.

Future research can be done to further compare the stakeholders identified from the empirical study to those identified with the literature, and this can be further expanded to identify the possible challenges when moving from the value chain level to the ecosystem level in the DTE.

References

1. Rocha-Jácome, C. et al.: Industry 4.0: A Proposal of Paradigm Organization Schemes from a Systematic Literature Review. Sensors. 22, 1, 66 (2021). https://doi.org/10.3390/s22010066.
2. Xu, Y., Päivärinta, T., Kuvaja, P.: Digital twins as software and service development ecosystems in Industry 4.0: Towards a research agenda. Commun. Comput. Inf. Sci. 1210 CCIS, 51–64 (2020). https://doi.org/10.1007/978-981-15-7530-3_5.
3. Grieves, M., Vickers, J.: Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems. In Kahlen F., Flumerfelt S., Alve A. Transdiscipl. Perspect. complex Syst. Springer, Cham. 85–113 (2017). https://doi.org/10.1007/978-3-319-38756-7-4.
4. Rosen, R., Von Wichert, G., Lo, G., Bettenhausen, K.D.: About the importance of autonomy and digital twins for the future of manufacturing. IFAC-PapersOnLine. 28, 567–572 (2015). https://doi.org/10.1016/j.ifacol.2015.06.141.
5. Durão, L.F.C.S., Haag, S., Anderl, R., Schützer, K., Zancul, E.: Digital twin requirements in the context of industry 4.0. IFIP Adv. Inf. Commun. Technol. 540, 204–214 (2018). https://doi.org/10.1007/978-3-030-01614-2_19.
6. Augustine, P.: The industry use cases for the digital twin idea. Elsevier Inc. (2020). https://doi.org/10.1016/bs.adcom.2019.10.008.
7. Wang, T., Liu, Z., Liao, M., Mrad, N.: Life prediction for aircraft structure based on Bayesian inference: Towards a digital twin ecosystem. Proc. Annu. Conf. Progn. Heal. Manag. Soc. PHM. 12, 1–8 (2020). https://doi.org/10.36001/phmconf.2020.v12i1.1261.
8. Silva, H.D., Azevedo, M., Soares, A.L.: A vision for a platform-based digital-twin ecosystem. IFAC-PapersOnLine. 54, 761–766 (2021). https://doi.org/10.1016/j.ifacol.2021.08.088.
9. Yan, X.: Construction of digital twin ecosystem for coal-fired generating units. J. Phys. Conf. Ser. 1748, (2021). https://doi.org/10.1088/1742-6596/1748/5/052037.
10. Rosen, R., Fischer, J., Boschert, S.: Next generation digital twin: An ecosystem for mechatronic systems? IFAC-PapersOnLine. 52, 265–270 (2019). https://doi.org/10.1016/j.ifacol.2019.11.685.
11. Zheng, Y., Yang, S., Cheng, H.: An application framework of digital twin and its case study. J. Ambient Intell. Humaniz. Comput. 10, 1141–1153 (2019). https://doi.org/10.1007/s12652-018-0911-3.

12. Armengaud, E., Sams, C., von Falck, G., List, G., Kreiner, C., Riel, A.: Industry 4.0 as digitalization over the entire product lifecycle: Opportunities in the automotive domain. Commun. Comput. Inf. Sci. 748, 334–351 (2017). https://doi.org/10.1007/978-3-319-64218-5_28.
13. Lee, J., Cameron, I., Hassall, M.: Improving process safety: What roles for digitalization and industry 4.0? Process Saf. Environ. Prot. 132, 325–339 (2019). https://doi.org/10.1016/j.psep.2019.10.021.
14. Aheleroff, S., Xu, X., Zhong, R.Y., Lu, Y.: Digital twin as a service (DTaaS) in Industry 4.0: An architecture reference model. Adv. Eng. Informatics. 47, (2021). https://doi.org/10.1016/j.aei.2020.101225.
15. Bhatti, G., Mohan, H., Raja Singh, R.: Towards the future of smart electric vehicles: Digital twin technology. Renew. Sustain. Energy Rev. 141, 110801 (2021). https://doi.org/10.1016/j.rser.2021.110801.
16. Wang, F., Lai, X., Shi, N.: A multi-objective optimization for green supply chain network design. Decis. Support Syst. 51, 262–269 (2011). https://doi.org/10.1016/j.dss.2010.11.020.
17. Tsujimoto, M., Kajikawa, Y., Tomita, J., Matsumoto, Y.: A review of the ecosystem concept – Towards coherent ecosystem design. Technol. Forecast. Soc. Change. 136, 49–58 (2018). https://doi.org/10.1016/j.techfore.2017.06.032.
18. Hove, S.E., Anda, B.: Experiences from conducting semi-structured interviews in empirical software engineering research. Proc. - Int. Softw. Metrics Symp. 2005, 10–23 (2005). https://doi.org/10.1109/METRICS.2005.24.
19. Thomas, D.R.: A general inductive approach for qualitative data analysis. (2003).
20. Yin, R.K.: Case study research. Design and Methods. 1, 93–95 (2009).
21. Niu, X., Qin, S.: Integrating crowd-/service-sourcing into digital twin for advanced manufacturing service innovation. Adv. Eng. Informatics. 50, 101422 (2021). https://doi.org/10.1016/j.aei.2021.101422.
22. Gackstetter, D., Moshrefzadeh, M., Machl, T., Kolbe, T.H.: Smart rural areas data infrastructure (SRADI) – An information logistics framework for digital agriculture based on open standards. Lect. Notes Informatics (LNI), Proc. - Ser. Gesellschaft fur Inform. P-309, 109–114 (2021).
23. Kanak, A., Ugur, N., Ergun, S.: A visionary model on blockchain-based accountability for secure and collaborative digital twin environments. Conf. Proc. IEEE Int. Conf. Syst. Man Cybern. 2019-Octob, 3512–3517 (2019). https://doi.org/10.1109/SMC.2019.8914304.
24. Javaid, M., Haleem, A., Singh, R.P., Suman, R.: Substantial capabilities of robotics in enhancing industry 4.0 implementation. Cogn. Robot. 1, 58–75 (2021). https://doi.org/10.1016/j.cogr.2021.06.001.
25. Dhanabalan, T., Sathish, A.: Transforming Indian industries through artificial intelligence and robotics in industry 4.0. Int. J. Mech. Eng. Technol. 9, 835–845 (2018).
26. Ebert, N., Weber, K., Koruna, S.: Integration Platform as a Service. Bus. Inf. Syst. Eng. 59, 375–379 (2017). https://doi.org/10.1007/s12599-017-0486-0.