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Leveraging Digital Twins to Support Industrial Symbiosis Networks: A Case Study in the Norwegian Wood Supply Chain Collaboration

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Abstract: Despite the powerful potentials of digital twins as regards achieving sustainable operations and supply chain management, there is currently very little research on using digital twins for industrial symbiosis, and even less research investigating user needs. Therefore, it is necessary to conduct sufficient research on the market and user needs before setting the framework of digital twins for industrial symbiosis. We interviewed six companies in the Norwegian wood industry that could potentially share one symbiosis network. Based on the interviews, we analyzed the needs of potential digital twins for industrial symbiosis, aiming to understand the user's point of view on digital twins for industrial symbiosis. The research is expected to provide intellectual support for future digital twins' design from the user perspective. This paper not only promotes the design of digital twins for industrial symbiosis from the user perspective, but also provides an analytical framework for the user perspective analysis before the development of digital twins-based supply chain collaboration in the industrial symbiosis network.

Keywords: digital twin; industrial symbiosis; supply chain collaboration; case study; Norwegian wood industry

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1. Introduction

To accelerate the transformation towards the circular economy, the European Commission acknowledges industrial symbiosis as the core strategic approach to improving resource efficiency while diminishing environmental impact [1]. The circular economy (CE) is prevailing across European and Asian countries with the enactment of government environmental regulations and increasing public attention to environmental issues. Although there has not been a unified definition of CE, due to its various characteristics and analysis levels, its core objective is the circular production paradigm shift, which minimizes manufacturing's impacts on the environment by implementing recycling, remanufacturing, and reusing to close the loop of resources, energy, and materials. Industrial symbiosis aims to establish ecological networks among industries with geographical proximity, reduce waste disposal, and improve production efficiency through enhanced industrial dependency [2]. Specifically, the production waste generated by one sector can be used as raw materials for another, optimizing resources, material and energy consumption in the whole social production process and thereby reducing waste disposal and resource depletion. Hence, industrial symbiosis networks are deemed to simultaneously promote companies' economic, environmental and social performance, constituting the triple bottom lines for companies from different industries to transition to a circular business model [3].

However, establishing industrial symbiosis networks also involves more suppliers and buyers, adding many burdens onto companies' supply chain management. Unlike traditional ones, supply chains in industrial symbiosis networks focus more on suppliers' by-products or disposal wastes than their core business products and outputs [1]. The transportation and exchange of these materials require more of a shared strategic perspective among firms, facilitating information sharing and mutual trust to make joint decisions in procurement and transportation. In this sense, more recent studies have suggested that technological support is the key to achieving supply chain management in industrial symbiosis networks and call for research to examine company needs in using prevailing technologies to achieve supply chain federation processes, especially from the operations and supply chain management perspective [3].

With the development of digitization in Industry 4.0 across various fields [4], digital twins shed light on the technical solutions for supporting supply chain collaboration in industrial symbiosis. Reflecting physical objectives and systems with virtual representations in real-time information exchange systems [5], digital twins have been extensively applied in the manufacturing industry at the workshop [6] and individual company levels [7], covering multiple issues in the production process, such as design [8], maintenance, and monitoring [9]. However, existing research is still lacking on the applications of digital twins at the supply chain level. This is due to the difficulty of digital twin construction caused by the great uncertainty of the supply chain [10]. Furthermore, the current application cases of digital twins at the supply chain level all belong to traditional industries, and we have little relevant knowledge in the context of industrial symbiosis networks. Considering digital twins used for supply chain collaboration in industrial symbiosis is still in the initial stage and has good prospects, but it is necessary to conduct sufficient research on the market and user needs before setting the digital twin for IS development framework.

This paper aims to understand users' needs in the context of applying digital twins to supply chain collaboration to achieve industrial symbiosis networks. Drawing upon semi-structured interviews, we investigated six companies with symbiotic potentials in the Norwegian wood industry and provided a framework containing users' needs to implicate digital twin-based supply chain collaboration in industrial symbiosis. We contribute to the current literature in several ways: First, this study expands the interdisciplinary research on qualitative research methods in the technological innovation represented by digital twins. At the same time, this study selects biomass industrial symbiosis as a case, which enriches the related research into digital twins in the field of biomass industry and circular economy, providing an idea for the potential use of digital twins in sustainable development. In addition, this study proposes a framework from the user perspective before designing digital twins, which provides an example for the analysis of the users' needs regarding digital twin-based supply chain collaboration. Since the application of digital twins in the industrial symbiosis field is still in its infancy, this study concludes user needs from multiple dimensions, promoting the practical application of digital twin-based supply chain collaboration to support industrial symbiosis networks.

The rest of the paper is organized as follows. We review the relevant literature on industrial symbiosis, supply chain collaboration, and digital twins in the next section. Section 3 articulates this study's research materials and methodology, while Section 4 shows the analysis results in economic, environmental, and technical dimensions. Section 5 further discusses the nexus of the three dimensions of economy, environment, and technology, while we conclude our findings and propose future research directions after discussing the limitations in Section 6.

2. Literature Review

2.1. Supply Chain Collaboration in Industrial Symbiosis

Industries with geographic proximity may have the potential to directly establish symbiotic relationships [1,2]. For instance, companies mainly producing boards require lumber materials, which are by-products and wastes from companies producing sawmills nearby. Meanwhile, board production companies can also provide woodfibers for floor production as well as bio-energy companies as their raw materials. In this sense, industrial symbiosis is proposed to improve the utilization efficiency of resources, materials and energies during the production process. Industrial symbiosis refers to the establishment of symbiotic relationships among various independent industries with highly geographic proximity, wherein the byproducts and disposal wastes of one industry could be utilized as resources and production materials by another [1]. Many policy-makers, researchers and practitioners contend that industrial symbiosis is the core strategic approach to achieving the circular economy transition, as it not only utilizes materials in a recycling manner but enhances the economic, environmental and social performance of companies across various industries [3].

Despite the promising benefits above, the development of industrial symbiosis also poses new challenges to companies' supply chain management. Specifically, supply chain management plays an essential role in the process of achieving industrial symbiosis, as it supports the transportation of by-products and waste from one industry to another as raw materials, and further changes the shape of the supply chain structures by adding various buyers and sellers from different industries [3,11–13]. At the same time, the biggest difference between supply chains in industrial symbiosis and traditional ones is that the goods in transportation are often by-products or wastes unrelated to the upstream companies' core business. Therefore, the proliferation of uncertainty in this process leads to establishing supply chains in industrial symbiosis often requiring stronger strategic information and trust [3,7]. In this sense, building supply chains in industrial symbiosis requires cutting-edge technology to reduce the need for information opacity between buyers and suppliers, enhance trust between the various elements of the network, and ultimately form supply chain collaboration to drive economic pursuits as well as achieve social and environmental responsibilities [14,15].

2.2. Digital Twins Applications

As one of the core pillars in Industry 4.0, digital twin has recently vied for the attention of academia and industries [16,17]. Even though no consolidated definition of digital twin has been given due to its rapid development, VanDerHorn and Mahadevan [18] illustrate a relatively clear definition of digital twin by synthesizing relevant studies between 2003 and 2021—"*a virtual representation of a physical system (and its associated environment and processes) that is updated through the exchange of information between the physical and virtual systems" (p. 2)*. In this definition, the digital twin consists of three essential elements: virtual representation, physical system, and information updated in a timely manner. Considering these factors above, the current research cases investigating digital twin applications are dominated by traditional industries, such as agriculture, food processing [19], logistics [15,20], manufacturing, pharmaceutical industry [21] and mining. For example, Klerkx et al. [22] conducted a literature review on digital twin application in agriculture and agricultural products. Defraeye et al. [23] developed a digital twin for fruit based on a mechanical model to improve the cold storage process and logistics to reduce food waste. Ma et al. [24] proposed an intelligent manufacturing framework based on demand response to improve production efficiency. Al-Saeed et al. [25] proposed a proof-of-concept framework for developing digital twin for construction products, aiming to reduce material waste in the manufacturing process. Greif et al. [26] proposed the concept of using a digital twin in the material SC of the construction industry and designed a decision support system for the storage and replenishment of construction materials. Marmolejo-Saucedo [27] proposed the design and development process of a digital twin based on the case of a pharmaceutical company. Semenov et al. [28] took Russian mining companies and contractors as examples for function optimization of digital twins in inventory management and transportation. However, few studies have delved into the context of industrial symbiosis, which limits our knowledge regarding how to utilize digital twins to configure supply chain collaboration in industrial symbiosis networks.

The current digital twins research concerned with supply chain management focuses on flexible production [13,20], real-time monitoring [29] and cost assessment [30]. For example, Barykin et al. [31] and Sundarakani et al. [32] proposed digital twin-based simulation and optimization to reduce suspension in supply chains caused by malfunctions and other uncertainties. Ivanov [33] emphasized the role of digital twins in responding to the outbreak of pandemic diseases such as COVID-19. Similarly, Park et al. [15] proposed the concept of distributed digital twins, aiming to solve the supply chains' bullwhip effect and ripple effect. Smith [34] established a farm digital twin system to improve the collection and analysis of farm information, providing a basis for supply chain decision support. Onwude et al. [35] proposed a digital twin-based real-time quality monitoring technology for agricultural products during transportation. Tozanli et al. [30] simulated the digital twin process in recycling electronic products and evaluated the cost of this process. However, these studies ignored supply chain construction in the context of industrial symbiosis, wherein optimization priority is given to environmental and social issues such as emission reduction and industrial dependence. VanDerHorn and Mahadevan [18] proposed that it is vital to understand buyers' and suppliers' multi-dimensional needs when constructing digital twin-based supply chains in industrial symbiosis, which turn out to be antecedents and drivers that are essential for achieving industrial symbiosis networks.

Table 1 demonstrates the research gaps in the extant literature and the contributions we aim to make in this study.

Table 1. Research gaps from existing literature and research aims of this paper.

Research Gaps	Contributions
Most prior studies employed engineering simulation methods rather than qualitative ones.	We apply the qualitative method of interviews to explore user demands as regards digital twins, and then provide insights as regards their design and applications.
Most prior researchers developed their studies from the perspective of technical pushes, which lacks either theoretical grounds or the demands of market pulls.	We investigate the potential needs of digital twins for industrial symbiosis from the user perspective.
Most extant literature applied digital twins in the manufacturing industry, regardless of achieving industrial symbiosis, circular economy transitions or supply chain construction.	We expound the application scenario of digital twins by demonstrating its potential for achieving industrial symbiosis as well as supply chain collaborations in the wood industry.

3. Materials and Methodology

3.1. Materials

In order to address the research gaps above, we aim to investigate multi-dimensional companies' user needs within digital twin-based supply chain collaborations in the Norwegian wood industry. Norwegian wood industrial symbiosis is in its initial stage of development, and there are few such digital twin-based supply chains. Therefore, companies in an industry symbiosis network under construction are selected to understand the digital twin's functional demand. Meanwhile, the construction of digital twins aims to promote information sharing and cooperation between upstream and downstream companies in industrial symbiosis. Therefore, it is only meaningful to build digital twins between companies that are likely to cooperate in reality. In addition, the selected companies should be willing to participate in the industry symbiosis network, ensuring that the cooperation between companies will not be affected by the geographical distance between them. In this sense, we selected our research materials following the criteria below: (1) the selected companies are all companies in the wood industry; (2) the selected companies have potential upstream and downstream relationships in the IS.

As a result, six companies are selected as the research material in this study. The main business of these companies and the relationship among the companies are shown in Figure 1. For confidentiality, the case company and the information provider are anonymous.

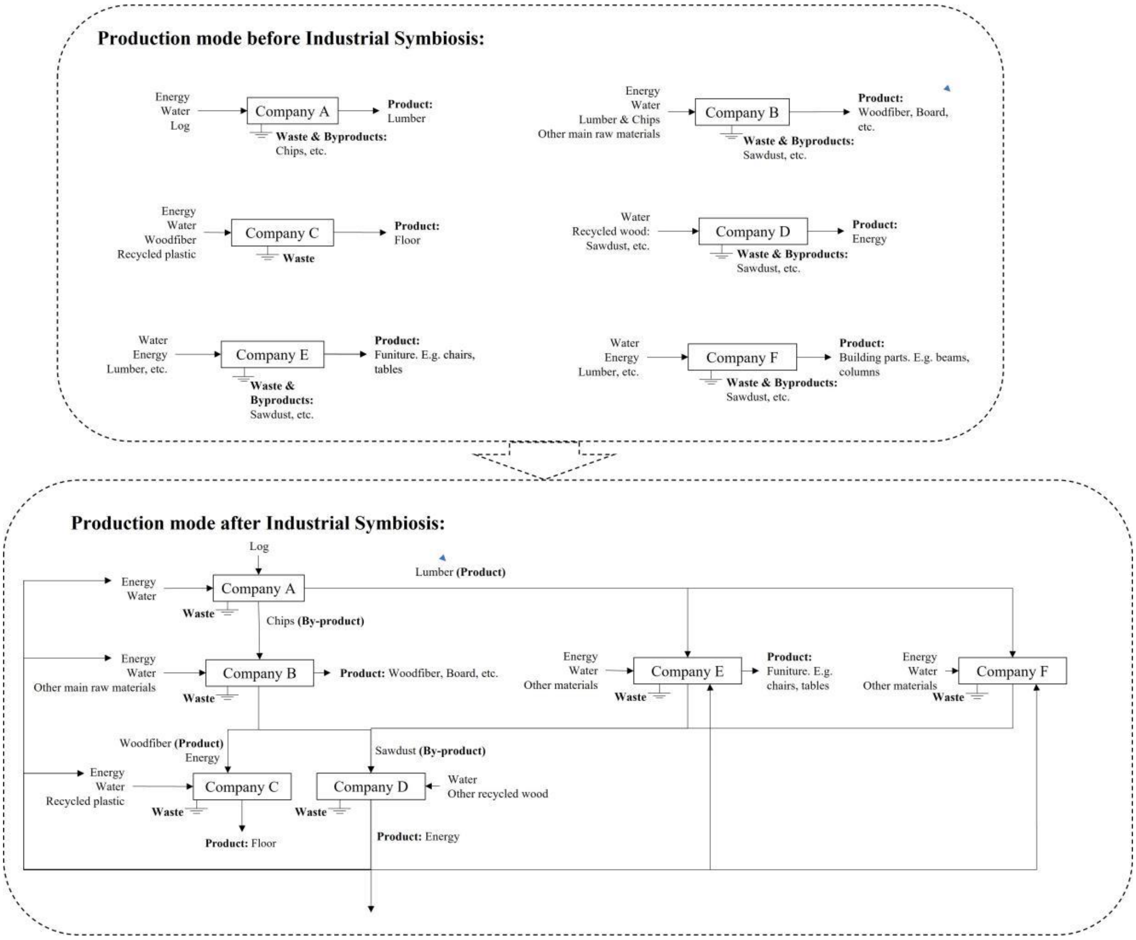

Figure 1. Digital twin-based supply chain collaboration for industrial symbiosis.

The upper half of Figure 1 shows the current production status of sampled companies. The companies are located in different locations and independently produce and process their own by-products and waste. The main business of Company A is to create lumber from logs and generate chips as the main waste/by-product. The main business of Company B is to use lumber, chips and other raw materials to produce boards for construction and woodfiber for building insulation. The main waste/by-product generated in the production process is sawdust. The main business of Company C is to use woodfiber and recycled plastic particles to make composite floors. The main business of Company D is to use recycled wood to produce energy. This production model has resulted in the wastage of by-products that can be reused, such as chips and sawdust. Company E and F share the same production inputs of water, energy, lumber and others, but produce different furniture and building parts products, respectively.

The lower half of Figure 1 is the potential production mode of these six companies after locating the industry symbiosis network with digital twin-based supply chain collaboration. The by-product of Company A, chips, can be used as the raw material of Company B. The product of Company A is the raw material of Company E and Company F. Sawdust from Company B, Company E and Company F can be used as the raw material of Company D. In addition to supplying its own users, the energy produced by Company D can also be used by the three other companies in industrial symbiosis. In addition, because the equipment used by different companies requires different temperatures during production, part of the waste heat in the production process can also be reused, such as the energy transmitted from Company B to Company C.

The potential production model poses greater challenges for digital twin-based information-sharing among companies than the current decentralized production model. In this sense, this study aims to analyze the multi-dimensional user aspirations of these companies in terms of changing the symbiosis mode, which includes needs, concerns, and evaluations for the concept of digital twin-based supply chain collaboration.

3.2. Methods

The methods section includes the general research steps and explains several vital steps. They are the theoretical basis, data collection based on semi-structured in-depth interviews, and data analysis methods based on grounded theory.

3.2.1. Theoretical Basis

The theoretical basis of this study is human-centered design (HCD). HCD is an interactive system development approach aimed at making systems usable and useful by focusing on users, their needs and requirements, and by applying knowledge and techniques. This approach improves effectiveness and efficiency (International Organization for Standardization, 2019) (Source: https://www.iso.org/standard/77520.html, accessed on 19 March 2021). HCD is applied because designing and developing based on a human-centered approach can bring economic and social benefits to both users and suppliers [36]. Highly available systems and products tend to be more technically and commercially successful. For example, in the field of digital twins for supply chain collaboration in industrial symbiosis, it is beneficial to strengthen the connection between potential users, improving the probability of symbiosis and reducing the economic cost and environmental cost.

According to HCD, the focus on the user is pivotal. The user concerns include the user needs and the potential functions that can be provided [36]. This paper focuses on **a** user needs analysis, and we use semi-structured in-depth interviews in the framework of qualitative research methods for analysis. The development stage of using digital twins for supply chain collaboration in industrial symbiosis determines the adoption of this method. The semi-structured interview is a semi-open exploratory process, usually applied in research in the early stage [37]. Currently, using digital twins for supply chain collaboration in industrial symbiosis is still in a conceptual stage. Besides this, we believe that the current user understanding of digital twins used for supply chain collaboration in industrial symbiosis is also in the early stages. Therefore, we adopted semi-structured in-depth interviews as the method of this study.

3.2.2. Data Collection

The data collected in this article are mainly from semi-structured in-depth interviews. The reason for this data collection method is as follows. Since digital twin use in information sharing is still in its infancy, there is not enough second-hand and potential user perspective-related information in the existing research, so interviews with qualitative research methods are used to obtain primary data. Furthermore, interviews are divided into structured interviews and unstructured interviews. Structured interviews are characterized by directed, standard procedures, while unstructured interviews are free-form conversations without directed, standard procedures. The questions explored in this study are fixed in terms of topic but unclear in extension, because we hope to acquire new knowledge from respondents rather than verify existing knowledge. Therefore, we choose semi-structured interviews, which are between structured and unstructured interviews.

Semi-structured interviews are more flexible than structured interviews. Respondents are allowed to provide new knowledge not in our interview framework but relevant to the topic [37]. At the same time, rather than unstructured interviews, it focuses more on the theme of this research, that is, the user's role in the concept of digital twin in information sharing for supply chain collaboration in industrial symbiosis. The primary data source is semi-structured in-depth interviews with senior executives of six companies. In total, 8 persons took the interview. All of them are between 18 and 67 years old, and have worked in their companies for more than 5 years. The focus of the interview was the function demand and the structure demand of digital twins for the companies' supply chain collaboration in industrial symbiosis. As new problems emerged in early communication, we collected data up to two times. As theories became saturated, we conducted shorter interviews with the last company. Our interview guide is given in Appendix A.

Since these data are different from the numerical values with fixed dimensions used in quantitative research, they are presented in videos that have not been sorted out and summarized. Data need to be pre-processed before further analysis. In this study, we have transcribed the respondents' responses in the video into text.

3.2.3. Data Analysis

The data analysis applied in this paper is Proceduralised Grounded Theory (GT) [37]. The reasons for applying GT for analysis are as follows. At present, there is academically little knowledge from the user perspective of digital twin use for supply chain collaboration in industrial symbiosis, and it is impossible to analyze the user perspective through the existing dimensions. The main purpose of GT is to build a theory from empirical data. Researchers do not make theoretical assumptions before the research, and start directly from observations and a summary of the original data. Then, the systematic approach is established. This is a bottom-up method of building theories. That is, it involves finding core concepts that reflect the essence of the phenomena by systematically collecting data and then constructing social theories through the connections among the concepts. This is an appropriate approach for the user perspective on digital twin use for supply chain collaboration in industrial symbiosis in the early stages of research.

4. Analysis Results

Based on the data analysis, the authors find two types of company requirements that are entirely different. Meanwhile, the authors believe that these requirements are related to the types of businesses and sizes of the company, as shown in Table 2.

Table 2. Needs of potential users based on interviews.

Aggregate Dimensions	Second-Order Themes	First-Order Concepts
Suppliers, small-size manufacturers and energy providers tend to standardize top-down digital twin	Flat structure meets the needs of small companies for inter-company information-sharing.	Separate from other management systems such as production system. Only used as an information-sharing tool between companies. Due to the small size of the company, a single authority is sufficient for obtain and exchange information.
	Functional requirements concentrating on	Before production: information acquisition regarding raw materials and orders.

	information-sharing for single business type.	In production: real-time monitoring of the logistics. Due to the small size of the company, complicated functions are not required.
	Cost is the main consideration.	The equipment and labor costs are as low as possible. A third party operates and maintains the digital twin.
Big-size manufacturers tend to customize bottom-up digital twins	Comprehensive multi-level structure to meet the needs of internal management and external information exchange.	Highly integrated database for multiple departments. Managing a variety of internal processes. Sharing some of the data with other companies. Different operational interfaces for employees with different permissions.
	Diversified functional requirements applied to different processes.	Before production: information acquisition of raw materials and orders. In production: real-time monitoring of production, environmental and cost assessment. After production: data storage and reuse.
	The efficiency and security of the system are the main considerations.	Train employees and hire specialists to ensure the efficiency of the digital twin. Operation and maintenance of the digital twin by the company itself to ensure the security of internal data.

According to Table 2, large-size companies with multiple core businesses prefer customized digital twins, while companies with relatively small sizes and fewer business types prefer more standardized digital twins. In this case study, the large-size companies refer to big-size manufacturers, while the small ones relate to suppliers, small-size manufacturers and energy providers. This conclusion is similar to the IT outsourcing of small- and medium-sized companies and the choice of customization by large companies [38]. Compared with IT outsourcing, the digital twin involves a broader range of data, and the data leakage poses more security risks to companies.

4.1. Need from Environmental Dimension

Due to the policy of increasing carbon tax in Norway (Norwegian Ministry of Climate and Environment, 2021) (Source: https://www.regjeringen.no/en/aktuelt/heilskapeleg-plan-for-a-na-klimamalet/id2827600/, accessed on 21 March 2021), the environmental impact on the production process will directly affect production costs. According to the analysis results of environmental need, the current companies can be divided into two categories: larger and smaller companies. These two types of companies have significantly different needs in the environmental dimension.

The first type of company is small in size and has a single business type. Such companies mainly include Company A, Company C and Company D. We think this is also related to the company's main business. The main business of such companies mainly focuses on the upstream raw material supply and downstream energy recovery of the SC. There is not much need for this type of business from an environmental perspective because

"Our carbon emissions are mainly from transportation, it depends on the location of the companies that orders from us, and we cannot control that";

"Most of the waste are recycled within our company";

"We use the waste wood in the production process as the heat source for office heating in winter";

"Our raw materials are all packed in airtight containers, and there is very little waste, so it is difficult to reduce emissions currently".

The second type of company is more prominent in size and has a wide range of business types. Such companies mainly include Company B, Company E and Company F. The second type of company's primary business is manufacturing. Such companies place obvious demands on the environment, which are mainly reflected in minimizing the emissions in manufacturing processes. Such companies also hope that

"Digital twin can monitor and evaluate the environmental impact of the company's production process, especially carbon emissions".

4.2. Need from Economic Dimension

Similar to 4.1, the cost is the main concern of small-size companies. For example,

"Our company has fewer than 5 long-term employees, so we don't have enough people to do things. If the cost of digital twin is not high, we can consider. For example, use cloud storage to save equipment and labour costs";

"Company cloud network is a simple and easy information sharing solution for our small business".

In contrast, long-term economic benefits are the focus of large-size companies. Rather than simply controlling costs, these companies care more about business returns. Specifically,

"We hope the effect of being as obvious as possible."

"If the price is high, but it can bring continuous benefits to the company, why not?"

At the same time, these companies are willing to pay a premium for more comprehensive functions and user-friendly platforms. This is expressed explicitly as

"Platforms that are efficient are often more expensive, which is normal and acceptable. It mainly depends on whether the system is easy to use";

"If the functions are practical and cannot be provided by other similar platforms, It's understandable that the price is slightly higher".

4.3. Need from Technical Dimension

There are mainly two types of technical needs based on the size of the companies. The first type of company is small in size and singular in business. Such companies mainly include Company A, Company C and Company D. The digital twin that these two companies hope to see is a top-down standardized digital twin. The main features of this digital twin are flat structure, low data integration, simple functions and low cost. The second type of company is more prominent in size and rich in business types. Such companies mainly include Company B, Company E and Company F. The digital twin structure that this type of company hopes for is a customized and company-centric bottom-up digital twin. This digital twin has a high data integration level.

Specifically, the need of the first type of company, in terms of structure, is that

"This digital twin is just a platform for sharing information with other companies, and there is no need to integrate the company's production data".

At the same time, these companies

"Have fewer employees and a single business. It is enough for only one specialist to communicate with customers on product and by-product information and transportation issues through digital twin".

In terms of the digital twin's function, information sharing is the main requirement of the first type of company. For example,

"It should be limited in sharing information with other (companies) and monitoring logistics";

"Our main business is simple. Information sharing is enough. Many big companies require complex internal management functions. We don't need it".

The second type of company

"Hope to centralize internal data on digital twin, so different levels of workers and departments can get their own operating platform but can also share information".

At the same time,

"These data should be used to support production and management decision-making";

"We hope to obtain as much information as possible about the available recycled raw materials for production";

"We have a large number of employees. I hope this system can provide different employees with different permissions and operating interfaces".

In terms of functions, in addition to cross-company information sharing and real-time logistics tracking in the procurement and sales process, the companies also want to integrate this information with their production line. The integration is for real-time monitoring and management in production, data storage and reuse, and production decision support.

"Because the quality of recyclable raw materials is inconsistent, we need to test each batch of raw materials. We hope to realize the internal communication from laboratory testing to workshop production".

Efficiency and safety are the concentration of such companies. For example,

"Employing specialists and training employees is indispensable for digitalization…great help to the efficient use of the digital twin platform";

"We hope to operate and maintain digital twin by ourselves, because this digital twin is associated with a lot of internal data. We do this for security reasons";

"If the third party leak company's confidential data, we will face great losses, so we must avoid it".

5. Discussions

Based on the three distinct dimensions of user aspirations analyzed above, we further discuss the nexus between the economical dimension, the environmental dimension and the technical dimension from the user perspective, and then provide a framework from the user perspective.

5.1. Framework from User Perspective

Based on the above case analysis results, larger companies have more functional requirements for digital twins and prefer to customize a bottom-up digital twin, while small companies wish to get a low-cost standardized digital twin that only shares information with other companies. After further segmenting and reorganizing the requirements, we obtained two functional requirements: information sharing and production management. Therefore, we have designed a modular digital twin-applicable framework for the IS to meet different companies' needs, as shown in Figure 2.

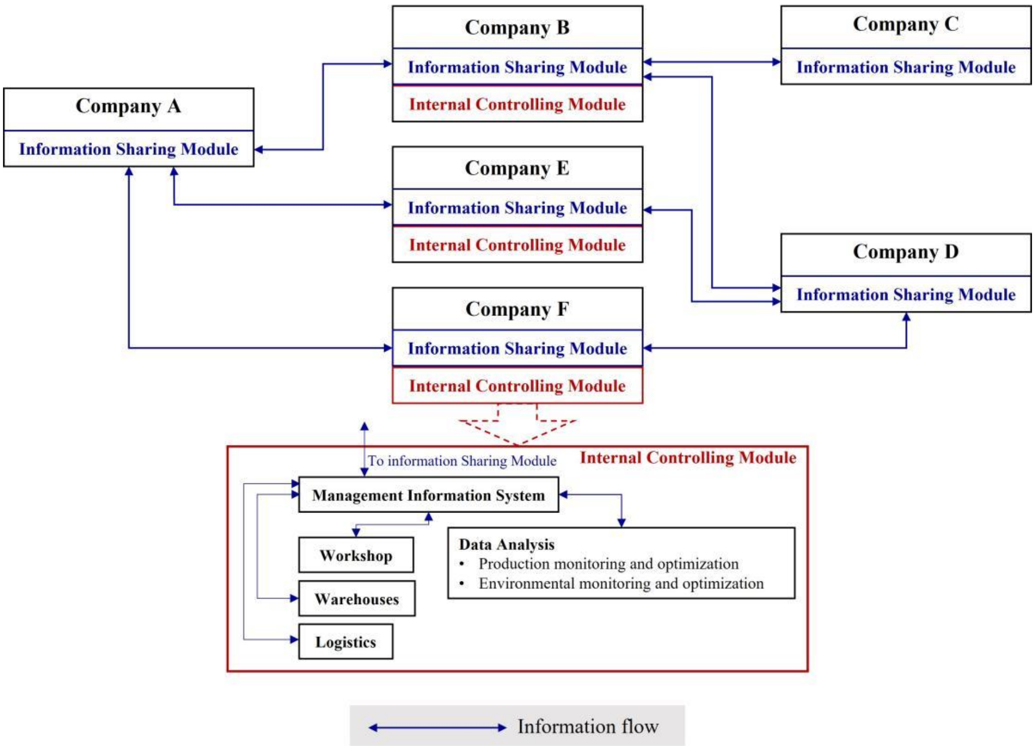

Figure 2. The functional framework of a modular digital twin for supply chain collaboration in the wood industrial symbiosis.

In Figure 2, the blue arrow indicates the information flow and the blue box indicates the external information exchange module used by the information enterprise to share information with other enterprises. The red box indicates the internal control module of the enterprise. The information in this module is not shared directly with other enterprises. If there is information to be shared from the internal controlling module, it will be sent to the information sharing module first, and then from the information sharing module to other enterprises. It is important to note that all arrows in the diagram indicate information flow. This is because the main role of digital twins is information exchange, while the material flow is based on information flow to make decisions, so it is not included in the diagram.

Comparing Figures 1 and 2, we can see that this digital twin framework mainly monitors and optimizes the material flow in industrial symbiosis. Moreover, there is no inter-company digital twin for energy recycling design. On the one hand, this is because the company's main focus on digital twins is the production of raw materials for products, and little attention is paid to the waste energy, mainly the heat and other by-products generated. The demand for heat recycling is not apparent, according to our interview. Besides this, all the companies, except Company D, have already recycled heat internally. Therefore, a cross-company heat recycling function is not designed. On the other hand, because energy is publicly sold, Company A, Company B, Company C, Company E, and Company F can choose energy from Company D or other energy suppliers according to their needs. Therefore, we did not include the energy production and use in this digital twin.

According to Figure 2, the author designed a modular digital twin, specifically the Information Sharing Module and the Internal Controlling Module. The advantage of modularization lies in the lower costs, because the function and structure of each module are similar. The Information Sharing Module is used for information exchange between the companies, which is marked in blue in Figure 2. The Production module is used for internal production management and control, and it is marked in red in Figure 2. The arrows between the two blue modules indicate technical standards for information exchange between the companies.

It can be seen from the interview results that, as small businesses, Company A, Company C and Company D only require information sharing. Specifically, as the upstream company in the wood industrial symbiosis, Company A only demands information sharing with the downstream companies. In contrast, the bottom companies, such as Company D and Company C, only demand information communication with the upstream companies. Therefore, the digital twins of these two companies only have the Information Sharing Module shown in Figure 2. It meets their basic information communication demand and ensures a simple structure and low cost.

However, apart from the information sharing demands of the upstream and downstream companies, the large-size companies, including Company B, Company E, and Company F, also need to integrate the transmitted information with the internal production data and make decisions through real-time monitoring and analysis of the data, in order to achieve flexible production and emission cost monitoring. Therefore, these three companies have two modules at the same time. This digital twin meets the multi-functional and high-efficiency requirements of the companies through highly integrated data and analysis functions.

5.2. Digital Twin-Based Information Sharing Framework between Companies

From the blue part of Figure 2, we can see that companies share data through the Information Sharing Module. The data shared by the module are purchase data and sales data. Purchase data include orderable inventory information, order information, and other information agreed by the company. Orderable inventory information includes product/by-product variety, quantity, specification, price, storage location and other information. Order information includes order confirmation, order change, delivery notice, real-time tracking of cargo information, statement of account, invoice, etc. Sales data mainly include ordering requirements and other information agreed by the company. Information about ordering requirements includes variety, quantity, specifications, and other information related to new orders agreed by the company. In the framework we designed, the relationship between companies is pairwise, which helps improve data security.

Due to system differences between the companies, European companies mainly implement electronic trade documents, such as orders, in standardized formats based on the EDIFACT (Electronic Data Interchange for Administration, Commerce and Transport) (ISO 9735-3) [39]. We believe a blockchain-based EDI system can be used in this communication process, as shown by the arrows between companies in Figure 2. Recently, IBM has developed this blockchain-based EDI [39]. This not only helps reduce the amount of error information based on the EDI system, but also simplifies information processing, thereby improving the entire system's efficiency. As a permanent, tamper-evident distributed ledger technology, blockchain is used to record all valuable transactions. Specifically, blockchain can connect the information flow, inventory flow and money flow of multiple parties involved in a transaction, reducing the errors and time delays caused by manual audits and inspections. Meanwhile, the tamper-evident, decentralized and traceable nature of blockchain reduces the risk of data loss and malicious tampering. Therefore, blockchain can reduce error messages in EDI systems.

Traditional communication protocols between companies include the HTTP (hypertext transfer) protocol, REST API (application programming interface), OFTP2 (Odette File Transfer Protocol 2), etc. The HTTP protocol has poor security, while REST API and OFTP2 have poor scalability [39]. Due to the high data integration characteristics of digital twin, higher requirements are placed on the company's data security and the system's scalability. According to the content of interviews with respondent companies, we believe these transmission protocols are not suitable for the needs of digital twins for the IS. It is noticeable that these protocols are extracted from the interview contents of our study. Based on this evidence, we believe that respondent companies in our interviews restricted digital twin use to intra-firm applications rather than integrating it into supply chain management, which elucidates the importance of data transmission security.

5.3. Emission Evaluation

To delineate the environmental impact of the digital twin-based supply chain collaboration proposed above, we further constructed a carbon emission monitoring and evaluation framework for each type of product of the three manufacturing companies from production to sales. The research objective of this study is to understand the demands and attitudes of potential users regarding digital twins for industrial symbiosis, providing market pull factors for designing and implementing such digital twins. Among these factors, reducing costs and carbon emissions are the priorities for company users of digital twin techniques. In this sense, it is notable that evaluating both economic and environmental performance during the implementation of digital twins for industrial symbiosis is important. Given that prior studies shed light on the economic aspects, we aim to delineate environmental surveillance as regards the use of digital twins for industrial symbiosis and help firms along the supply chain to maintain sound collaboration relationships with each other. The calculated results will be fed back and aggregated to the company level. This facilitates the separate analysis, management and control of different production lines. This carbon emission monitoring and framework is shown in Figure 3.

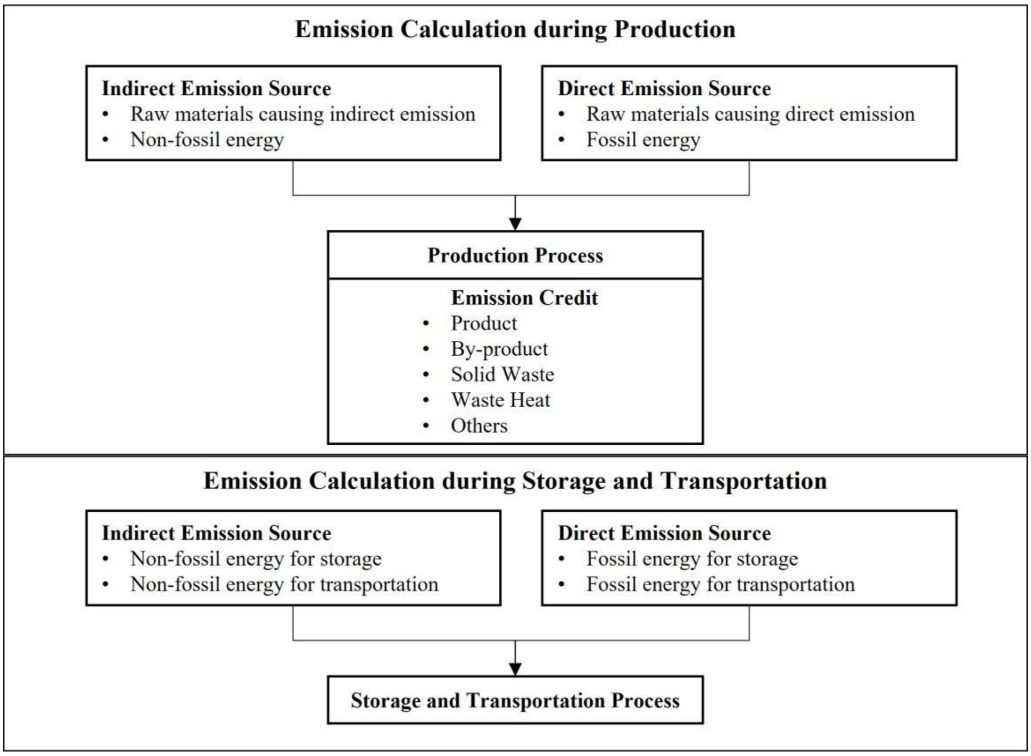

Figure 3. The system boundary of the carbon dioxide emission calculation for the products.

The calculation of carbon emissions during the production process mainly includes carbon emissions and emission credits, as shown in the upper part of Figure 3. Carbon emission sources include indirect emission sources, such as some of the raw materials and non-fossil energy consumption, and direct emission sources include those generated by fossil energy and other materials in the production process. Carbon emission credit sources include products, by-products, solid waste and external waste energy supply. Since the company only recovers heat internally, in our model, waste energy external supply refers to use outside the production center and within the company.

In this calculation system, carbon emissions are mainly derived from the production and storage and transportation processes. Storage and transportation processes contain the storage and transportation of products, by-products and solid waste. Emission sources include direct emission sources represented by direct fossil energy consumption and indirect emission sources represented by electricity, as shown on the bottom part of Figure 3.

The data used in the above calculation come from different modules in digital twin. The direct and indirect emission data and transportation data in the production process come from the Information Sharing Module in Figure 2, and the other data come from the Internal Controlling Module. The parameters of the calculation process are set according to the specific technology and processes of production.

6. Conclusions

This study takes the potential companies that could join the industrial symbiosis network as an example and applies the method of interviews to analyze the potential user needs of digital twins for supply chain collaboration. This paper aims to understand the users' aspirations regarding digital twin use for industrial symbiosis, and hopes to provide knowledge support from the perspective of potential users for designing digital twins for IS.

Through in-depth interviews with six companies in the Norwegian wood industry, we found that large companies with multiple business types prefer customized digital twins and pay more attention to environmental issues, such as reducing carbon emissions, while relatively small companies with fewer business types prefer standardized digital twins and pay more attention to reducing personnel and cost issues. Therefore, we develop a general framework and an inter-company emission-monitoring framework from the user perspective to delineate the digital twin-based supply chain collaboration for supporting industrial symbiosis networks.

The main contributions of this paper are as follows. First, the application framework of the digital twin is currently mainly at the company level, while there are few inter-company digital twin frameworks. Moreover, the frameworks currently used are usually general and have limited application value in practice. Based on a case study, this paper constructs a digital twin for supply chain collaboration in an industrial symbiosis framework from the user perspective, which enriches the current research on digital twins at the SC level.

Second, the digital twins are mainly applied to traditional manufacturing, while little attention has been paid to industrial symbiosis. In this article, a digital twin functional framework from the user perspective is constructed based on cases of companies in the wood industry. This research is conducive to solving the problems faced by companies in the newly built industrial symbiosis, and provides a method of analysis for digital twin designs for other IS. It is necessary to consider both the technique and user perspectives when building up a digital twin with a well-structured data model. Besides this, the scope of this paper is limited to a user perspective, i.e., a preliminary and exploratory analysis of user requirements. Hence, the conclusions obtained in this study are more of a summary and expansion of current user demands regarding digital twins in the process of industrial symbiosis, providing a basis for technical analysis to avoid developing features that users do not need or missing necessary features in a potential digital twin.

Third, reducing pollution is the original intention of industry symbiosis and is also the trend of manufacturing development. However, few studies incorporate environmental factors into the digital twin framework. After understanding companies' demands through interviews, the monitoring and calculation functional framework of carbon dioxide emissions are added. Based on the company's demand, this function gives this digital twin framework higher application value.

Akin to prior studies on the same topics, this paper also has several limitations that need to be addressed in future research. First, the selection of cases in this study resulted in insufficient data from the cases. This is because the case selection conditions in this paper are relatively strict, requiring a potential symbiotic relationship between the case companies. Therefore, few cases meet the requirements. With the development of digital twin-based supply chain collaborations, many industrial symbioses will be established. We hope that in completed industrial symbiosis, analysis based on the real data of companies could be obtained. Moreover, researchers should communicate with the companies at different stages of digital twin development for industrial symbiosis, and adjust the design plan in time according to the feedback and needs of the companies, so as to increase the impact of users on the design and iteration process of the digital twin-based supply chain collaboration for industrial symbiosis.

Second, the digital twin framework in this article does not include the cross-company recovery of waste heat. This is because the case companies already have internal waste heat recovery, and there is no clear need for cross-company waste heat recovery. Besides this, there are currently few studies on the real-time carbon emission monitoring functional framework, though there are applications and case-based studies on the information-sharing framework proposed in this paper. The real-time carbon emission monitoring function is also a future research direction of digital twin use for industrial symbiosis. Moreover, the user perspective framework proposed in this research can support the design of digital twins for industrial symbiosis, but cannot directly guide the development of digital twins for industrial symbiosis or the elaboration of the application validity. This is because the scopes of the user perspective framework in this paper and the application development framework are inconsistent. In establishing an application development framework, future studies should be integrated from a user perspective with a technical one, demonstrating the application development framework and elaborating its validity.

Third, it is noticeable that we only focused on the Norwegian wood industry, and these findings may not be transferable to and applicable in firms from other industries. As firms from different industries may have totally different demands and aims regarding the digital twin use for industrial symbiosis, future studies can employ the methods of this paper to confirm our findings, and then help both researchers and managers to understand the demands for digital twins in other areas of industrial symbiosis.

Finally, as our study explored the user demands of digital twin use for industrial symbiosis, we exclude technique-related analysis in this study. Future studies could integrate demand factors from the user perspective with technical ones, which could provide much more vertical suggestions for deploying digital twins to achieve industrial symbiosis.

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Appendix A

Interview guide: Upstream company
Section 1: Background

1. Company information
   (1) Company scale
   (2) Cooperation with downstream companies: age of company–company relationship; formal or informal tie; independency; age of individual–individual relationship; frequency/duration of projects with this company
2. Personal information
   (1) Position
   (2) Working time in the industry
   (3) Working time in this position
   (4) Number of participating cooperation

Section 2: Cooperation mode

1. Product sales
   (1) Product type
   (2) Cooperated company, time, and mode
2. By-products and their disposal
   (1) Types and disposal methods
   (2) Cooperated company, time, and mode
3. Differences and similarities between selling waste and selling products

Section 3: Demand of Digital twins

1. Function Demand
   (1) Demand before sale
   (2) Demand in the sales process
   (3) Demand after sale
2. Structure Demand
   (1) System construction: top-down or bottom-up
   (2) System maintenance: budget, training and outsourcing

Interview guide: Downstream company
Section 1: Background

1. Company information
   (1) Company scale
   (2) Cooperation with upstream companies: age of company–company relationship; formal or informal tie; independency; age of individual–individual relationship; frequency/duration of projects with this company
2. Personal information
   (1) Position
   (2) Working time in the industry
   (3) Working time in this position
   (4) Number of participating cooperation

Section 2: Cooperation mode

1. Raw material procurement
    (1) Type of the raw material
    (2) Cooperated company, time, and mode
2. The procurement of recycled materials
    (1) Type of the recycled material
    (2) Cooperated company, time, and mode
3. Differences and similarities between purchasing recycled materials and raw materials

Section 3: Demand of Digital twins

1. Function Demand
    (1) Demand before purchase
    (2) Demand in the purchase process
    (3) Demand after purchase
2. Structure Demand
    (1) System construction: top-down or bottom-up
    (2) System maintenance: budget, training and outsourcing

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