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Integrating Digital Twins and Extended Reality for Smart PSS Design: A Case Study on Smart Electric Tour Bus Development

Zhang Yan[a] *, Tobias Larsson[a], Wang Haoqiang[a], Huang Chunjun[b]

[a]Department of Mechanical Engineering, Blekinge Institute of Technology, Karlskrona 371-79, Sweden
[a]Design Center, Xiamen King Long United Automotive Industry, Xia men 361023, China
[b]College of Communication and Art Design, University of Shanghai for Science and Technology, Shanghai 200093, China

* Corresponding author. Tel.: +46 (0)766-042009 fax: +46 (0)766-042009. *E-mail address:* zhang.yan@bth.se

Abstract

The increasing digitalization of manufacturing is transforming product development towards intelligent, service-oriented systems. This study explores the application of Digital Twins (DT) technology in smart Product Service System (sPSS) design, proposing a framework of Super-System Digital Twin (SSDT) and eXtended Reality (XR) for supporting design. The SSDT integrates service offerings, user scenarios, and product features throughout the design process. Case is applied to the conceptual design of a Smart Electric Tourist Bus in collaboration with a global manufacturer, the framework utilizes eXtended Reality (XR) environment to enhance decision-making and prototyping. This research validates SSDT's role in fostering participatory design and collaborative innovation, while addressing its limitations and proposing future improvements.

Keywords: Digital Twins, smart PSS design, eXtended Reality, Decision-making, Case study, Smart electric tour bus

1. Introduction

As the digital servitization transformation of the manufacturing industry accelerates, product development is gradually evolving from the traditional product-centric models to service-oriented solutions [1], driving the emergence of smart PSS (PSS). This trend has prompted manufacturing companies to seek innovative methods approaches in the connection of products and services, and decision-making capabilities of stakeholders from different backgrounds to increase the demand for innovative development methods [2].

The support design tools around smart PSS (sPSS) have become the focus of recent academic discussions, among which advanced technologies such as Digital Twins (DT) technology and eXtended Reality (XR) technologies are gradually becoming important tools to assist the innovation of the design and development of smart PSS (sPSS). Digital Twins (DT), interpreted as a cutting-edge simulation paradigm, has been gaining increasing attention in the research area of smart PSS [3]. These simulations are often coupled with immersive 'experience environments' facilitated by Augmented Reality (AR) [4] and Virtual Reality (VR) applications [5], aiding companies in advancing their servitization journey. Though literature study, Digital Twins and eXtended Reality technologies are often considered to be the core support for the transformation of Industry 5.0 [6] because they give humans deep insight and precise control over various devices, activities, processes, and systems. Their combination allows data to be expressed briefly, with an effective real-life feeling, and effective synthesize, making insights more influential and meaningful [7]. More current researchers have proposed that the technologies of Digital Twins and eXtended Reality are seen as key foundational technologies in designing future product and system [8].

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Digital Twins (DT) technology achieves synchronization between real products or systems and their digital simulations through real-time and continuous data transmission. However, eXtended Reality (XR) technologies, a general term for Augmented Reality, Virtual Reality, and Mixed Reality, integrates virtual and physical environments to enhance the Human-Computer Interaction experience [9]. Although the combination of Digital Twins and XR will be one of the technologies with the greatest potential in developing new service-oriented business offerings, simulation tools are still rarely used by practitioners [10]. However, with limited research showing how virtual simulation systems can maintain effective communication with stakeholders, especially in terms of continuous interaction and feedback at the scenario level. This means that the potential of using virtual environments to support multi-party collaboration and information sharing in complex design and decision-making processes has not been fully explored and with real applications still missing. To solve these issues and opportunities, this study proposed a systematic way to explore how to bridge the communication gap between virtual simulation and stakeholders through the application of the Super- System Digital Twins (SSDT) framework introduced by Haynes and Yang [11].

At the same time, two research questions will be explored in the research process, which can be described as:

- How do Digital Twins support decision-making and conceptual interaction in the early phase of smart PSS design?
- How can the Super- System Digital Twins support the smart PSS in the XR environment to facilitate communication within decision-making in the manufacturing company?

The results from the work have brought to application of an industrial case study in collaboration with global manufacturers to develop a Smart Electric Tour Bus. Then, the case study presents the results of the illustrative study through a framework, clarifying the specific ways in which SSDT and XR support the design process. The effectiveness of the framework is further verified through the example of a smart electric tourist bus developed in cooperation with the case company. The discussion section reveals the results of the validation activities conducted during the design process, while the key findings, research significance, shortcomings, and future studies areas are summarized in the last section.

2. Knowledge Background

2.1. Design Challenges of smart PSS

With the rise of the Fourth Industrial Revolution (FIR), especially in manufacturing, have triggered the emergence of Industry 4.0. Industry 4.0 is characterized as an advanced stage of industrial maturity driven by the connectivity enabled through the Industrial Internet of Things (IIoT), and the integration of various digital technologies, including Big Data, Cloud computing, Artificial Intelligence [42].The current studies show with the fast development of digital technology, smart connected products (SCP) and digital technologies are increasingly integrating into traditional PSS, industrial Internet, cloud computing and big data analysis [12], and thus gradually developing into development of smart PSS (sPSS). Among them, the application of Information Technology (IT) is becoming more and more extensive. In particular, the introduction of technologies such as the Internet of Things (IoT), big data analysis, and Digital Twins has enabled smart PSS to provide context-aware customized services through ongoing data tracking and examination, further optimizing the user experience [13] [14]. Existing research has extensively examined design methods for Product-Service System (PSS). In addition, there is a limited conceptualization regarding the important of digital technologies playing in smart PSS design although the concept of smart PSS has been recognized in design, there is still much room for research in many areas such as its operation, influence and innovative performance [15]. The body of work addressing design methods for smart PSS remains scarce [16] [17]. The transition to smart PSS design shows challenges to traditional PSS design approaches. Therefore, developing ways of application specifically for the special features of smart PSS has become a crucial part of discussion [3].

2.2. The core role of Digital Twins supports smart PSS design

The original introduction of Digital Twins (DT) was firstly given by Grieves in a speech on PLM at University of Michigan in 2003 [18]. The theory of Digital Twins (DT) has been highly valued in recent years, principally with the fast development of the Internet of Things (IoT), which creates a data-rich environment that enhances decision-making during product design and development process [19]. However, Digital Twins (DT) integrates 3D virtualization and sensor data from the physical product or prototype, making them a promising tool for supporting product design in the early phase. In smart PSS, where products are embedded with sensors and connected to digital platforms, Digital Twins plays a essential function in communicating the complexities of product-service interactions [16]. As Valencia et al argue, the inclusion of smart components necessitates more sophisticated design processes, where Digital Twins enables real-time tracking, optimization of product-service lifecycles and predictive maintenance in the use phase.

Based on new literature study on Digital Twins, Super-System Digital Twins (SSDT) represents a more complex evolution of DT [11]. Unlike traditional DT, which focuses on a single physical system is represented by the digital system, SSDT is a further extension of traditional Digital Twins technology. It integrates complex interactions of multiple subsystems and levels to provide a more accurate, operational and flexible multi-dimensional virtual system for the global system. SSDT is not limited to replicating physical assets, but also comprehensively considers their behavior, service conditions and interactions with other systems in a specific environment to form a complete, full-life cycle digital simulation system [20]. In particular, in designing of smart PSS, designers can gain a deeper involving of the product usage environment according to integrate with environmental data and user interaction data, thereby enhancing logical reasoning about decision-making [21]. In addition, the core advantage of SSDT lies in its strong cross-system collaboration capabilities [22]. Therefore, transaction space [23] combined with interactive information visualization interface has become a decision support method recently proposed to deal with these perception limitations [24]. It not only emphasizes the cooperation between manufacturers, service providers and customers, but also collects and analyzes data during user use through technical means to continuously improve services and enhance user experience [25].

2.3. XR empowers decision-making of smart PSS design

EXtended Reality (XR) is a way to bring users feelings other than the five senses, providing synthetic perceptions that are the same as real objects [26]. The existing research regarding the application of eXtended Reality (XR) technologies in user research has been widely used in many fields, and it has gradually emerged as an important tool for behavioral research. It provides researchers with an opportunity to conduct multi-user interaction research in a controlled and repeatable simulation environment, which is particularly suitable for exploring behaviors in collaborative or competitive scenarios, thereby deepening their understanding of complex processes. The operation of XR mechanism can effectively enhance the cooperative capabilities of design operations that can be further optimized to support and make the engineering design process more convenient.

Having XR experience and an environment suitable for using XR for simulation can assist product design during various periods and enable the development and analysis of smart PSS [27]. For example, XR activities are collaborative, through the use of corresponding tools, various participants and stakeholders with different backgrounds and knowledge can be involved, and customers and end users can be authorized to participate in collaborative design and evaluation [28] [29]. In addition, XR environment can well support value creation of smart PSS design and further promote the identification and prioritization of requirements and design evaluation based on these requirements through sensory simulation effects on the theoretical basis of Digital Twins systems [5]. XR systems not only support the contextual simulation capabilities of smart PSS, but also allow the implementation and presentation of multiple possible and future environments [30] [31]. XR activities can overcome the perceptual limitations of current support virtual and digital environments by achieving reconfigurability and hybrid trends in simulation [32], breaking the traditional way and improving the safety and adaptability of manufacturing systems.

3. Research Methodology

3.1. Research framework and case design

To improve the procedural rigor of the research – and to balance industrial relevance with scientific consistency-this research adopts the Design Research Method (DRM) framework proposed by [33]. The single-case design [34] is justified by the opportunity it provides to thoroughly explore existing conditions, validate design requirements, and evaluate the effectiveness of design support. The case study is based on a global bus manufacturer to deeply analyze its innovative design in the field of Electric Tourist Buses. The method of case design provides a practical opportunity to applied proposed framework into application of tourism solutions in the complex industrial environments, especially how to effectively use Digital Twins (DT) and eXtended Reality (XR) environment to enhance the efficiency of smart PSS design and decision-making.

3.2. Data collection method

Semi-structured interviews served as a key data collection way for validating the research findings [35]. The semi-structured interviews conducted between 15 minutes and 30 minutes in Chinese, the authors transcribed and translated the information into English, and respondents validated the transcriptions. In most cases, interviews were audio-recorded and transcribed later; concluded by a written summary of the content shortly afterward. As the research progressed, these interviews also served as a crucial mechanism for validating and refining the proposed Digital Twins approaches and XR environment. **Design experiments:** The design experiment provides understanding and testing design decisions for designers [36]. One design experiment was developed and conducted involving cross-functional design teams from case company to collect and analyze the utilizing of the proposed framework during design phase. The validation included three steps, focusing on verifying SSDT's support for the design by engaging four internal King Long designers to conduct a structured evaluation: step 1: setup and instruction, step 2: scenario-based interactive exploration, step 3: evaluation and feedback collection. The Super-System Digital Twins approach was employed to collect data from the design sessions step-by-step. Included photographs and audio recordings of the sessions, which were analyzed post-experiment.

3.3. Research evaluation method

The information collected from design tests were analyzed using protocol analysis [37]. The coding and analysis of qualitative data from the experimental validation employed both deductive and inductive approaches. This combination facilitated the creation of a dimensional framework that effectively summarized the collected feedback. The evaluation phase focused on verifying the proposed SSDT framework and interaction model within a controlled eXtended Reality (XR) environment. A verification experiment was conducted in the Virtual Production Studio Lab (VPSL) [1] at Blekinge Institute of Technology (BTH) in Sweden. The research setting and case study are derived from BIGSimulo [2] and King Long[3], organizations where the authors are actively involved.

4. Result

4.1. Overview of the Super-System Digital Twins (SSDT) framework

In this study, the Digital Twins (DT) technology is further extended to the Super-System Digital Twins (SSDT), so that the design platform not only brings together multiple core components, but also helps the innovation team to achieve dynamic and real-time modeling, support iterative design processes, and optimize service delivery. Through the SSDT framework (as shown in Figure 1), the design object is no longer a traditional three-dimensional model, but a design object that integrates **3D virtual models**, **behavioral models**, and **simulated visual control modules**, and evaluates and demonstrates the value of the smart PSS through a data-driven immersive experience.

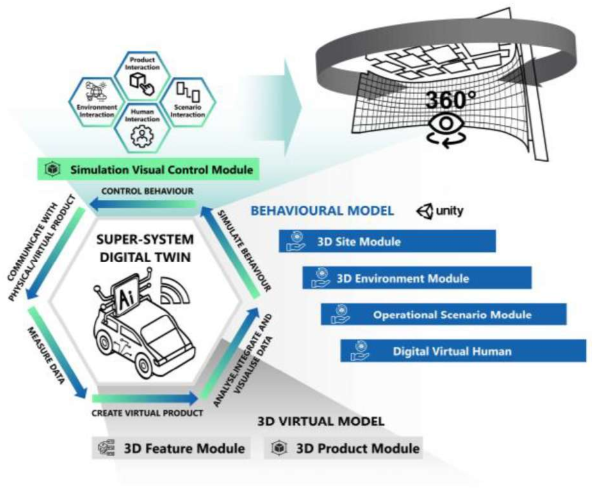

Fig. 1. High-level description of the SSDT framework and its main modules.

The SSDT framework comprises a **3D virtual model,** offering a comprehensive representation of the product platform, specifically focusing on the type of vehicle under investigation. It includes functional components for a seamless simulation of various product functions, such as wheel steering, physical effects, cockpit adjustments, and changes in color and material. However, the SSDT framework comprises the core of the **behavioral model** [38] and drives the value analysis for the different design concepts. The main objective of the 3D Site is to accurately replicate real-world complexities, for instance, by incorporating in the value simulation diverse types of roads, traffic conditions, environmental aspects, and other contextual factors that can influence the perception of the decision-makers and the outcomes of the value study. The 3D Environment module is added on top of the 3D Site to further enhance the experience the proposed design concepts with maximum realism and immersion.

This research, explore the **The control model of behavioral activity** (Multidimensional Control Model), has been studied in literature, especially in Human-Computer Interaction (HCI) [39], intelligent systems, and Virtual Reality (VR) [40]. As the core of user experience design, behavioral activity control models aim to provide users with comprehensive interactive experience and control capabilities. The behavioral activity control model focuses on four major modules: Product Interaction, Environment Interaction, Service Interaction, and Digital Human Interaction. Through **Product Interaction**, users can control the functions and physical characteristics of the design object, such as switching the states of different components of the device, setting parameters, or activating specific functional modules. **Environment Interaction** focuses on users' dynamic adjustment of environmental factors in the scene, including variables such as light, temperature, and scene, to ensure higher environmental adaptability and stronger immersion during the interaction process in different environments. The **Service Interaction** module allowing users to obtain real-time feedback, technical support, and remote operation, further improving the flexibility and speed of service response. **Digital Human Interaction** allows participants to experience the state of the role through simulated virtual characters. In this way, participants can understand and manipulate complex systems more intuitively, enhance their sense of participation and satisfaction, feedback to the XR environment, and be able to obtain the best user experience in subsequent specific scenarios.

4.2. Proposed framework of SSDT and XR environment for smart PSS design

Extended Reality (XR) technologies—play a critical role in enhancing the Digital Twins [41]. By combining Digital Twins with XR, stakeholders can interact with virtual prototypes of the smart electric bus, allowing them to visualize, simulate, and repeatedly test design choices. This study proposes a framework of combination of XR technologies with Super-System Digital Twins (SSDT) to support design-decision making process of smart PSS (as shown in Figure 2).

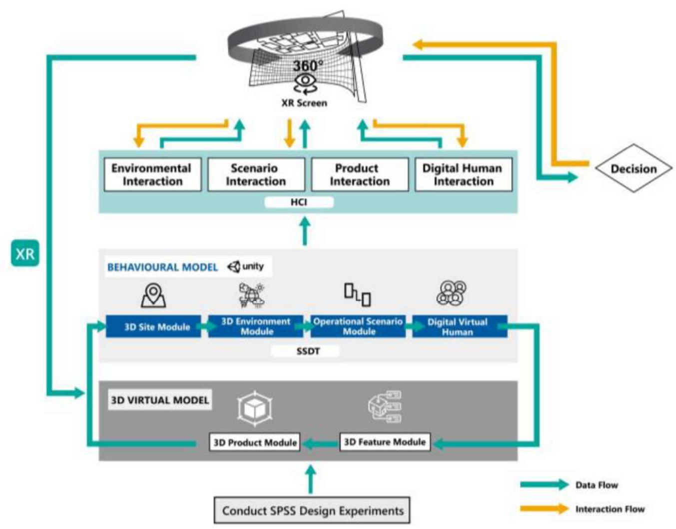

Fig. 2. Proposed framework of SSDT and XR for smart PSS design.

XR technology, as the core interactive interface, enables users to interact deeply with design objects in an immersive environment. This combination makes the design object not only limited to simple product operations, but also covers various forms of interaction, including product detection, exploration of functional features, and various user interaction experiences, thereby achieving a higher level of Human-Computer Interaction (HCI). On this basis, the SSDT framework builds a 3D virtual model containing product configuration, while also covering the behavior models of site, environment, scenario, and digital human. This integration enables the design object to not only reproduce the physical form, but also have dynamic response capabilities in virtual scenario. Participants can immerse themselves more deeply in the scenario in the XR environment, experience the performance of the design product in the real environment, and comprehensively evaluate the design details. At the same time, the study will delve into the behavioral activity control model and establish environmental interaction, scenario interaction, product interaction, and digital human interaction, so that participants can immerse themselves more deeply in the scenario.

In addition, the system can integrate participants' feedback into the original design in real time, which greatly facilitates continuous optimization and iteration. Through data-driven analysis, the design team can keep abreast of user needs and behavioral changes, so as to quickly adjust and improve in the design process, forming a self-reinforcing cycle and promoting continuous innovation of products and services.

5. Case Study on Developing a Smart Electric Tourist Bus

This study uses the project of developing Smart Electric Tourist Bus in collaborative with King Long as a case study to explore the practicality of combining the Super-System Digital Twins (SSDT) framework and eXtended Reality (XR) technology, and also uses smart PSS design as a basis to achieve early design decisions for optimized product development.

5.1. Application of proposed framework

The SSDT framework provides an effective platform for virtual prototyping, data-driven decision-making, and fostering multi-stakeholder collaboration. Leveraging this framework, team members from different departments can share design data, virtual simulation results, and user experience feedback in real-time, enabling seamless integration of bus design, manufacturing, service, and customer feedback.

5.1.1. Super System Digital Twins Creation of Tour Bus

Firstly, the Super-System Digital Twins was developed by authors based on design data comes from King Long SE-tour bus. This case study focuses on applying smart electric buses to a Tibetan tourism scenario, combining transportation services with diverse customer profiles to create customized engagement experiences (as shown in Figure 3).

Fig. 3. The proposed framework in early phase of smart tour bus development, King Long case.

Building on this, the Digital Twins creation is structured around a 3D virtual model and a behavioral model. The 3D virtual model is comprised of a 3D product module, which simulates the core SE-tour bus structure, and a 3D features module, detailing specific components and interactive elements that users can engage with in an immersive environment. Meanwhile, the behavioral model includes multiple contextual modules: a 3D Tibet environment module and a 3D park module that simulate the environmental contexts, a service scenario module that maps different service interactions for each tourist profile, and some digital virtual human module that represents different virtual characters in travel, enabling realistic, scenario-based interactions. Together, these integrated models enable a comprehensive Super-System Digital Twins that supports advanced testing, user interaction analysis, and real-time service customization, ensuring the smart electric bus meets the unique demands of mountain tourism.

5.1.2. Super System Digital Twins Creation of Tour Bus

These interactive behaviors are unified into the “Simulation Visual Control Module” framework, which is centered on the gameplay interface. To enhance the immersive experience of participants, the framework supports deeper interactions by receiving input from three major types of interactions. Based on the original model, four specific interaction modules are defined (as shown in Figure 4): environmental interaction, scenario interaction, product interaction, and digital human interaction. Together, these modules form the “Simulation Visual Control Module”, each of which is connected to the corresponding sub-interfaces - environmental interface, scenario interface, product interface, and digital human interface, helping users to more fully understand the functional characteristics, operational response, environmental adaptability, and user experience details of the design object.

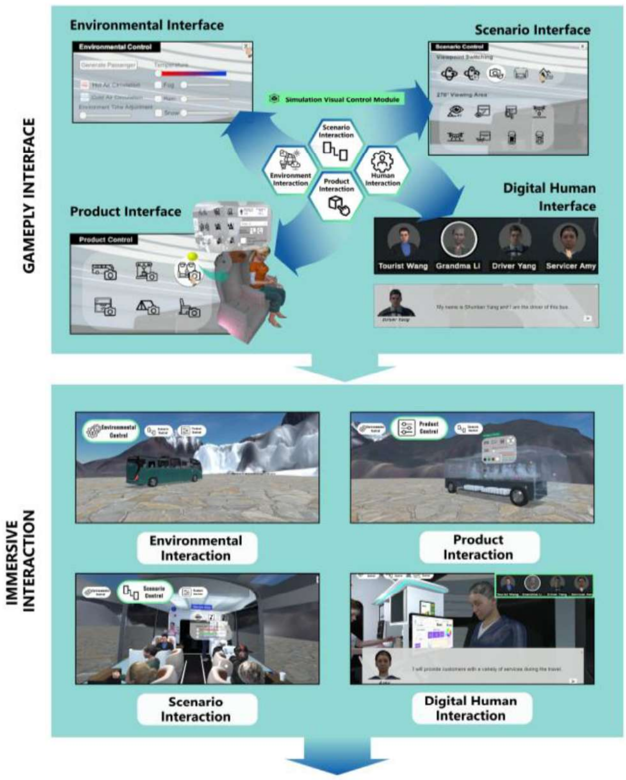

Fig. 4. The design interaction further enhanced by the Simulation Visual Control Module., King Long case.

In the game interface, this study attempts to more enhance the immersive experience for decision-making through interactive designs such as color change, universal black and white icon, hover status indication, trigger preview function and world space UI panel in the four major modules. Therefore, this immersive layer can assist different participants to achieve more intuitive and real-time participation in an interactive environment, enhance the depth and realism of each interaction, thereby creating a fully integrated experience and enhancing their insight and decision-making capabilities.

5.1.3. XR environment enhanced Collaborative Innovation and Decision Making

To enhance the collaborative innovation in this project, XR environment is proposed as a key approach to achieve. The SSDT framework combined with the visualization of the XR environment allows innovation team from case company interact with the concept prototype in a fully immersive virtual environment, enabling more accurate (environmental prototype, service prototype, product prototype, and virtual character prototype decisions) (as shown in Figure 5).

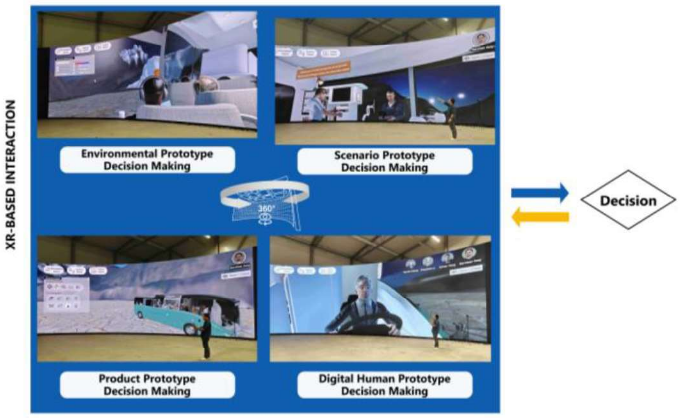

Fig. 5. XR environment support —— decision making of SE-tour bus design prototype in the VPSL lab, Sweden.

Using XR environment, product designer and design engineers at bus manufacturing companies can visualize virtual prototypes of buses in 3D space, allowing them to:

- **Enhanced Immersion:** 360-degree screen technology offers a highly immersive visualization environment that draws users into a realistic 3D space, enabling them to experience and operate the virtual bus more naturally while simulating its performance in the Tibetan environment.
- **Real-time Feedback and Interaction:** XR environment can directly connect user interactions with virtual objects, providing immediate feedback.
- **Cross-departmental Collaboration**: Through XR environment, team members can transcend the limitations of physical space, entering the same virtual environment to collaborate simultaneously.
- **Design Process Optimization:** During the design phase, XR environment enables the design team to efficiently evaluate concept though a virtual prototype, significantly reducing the reliance on physical prototypes.

5.2. Validation

The result was validated in a later stage to evaluate the specific impact of SSDT on SE-tour bus design. The experimental process was structured as an online workshop, emphasizing the validation of the feedback on the use of SSDT and the testing of the interaction model, and supported by the smart PSS through online interviews and practical tasks. The final verification content of the discussion will be extracted by codes and organized into a table for visualization (as shown in Table 1).

Table 1. Quotations from the interviews in the experimental session.

Dimensions	Confirming quotations (selection)	Challenge quotations (selection)
Offer integration	"By integrating different modules and configuration options, it can help meet customers' personalized order needs."	"I think we can add more modes based on this in the future according to user habits."
Usability	"Dividing it into four modules, namely scenarios, products, environment and users, can make the overall operation more straightforward."	"I hope to have real-time editing capabilities, such as the deployment of jobs, which can be adjusted so that they can be shown to customers." "I hope the scenario will be more concrete, giving people a sense of integration with the entire local environment."
User Experience	"Through the integration of large screens, we can be immersed in the experience and see the design from a user-centric first-person perspective."	"The program lacks a first-person perspective camera, which cannot provide a better sense of immersion." "The operability is not sensitive enough, and it is difficult for the program to give highly accurate feedback."
Intuitiveness	"I feel that it will be more intuitive to verify the interior and the outside space，therefore, it will be more intuitive to see the rationality of the whole layout of the whole bus space." "I think it is very intuitive in terms of business result and usage scenarios."	
Collaboration	"In this way, we can express some of our ideas more intuitively."	"We designers focus more on the work, so we ignore the user's point-and-shoot perspective."
Decision Making	"It can reduce communication costs, directly demonstrate the design effect, and enable customers to make decisions quickly."	
Efficiency	"The XR screen display can produce more detailed modularization and visualization effects, reduce communication links, and reduce drawing and modification time."	

Based on confirming quotations analysis from experiment, customer-specific options, usability and intuitive design evaluation can be enhanced using Super-System Digital Twins (SSDT). Participants like the modular simplified navigation layout and believe that the human-computer interaction interface can provide an immersive, user-centered view, making collaboration more effective and decision-making faster. This SSDT approach significantly increases efficiency, makes decision-making more immersive, and reduces communication requirements and adjustment time, highlighting the practical benefits of SSDT in the user experience and decision-making process.

Comparison between the confirmation side, according to challenge quotations analysis from experiment, the design faced challenges in usability, offer integration, and user experience. Participants noted the lack of real-time editing and the restrictions on modes that targeted user habits. They also pointed out the difficulties in creating immersive environments and precise, responsive controls, which affected operability and collaboration.

The lack of a first-person perspective reduced the sense of immersion, and the designer's focus on technical aspects sometimes neglected the user's perspective, indicating areas that need improvement in achieving a fully cohesive and intuitive system.

6. Discussion

This study demonstrates that the proposed framework of SSDT with XR environments not only improves communication during smart PSS design but also supports decision-making processes and strengthens cross-functional team coordination by aligning diverse requirements more effectively. This study investigated the SSDT framework supports service design to be integrated with the product design, effectively aligning with diverse user needs and fostering a service-oriented approach to the bus development case. By integrating service dimensions such as operating conditions, user interactions, and service environments on the simulation platform, the SSDT framework equips the case design team to forecast and refine bus performance across a spectrum of real-world scenarios early in the entire development process. Through this layered model combining quantitative system data with qualitative user insights, the SSDT significantly enhances the precision of design decision-making, reducing potential issues and design flaws, thereby improving service quality according to service scenario development.

However, challenges and limitations remain in fully applying the SSDT with XR in the smart PSS design. First, integrating data from multiple sources can cause update delays, with data reliability directly impacting simulation accuracy, which is crucial for high-precision design verification. Additionally, the current system lacks good camera view to support for a first-person perspective efficiently, limiting the authenticity of virtual user states. Furthermore, the existing SSDT framework faces constraints in real-time editing and digital service modeling, which hampers its applicability to complex service scenarios to some extends. While the SSDT-XR integration improves system immersion and interactivity, the high costs of investing hardware and software pose significant barriers, particularly for resource-limited design teams in manufacturing industry. According to validation, despite certain limitations, combining SSDT with XR has demonstrated considerable advancements in early-stage design, final decision-making, and stakeholder collaboration. This approach offers an efficient, collaborative pathway for future smart PSS development and robustly supports innovation in product development across related fields.

7. Conclusion

From literature study, this study explores how the implementation of the Super-System Digital Twins (SSDT) framework and eXtended Reality (XR) environment enhances decision-making capabilities in the early phase of smart Product-Service Systems design (sPSS). This framework not only improves the understanding of new product development in complex operation environments but also enhances communication and collaboration among stakeholders during the design process. The application of XR environment allows decision makers and design teams to interact the virtual prototype in real-time within a virtual environment, increasing the potential for enhanced user experience and design innovation. In conclusion, the combination of SSDT and XR opens new pathways for designing smart PSS, improving service quality and customer satisfaction while providing valuable experience for further research and practice in this field. Future research should focus on the scalability and customization of this framework in more application scenarios and exploring its potential applications in other types of smart PSS design.

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