Exploring a Scenario-Driven Design Model for Leveraging Virtual Simulation in Future Transportation Service Innovation: A Case Study of Smart Electric Van in Europe

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Abstract. The increasing digitalization of manufacturing is transforming product development towards intelligent, service-oriented systems. The existing literature shows the designing of smart vehicle will adapt to the scenario-driven of different activities in countries and cities. This study will explore a scenario driven design model for smart cockpits design based on Virtual Simulation technology and obtain design data through feedback from service industry, users, and then feedback to car companies to co-design the service offering of smart cockpit. A case is applied to the product development of a new Smart Electric VAN in collaboration with a global car manufacturer, the result of this study is based on the virtual simulation of the future service scenario in Europe. The research shows Virtual Simulation technology to enhance decision-making and prototyping for customizing the scenario-driven smart cockpits in early design stage. The smart cockpit design can be dynamically adjusted according to scenario changes to meet the cultural, regulatory and user needs of different city regions in Europe. This study verifies the effect of the scenario-driven design model in improving the adaptation of smart cockpits design to different city environments and optimizing passenger experience, while addressing its limitations and proposing future improvements.

Keywords: Smart Product-Service Systems, Scenario-driven design, Virtual Simulation, Logistics services, Smart cockpit.

1 Introduction

Globalization, coupled with the rapid advancement of new technologies, has generated a highly competitive and dynamic environment for the manufacturing industry. This environment is characterized by increased competition, changing consumer expectations, and narrowing profit margins [1]. In response to these challenges, global manufacturing industry is undergoing a shift from being solely a product provider to becoming a service solution provider, resulting in a growing convergence of traditional distinctions between products and services [2,3]. By offering a sustainable integrated solution – the concept of smart Product-Service Systems (sPSS) that incorporate IoT (Internet of Things), Digital Twins, and cloud computing to enable real-time monitoring, adaptive service offerings, AI (Artificial Intelligence), predictive maintenance, and data-driven decision-making [4]. Existing design approaches often face challenges in addressing the inherent **uncertainties and dynamic interactions** in the early stages of smart PSS design [5]. Recent academic discourse on smart PSS has explored the impact of advanced simulation technologies on the design of innovative business propositions, hardware, and associated services [6, 7]. Virtual simulation has increasingly been recognized as a transformative tool, enabling designers to conceptualize, assess, and refine complex systems under various operational scenarios [8]. Despite the potential of virtual simulations in smart PSS design, their application remains hindered by several critical challenges. A major issue is the lack of comprehensive methodologies that enable designers to effectively simulate, analyze, and optimize the interactions between physical products, digital services, and user behaviors within dynamic scenarios [9]. These constraints impede the ability to make well-informed design decisions, particularly in industries such as automotive manufacturing, where sustainability and digitalization are essential [10]. To address these challenges, this paper introduces a scenario-driven design model tailored for the automotive manufacturing industry, demonstrating its potential to enhance decision-making processes during the early stages of smart PSS design.

According to a case study of a smart cockpit design for a new Electric Van designed for the European market, this paper demonstrates how the scenario-driven design model, leveraged by virtual simulations approach, a Super-System Digital Twins (SSDT) framework [11] can resolve key issues in smart cockpit design to construct realistic and dynamic scenarios that reflect logistics service operational and city environmental complexities [12]. These scenarios guide iterative design exploration, enabling stakeholders from automotive manufacturing companies to validate and make informed decisions regarding smart cockpit concepts using eXtended Reality (XR) [13]. The findings of this research highlight the critical role of scenario-driven design model and virtual simulation in enabling a systematic, data-driven approach in the early-stage smart PSS design. The discussion section reveals the results of the validation activities conducted during the design process, although the key findings, research significance, shortcomings, and future study areas are summarized in the last section.

2 Knowledge Background

2.1 Design Challenges of smart PSS

The evolution of smart Product-Service Systems (sPSS) has introduced multifaceted challenges for design teams, primarily due to the increasing complexity of integrating complex product functionalities and service offerings, ensuring adaptability to diverse customer needs, and maintaining seamless communication between stakeholders [8]. Unlike designing the traditional product, smart PSS design requires considering dynamic interactions among cultural differences, environmental conditions, and system functionalities. One significant challenge is decision-making under uncertainty, particularly in the early design stages, where incomplete or ambiguous information about customer needs and service scenarios can hinder innovation [14]. Moreover, achieving alignment between user demands and technical capabilities is becoming increasingly challenging in diverse and fast-changing city environments, such as those across Europe [12]. The regulatory landscapes and cultural preferences of each region amplify the need for adaptive solutions, as traditional static designs often fail to accommodate such diversity [14]. Lastly, integrating real-time feedback mechanisms and co-design methodologies with end-users remains underexplored, despite their potential to address some of these uncertainties [15]. The dynamic nature of city environments further complicates the design process, as smart PSS must adapt to varying cultural, regulatory, and infrastructural conditions [16].

2.2 The Scenario-Driven Design Model for smart PSS

Scenarios play a central role in capturing the contextual, operational, and experiential aspects of smart systems, bridging the gap between technical specifications and user expectations [17]. In the field of design, the concept of scenario-based design was first introduced by Carroll, a prominent scholar in human-computer interaction [18]. He applied scenario theory and developed the Scenario-Based Design (SBD) approach, utilizing it in the usability engineering of interactive products. This method includes analysis based on problem scenarios, design based on real scenarios, and prototyping and evaluation based on actual scenarios. The concept of the scenario-driven model for smart product design, detailing operational processes for requirement extraction based on user scenarios, product design based on conceptual scenarios, and product validation and feedback derived from real-world scenarios [19]. The concept of scenario-driven design has emerged as a viable strategy to tackle the complexity of smart PSS development. Scenario-driven design focuses on constructing and analyzing realistic and context-specific use cases to inform design decisions, enabling stakeholders to predict system performance, user satisfaction, and service feasibility. Scenario-driven design is a critical approach in smart PSS development, as it allows designers to simulate and evaluate product-service interactions in specific contexts [17].

For example, smart electric vehicle (SEV) designs must address operational variability such as city environment, road conditions, and city density across different European regions. By employing a scenario-driven approach, designers can explore multiple configurations, optimize features for specific contexts, and align the system's functionalities with the regulatory and cultural requirements of each locale [20].

The adaptability of scenario-driven design makes it particularly suitable for smart PSS, where the integration of digital and physical components requires dynamic simulation and iterative refinements [12]. This approach not only fosters collaboration among multidisciplinary teams but also ensures that end-users and service providers are active participants in the early design process, improving the relevance and acceptance of the final solutions.

2.3 Virtual Simulation Empowers Scenario Design of smart PSS

Virtual simulation technologies, such as Digital Twins (DT) and eXtended Reality (XR), have revolutionized the way scenario-driven designs are conceptualized, validated, and optimized. [4,21]. By creating immersive environments that replicate real-world conditions, these technologies allow designers to visualize, analyze, and refine their solutions before physical prototypes are developed [22]. Digital Twins offer real-time synchronization between the physical system and its digital counterpart, enabling continuous monitoring, simulation, and optimization of design parameters [23]. This real-time feedback loop enhances the accuracy of decision-making during the early phases of smart PSS design, where understanding system behavior under various conditions is critical [24]. The implementation of Digital Twins allows stakeholders to explore **"what-if" scenarios**, assess the impacts of design changes, and predict system performance with greater confidence. Despite their potential, the application of virtual simulation tools in the early phase of smart PSS design in the manufacturing industry remains limited, often due to a lack of integration frameworks and stakeholder communication channels [10]. The Super-System Digital Twins (SSDT) framework addresses this gap by integrating scenario-driven virtual simulations with real-time collaboration features [11]. By combining data-driven insights with immersive technologies, SSDT enables iterative design refinements, fostering a co-design approach where feedback loops between users, service providers, and manufacturers are seamless and continuous. Moreover, 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 [25]. In addition, 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 [27].

3 Research Methodology

This section outlines the methodological framework and tools employed in this study to explore how the Super-System Digital Twins (SSDT) framework facilitates scenario-driven design for smart Product-Service Systems. This research adopts the Design Research Method (DRM) framework proposed by [28]. The single-case design [29] 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 collaboration with Chery Commercial Vehicles, a global automotive manufacturer to deeply explore this methodology applied into a smart PSS design of smart cockpit for the new Electric Van offerings. The methodology is structured into three key phases: data collection, scenario design, and validation by simulation. Each phase is detailed below, emphasizing their relevance to the case study of designing a smart cockpit offering. Data collection serves as the foundation for creating realistic and context-specific scenarios in smart PSS design. A mixed-methods approach was utilized, combining qualitative insights from five European cities' field studies (Milan, Paris, Gothenburg, Barcelona, and London), involved real-world observations of existing logistics operations to understand the environmental and operational conditions the Electric Van would face in Europe. Based on the collected data, three representative scenarios were constructed to guide the smart cockpit design process. The validation by virtual simulation involved three iterative cycles: design exploration, virtual simulation, and stakeholder feedback incorporation. The integration of data-driven insights with immersive simulation techniques ensures a holistic approach to addressing the complexities of smart PSS design. The results and validation of the proposed methodology are presented in the case study.

4 Result

Uncertainty is one of the main challenges in predicting future design decisions. By establishing scenarios that correspond to the design concept, product design team can develop a deeper understanding of potential demand and enhance forecasting accuracy. By simulating the performance of the product and service across scenarios- along with analyzing the impact changes-enables teams to visualize these dynamics effectively. This process enhances product design team's deeper understanding of the scenarios, ultimately facilitating the smart PSS design decision- making in uncertain environments.

4.1 Method of Scenario-Driven Design Model

Toller et al.[30] have highlighted that multilayer network graphs enable product designer to directly comprehend the complex and multidimensional relationships among entities, which is essential for understanding the interactions and interdependencies between different elements. This approach provides an intuitive representation of intricate relationships by visualizing multilayer network graphs, where parallel nodes are interconnected via linking bands. It supports exploratory analysis and inferential reasoning within design teams. Building upon this foundation, this study integrates the Scenario-Driven Design Model (as shown in Figure 1), which systematically collects value metrics and operational data for various Smart Product-Service Systems (sPSS). This model facilitates a structured mapping of values, core processions, and multiple scenarios, thereby enabling a precise characterization of the design object. Value defines the overarching design objectives, while core processions encompass the critical business operations supporting these values. Each process is further decomposed into multiple scenarios, ensuring an accurate representation of user needs. Upon identifying these needs, the corresponding key functionalities and design attributes are specified within each scenario, ensuring the product's adaptability across diverse application environments. Additionally, these refined scenarios are aligned with specific functional requirements to enhance the adaptability of the design object. In the Value Capture phase, value is concretized into product features, allowing for measurement and assessment of its realization and transformation. This framework follows a progressive, hierarchical logic, ensuring that the design object aligns with market positioning requirements and remains adaptable across varying contextual scenarios.

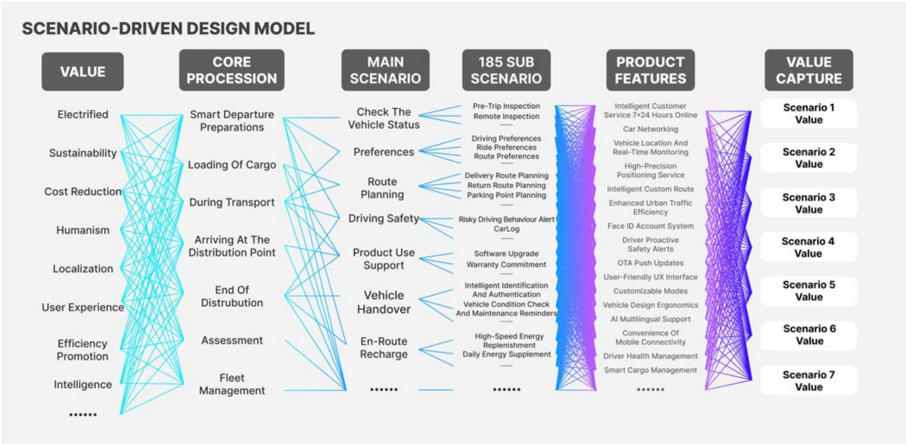

Fig. 1. Proposed Scenario-Driven Design Model.

4.2 Overview of the Super-System Digital Twins (SSDT) Framework

In this study, the Super-System Digital Twin (SSDT) design framework is used to simulate the design concept in real-time [11]. The system organically integrates components in different systems in multiple dimensions, and is data-driven, and can evaluate, record, and effectively communicate the value of smart PSS through virtual simulation and immersive enhanced experience (as shown in Figure 2). The SSDT framework structure includes a 3D Product Module, which is used to fully visualize the product under design, including its appearance structure, and functional characteristics. At the same time, this product module is combined with a 3D Feature Module to simulate specific functions and provide a more fine-grained design representation. Based on the virtual model, the system introduces multiple behavioral models [31], namely 3D Site Module, 3D Environment Module, Operational Scenario Module, and Digital Human Module. These modules can be used to simulate and reproduce the dynamic performance of the design concept in various situations encountered in the real service operation environment, evaluate the future status of the design concept and predict possible problems, and help product design team study and optimize the performance of the system.

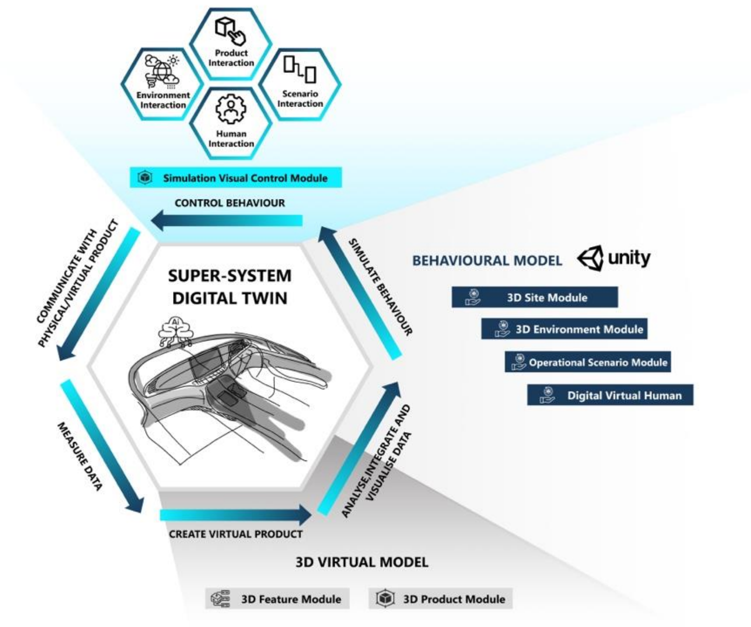

Fig. 2. High-level description of the SSDT framework and its main modules.

This study focuses on the Simulation Visual Control Module within the SSDT framework, which has been explored in previous literature, particularly in the context of Human-Computer Interaction (HCI) [32]. Given that the core of user experience design lies in the behavioral activity control model, the primary objective of this module is to create highly immersive interactions while providing participants with comprehensive operational capabilities. By leveraging environmental interaction, product interaction, scenario interaction, and digital human interaction, designers and decision-makers can fully immerse themselves in the Super-System Digital Twin, enabling real-time exploration of virtual scenarios. This approach allows designers to directly control the functions of the product, dynamically adapt to various scenario conditions, and engage in multi-dimensional feedback - including auditory and visual inputs through human-computer interaction between digital human and design concepts, thereby the module enhances overall user experience and engagement while offering and an intuitive and effective approach for design decision-making.

During prototyping and validation phase, this module leverages XR technology to support virtual simulation and decision-making. By enabling real-time dynamic virtual simulations and provide timely evaluations, it facilitates collaboration between design team from diverse backgrounds, supporting the iterative design process and ultimately optimizing the delivery of final design outcomes.

4.3 Proposed Scenario-Driven Design Model Integrated with Virtual Simulation

Toller et al (2024) builds upon the hybrid simulation model (Class II) originally proposed by Shanthikumar and Sargent (1983), enhancing its capabilities to effectively reduce development costs and computational burden while integrating external analytical models[12] [33]. This improvement enables automatic adaptation to specific contexts, delivering satisfactory results without user intervention.

Under the constraints of limited research time and the absence of physical prototypes for designing the future products that don't exist today, integrating this hybrid virtual simulation framework with the Super-System Digital Twin (SSDT) facilitates the development of a virtual model enriched with real-world data as shown in Figure 2. Driven from top scenario data, this framework enables the comprehensive simulation of design concept entire operational process from the initial to the end. After that, the scenario data then enters the scenario-driven design model, each scenario within the process is defined by specific features cluster combinations, which can be dynamically combined to generate multiple design alternatives. At the center of the SSDT framework consists of three models, **city model, vehicle model and cockpit model,** representing the models from the entire environment of life scenarios to the development of product and service functions. The center is the vehicle model, which relies on data from a realistic city model, including traffic flow, road network, and environmental conditions, to enhance the fidelity of the simulation and align it with real-world operational scenarios. Simultaneously, the vehicle model transmits its operational condition back to the city model to support intelligent traffic management and service data optimization. As the primary research object, the cockpit model acquires relevant vehicle configuration data from the vehicle model to deliver an optimized user experience. Conversely, it also transmits user input to the vehicle model, enabling dynamic cockpit configuration adjustments to enhance user interaction . The bidirectional data exchange among these models ensures a highly realistic simulation environment, facilitating an in-depth evaluation of the design concept's adaptability within complex operational conditions. Finally, the XR environment facilitates iterative validation of the design by stakeholders from diverse backgrounds, enabling continuous refinement of cockpit's conceptual solutions. This iterative process enhances the system's adaptability to dynamic environments while providing data-driven insights to support informed design decisions (as shown in Figure 3).

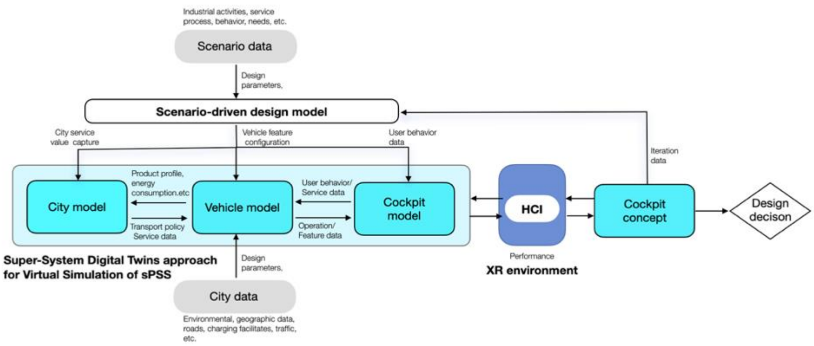

Fig. 3. An Integrated Design Framework of Scenario-Driven Design Model for Virtual Simulation.

This ensures continuous stakeholder involvement in the iterative design process. Ultimately, decision-makers and product designers collaboratively validate simulations within the XR environment. Participants interact with the system (e.g., adjusting screens, seats, or control interfaces) to adapt to specific scenarios, observe how the design solution responds under complex conditions, and refine the conceptual design accordingly. Design solutions undergo evaluation and comparison, integrating scenario simulation data and user feedback to comprehensively consider performance, cost, and user experience, collectively defining the final product design.

5 Case Study on Designing the Smart Cockpit of Electric Van

This paper explores a design methodology that leverages a scenario-driven design model for virtual simulation. Using the smart cockpit design project in collaboration with Chery Commercial Vehicles as a case study, it investigates the feasibility of an SSDT-XR integrated design methodology driven by scenarios. The study aims to enhance the design of smart cockpits for Electric Van within future city logistics service scenarios in Europe through virtual simulation. By improving adaptability to complex real-world city environments, the proposed approach seeks to optimize passenger experience while reducing uncertainties in the early-stage product development and minimizing high operational costs in later operation phases.

5.1 Define the Scenario-Driven Model

Europe is a vast and diverse continent characterized by complex environments and significant variations in traffic conditions across different countries. To ensure that the designed smart cockpit can adapt to the complexity of the European environment, a scenario-driven design model can be employed to analyze and correlate the required product configurations and values across different scenarios. This necessitates the supplementation of scenario data, which is derived from a comprehensive analysis of the full-service process in the logistics industry (as shown in Figure 4), as well as extensive desk research. Additionally, the authors conducted empirical scenario validation studies in selected European countries. For data analysis, Gephi network graphs [34] were utilized to establish a multi-dimensional visualization framework driven by service scenarios for future smart cockpits. Key dimensions, such as **scenarios, product feature configurations and value capture**, were translated into visualized nodes and connections. The corresponding product feature configurations vary across different service scenarios.

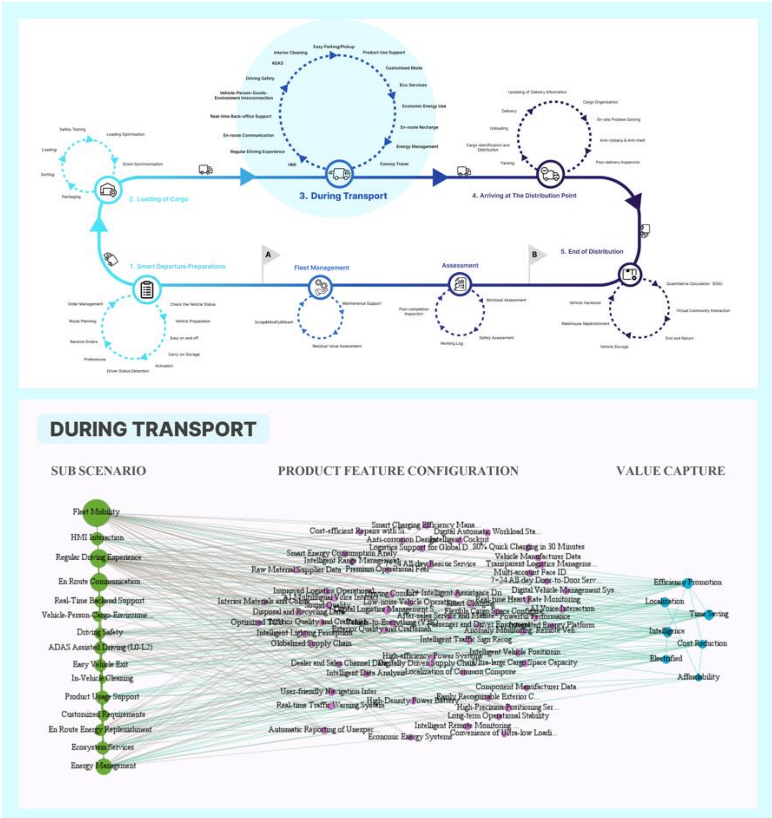

Fig. 4. Scenario-driven design model network graph: Visualizing the relationship between scenario, product feature configuration, and value capture (Taking "During Transport" as an example).

Taking the "During Transport" service scenario as an example (as shown in Figure 3), the network graph illustrates multiple sub-scenarios within this broader transport scenario, each associated with specific smart cockpit feature configurations. Designer may encounter various sub-scenarios during cargo transportation, (such as fleet operation, HMI interaction, driving safety, and Advanced Driver Assistance Systems(ADAS)-assisted driving). Focusing on the " ADAS -assisted driving" sub-scenario within the broader "During Transport" scenario, the corresponding product feature configurations include (Google high-precision mapping services, intelligent route optimization, digital remote-control systems, and innovative remote monitoring and diagnostics, etc.). These product configurations collectively contribute to multiple value dimensions, (such as time savings, efficiency enhancement, localization optimization, intelligence, and cost reduction), in response to the demands of different service scenarios. The data derived from the "During Transport" service scenario provides insights into the conveyed information and its functionality and significance within specific contexts. In the corresponding network diagram, green color nodes represent logistics service scenarios in Europe, collected by the author of this study. Purple color nodes indicate product feature configuration data provided by the case company's product team, illustrating the association between these features and the generalized service scenarios and their corresponding configuration characteristics. Blue color nodes represent the commercial value of product feature configurations within their respective scenarios. The edges connecting each node link interrelated elements; for instance, specific product configurations (such as intelligent remote monitoring and fault diagnosis, innovative warehouse management, digital remote-control systems, real-time vehicle tracking and positioning, and digital equipment management, etc.) closely related to specific scenarios (such as route planning, fleet operations, HMI interaction, ADAS-assisted driving [L0-L2], and energy management, etc.). These relationships dynamically adjust based on scenario variations.

The aggregated and interconnected scenario data serve as input for conceptual design proposals, where scenario selection directly influences the choice of product feature configurations and determines their commercial value realization. The integration and association of scenario data facilitate scenario-driven customization in smart cockpit design, enhancing its functionality and value capture to ensure optimal performance and user satisfaction across diverse contexts.

5.2 Scenario-Driven Development of SSDT for Smart Cockpits

Subsequently, the scenario-driven design model is introduced to transform multidimensional information from various service scenarios into core driving factors for smart cockpit design. Taking the three primary service scenarios**—"Departure Preparations," "During Transport," and "End of Distribution**"—as examples (as shown in Figure 5), the "During Transport" scenario comprises 15 sub-scenarios, each corresponding to specific product feature configurations required for the smart cockpit in that context. This study extracts a subset of the product feature configurations associated with this service scenario for illustration (as shown in Figure 6). The "During Transport" scenario encompasses multiple relevant product configurations, including driving assistance, driving safety, vehicle access and startup security, and HMI-based central control and entertainment systems. Users can personalize cockpit settings by selecting configuration table functions according to their preferences. For instance, designers can enable interactive displays, adjust in-cabin speaker volume, activate vehicle-to-smartphone connectivity, utilize intelligent navigation, or access other innovative vehicle features and services. This ensures that driving experience and safety measures within the corresponding service scenario are effectively aligned and enhanced. User requirements are systematically linked to product feature configurations by mapping scenario data. This enables developers to design and simulate various aspects of the smart cockpit, including the layout of display screens, in-cabin feature configurations, voice assistant interactions, and instrument panel interfaces, ultimately generating multiple design solutions tailored to diverse user needs.

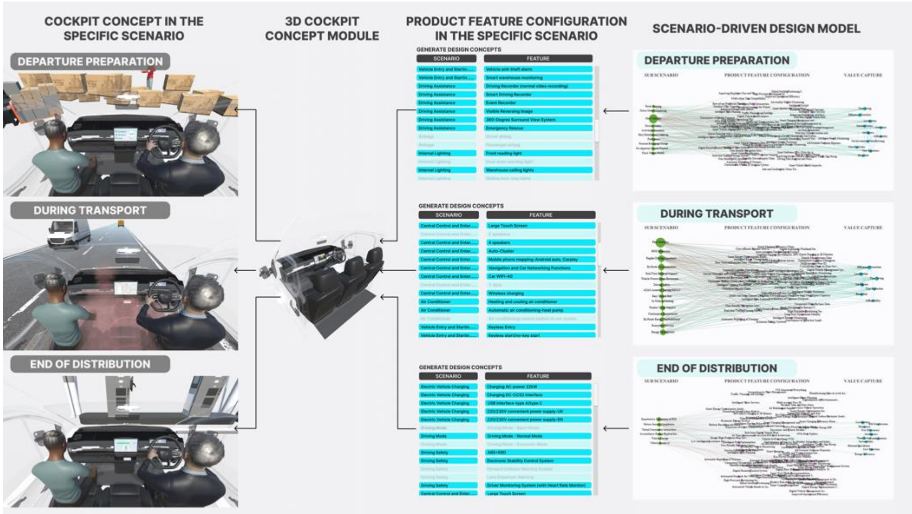

Fig. 5. Scenario-Driven Smart Cockpit Configuration and Virtual Simulation Process.

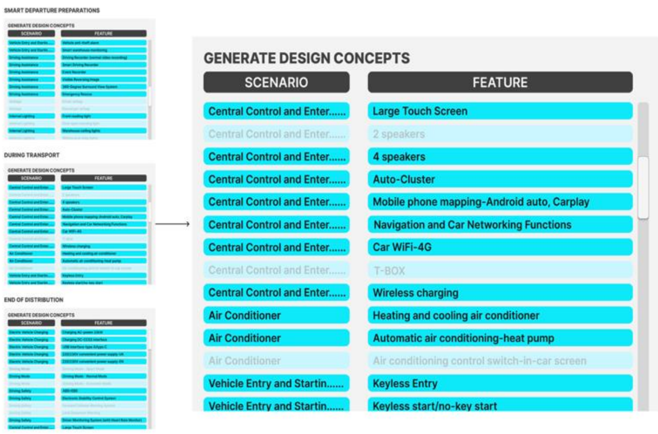

Fig. 6. Product Feature Configuration Cluster Table for Smart Cockpit under the "During Transport" Service Scenario.

Once the design strategies are formulated, scenario-driven design data is visualized through the SSDT. As a supporting framework for virtual simulation, SSDT integrates service scenario definitions with scenario-driven product feature configuration, providing real-time simulation assistance for the conceptual design of the smart cockpit.

5.3 Virtual Simulation of Logistics Service Scenarios in the European City

By employing a scenario-driven design model, multi-dimensional data from selected service scenarios, particularly product feature configuration are integrated into the

Super-System Digital Twins (SSDT). framework and transformed into 3D virtual models. This process provides critical support for generating and validating conceptual design solutions. However, a fundamental industrial cockpit model combined with corresponding product feature data alone is insufficient to validate its performance in the complex city environments of Europe, (which encompass diverse terrains, infrastructure, weather conditions, and cultural factors). Therefore, it is essential to incorporate relevant city data to simulate real-world city conditions, enabling dynamic testing of the system's performance and adaptability. To further examine whether these design solutions can effectively meet user needs and adapt to changing environmental conditions in real-world scenarios, it is necessary to conduct testing within an actual European city environment in the SSDT.

This study selected a specific area within the central business district of London, UK, as the testing city. London, with its high traffic density and intricate road network, provides a rigorous setting to assess the adaptability of the smart cockpit under high-load conditions. London's highly variable weather and culturally diverse population also contribute to increased complexity and uncertainty in user demands. These factors present a valuable opportunity for comprehensive performance validating of the smart cockpit across different environmental conditions. During real-world scenario simulations (as shown in Figure 7), the smart cockpit should respond to environmental changes and driving behaviors, preferred driving modes, and various external factors that influence its overall performance. Each scenario, whether at the macro or micro level, represents a specific challenge that future Electric Van will encounter when operating within London's business district for deliveries. By refining these scenarios, the development team can account for numerous uncertainties, ensuring that every aspect of the design is adaptable to varying environments and user requirements while undergoing comprehensive performance assessment and optimization.

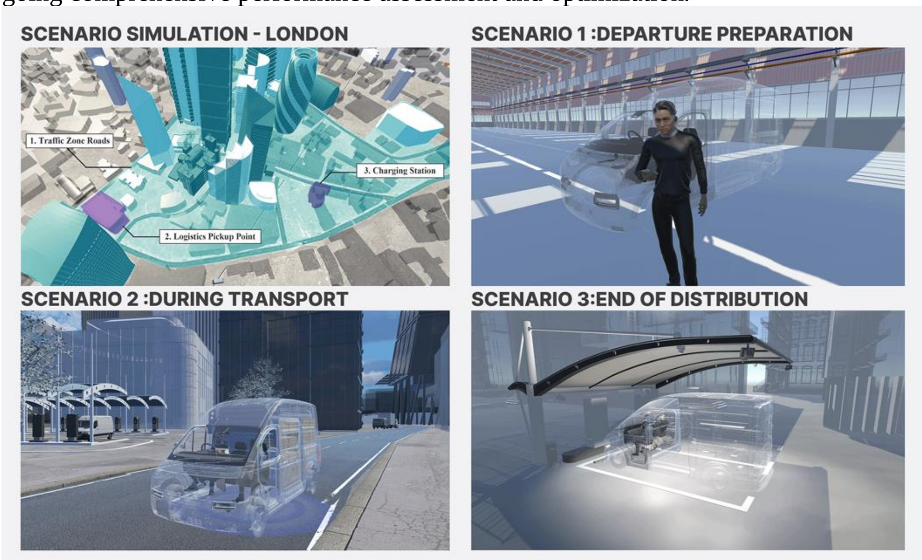

Fig. 7. Virtual Simulation of Logistics Service Scenarios in the Digital Twins of London City.

5.4 Leveraging XR to Support Design Decision-making and Validation

To ensure a more realistic assessment of the proposed solutions in terms of performance and user experience, validation should be conducted through XR technology within the framework of the Super-System Digital Twin (SSDT). This study utilizes Unity as an interfacing system for scenario interaction and virtual simulation development, with XR technology (eXtended Reality) serving as the primary interaction modality. By integrating XR technology with the digital twin framework based on real-world physical configurations, the study facilitates seamless interaction and dynamic integration between the SSDT and virtual conceptual models. During the simulation process, a central business district in London has been selected as the primary testing environment to examine the operational performance of the smart cockpit in key scenarios, including traffic roads, charging stations, and pick-up points.

To enable a more immersive interaction between the conceptual design of the smart cockpit and the mentioned key scenarios, it is essential to integrate Human-Computer Interaction (HCI) technologies alongside XR (eXtended Reality) and user experience (UX) design. Furthermore, leveraging the scenario-driven model support SSDT framework not only enhances the real-time dynamism of the model but also fosters the seamless integration of complex scenario elements with the core functionalities of the cockpit. This approach allows participants to interact within a highly realistic virtual environment, allowing them to engage in how the smart cockpit adapts to different key scenarios. As a result, the interaction process becomes more intuitive and contextually relevant, matching with real-world situational demands (as shown in Figure 8).

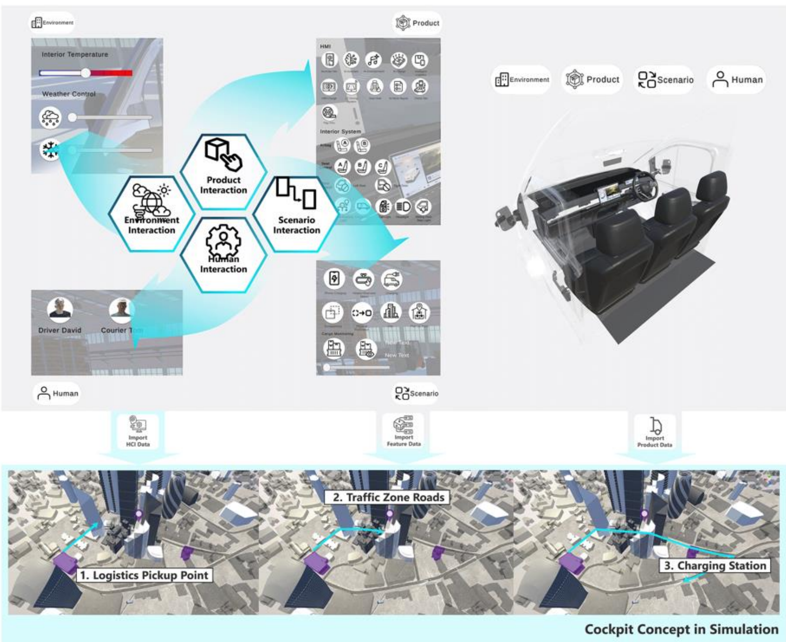

Fig. 8. XR-Enhanced Scenario Simulation for Validation of Smart Cockpit Design Concept.

To substantiate the practicality of the proposed framework, this study selects **"Departure Preparation," "During Transport," and "End of Distribution"** as three key scenarios for demonstration (as shown in Figure 9). In the "Departure Preparation" scenario, participants are offered a first-person from driver's view, enabling them to activate the vehicle and check its status via mobile phones. Additionally, the cockpit is equipped with AI, allowing participants to access information about the delivered goods through the AI assistant, which provides intelligent navigation and other customized preference modes. The integration of AI strengthens the connection between participants and the smart cockpit, facilitating a more intuitive perception and operation of the cockpit's functions.

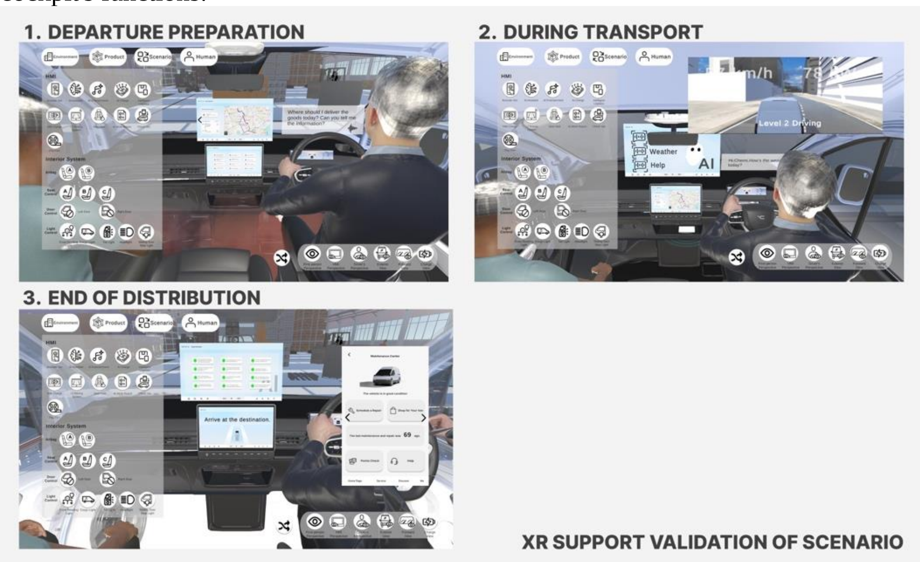

Fig. 9. XR Support Validation of Scenario: "Departure Preparation"," During Transport"," End of Distribution".

In the "During Transport" scenario (as shown in Figure 9), the simulated environment of the London commercial district offers a realistic transportation setting. It tests the smart cockpit's adjustability in London's complex traffic environment. During transport, participants can simulate local weather conditions, analyze and optimise transportation routes. Furthermore, they can use the AI to monitor the vehicle's status, such as speed or battery level.

Including a section of the London commercial district environment provides real-time, authentic simulation data. This simulation incorporates the three key elements of "**human, smart cockpit, and city environment**," allowing interactions to realistically reflect the complex city delivery scenarios in London, enhancing the realism of the simulation. Additionally, participants can switch between multiple camera angles to view the same scenario from different perspectives. This flexible and immersive interaction not only personalizes the design but also enables participants to fully engage with the adaptability and function of the smart cockpit under diverse external factors.

During the validation process, testing and verifying design solutions within a con~~trolled virtual environment alone is insufficient to assess smart cockpits' operational~~ application and user experience extensively. Honest user feedback and input from professionals and relevant stakeholders are essential. Such feedback can support designers and engineers overcome cognitive limitations and broaden their design perspective.
In subsequent research, relevant researchers, cockpit leaders, and decision-makers from case companies will be invited to participate in immersive simulation experiences of smart cockpit design solutions and provide their feedback as part of validation. The key selected components of the final validation content discussed will be extracted and organized into a table for visualization, facilitating intuitive analysis (as shown in Table 1)

.**Table 1.** Selected Stakeholders' Feedback on Design Validation from Case Company

1. Feedback from Researcher	1. *“This method can help stakeholders optimize solutions without physical objects, and support companies to simulate the performance of design concepts in different scenarios* ***to reduce uncertainty****. At the same time, this method can also provide reference for more car companies to reduce design risks.”*
2. Feedback from the Cockpit Manager of the Case Company	1. “*Functional development needs to be valued based on market data rather than going directly to the verification stage. OEM user data collected through external suppliers or data channels can be integrated and analyzed in the digital twin system to determine the actual demand and potential of the function in a specific market. Such analysis results can also provide a clear direction for the development of corresponding functions, which is* ***highly consistent with the scenario-driven analysis method*** *in the SSDT framework*.”
3.Feedback from the Decision-Maker of the Case Company	1.“*Through such cases, car companies can gradually master the scenarios across Europe and make the overall value assessment system more and more complete. However, attention should also be paid to after-sales service and the sale of residual value of used cars, such as the content of TCU, which customers will want to know.”* 2.“*There is little customized content, and we hope to be able to provide customers with the delivery location, delivery cycle and service terms of the solution to make the solution delivery process clearer.”*

By synthesizing feedback from different stakeholders, it is possible to understand how a scenario-driven XR can support related stakeholders in predicting the challenges faced by design concepts in complex environments in real-time. This helps reduce uncertainties and provides key information for the design iteration. As a result, the design of the smart cockpit can meet the demands of complicated city environments, and user needs while reducing costs and enhancing its adaptability and competitive edge in the European market. Moreover, this approach offers a new research perspective for automotive companies seeking to expand globalization.

6 Discussion

This paper proposes a scenario-driven design model integrated with the Super-System Digital Twins (SSDT) framework and Virtual Simulation technologies, offering a systematic approach to address uncertainties in smart Product-Service Systems (sPSS) design. This integrated design framework is driven by scenario-based data, integrating the SSDT with XR technology to enable virtual simulation and interaction, thereby supporting the development of virtual models for smart PSS. Its core principle lies in leveraging XR-based simulation to explore and validate design solutions. Within the SSDT framework, product design teams gain access to dynamically visualized 3D virtual models, facilitating the assessment of product design, scenario variations, and human-machine interaction while mitigating the need for high costs and extensive time investments.

By enabling real-time dynamic scenario simulations, this approach bridges the gap between static design models and the dynamic requirements of city logistics services in Europe. The immersion and practicality of this method can be assessed, demonstrating its ability to optimize the overall design while enabling rapid iteration at a low cost. Additionally, the integration of the SSDT framework and XR technology supports stakeholders in predicting and enhancing overall performance across a series of real-world service scenarios. The case study with Chery Commercial Vehicles validates the model's applicability in designing smart cockpits for a new Electric Van offering. The SSDT framework facilitated iterative design refinements, reduced physical prototyping costs, and enhanced adaptability to diverse European city environments. This approach effectively reduces potential uncertainties and provides insights for automotive companies seeking to expand service solutions into the European market. Despite its contributions, this study has several limitations: The single-case design limits the scalability of findings. While the case provides depth, multi-case studies across industries (e.g., public transport or healthcare) are needed to validate the model's broader applicability. The paper emphasized European contexts but did not fully address intra-regional cultural differences (e.g., Southern vs. Northern European user preferences). Field studies focused on one European city-London, potentially overlooking nuanced regional variations (e.g., Eastern European infrastructure or rural logistics). To address these limitations, future work should focus on: Expanding validation through cross-industry and multi-regional case studies. Enhancing SSDT framework with AI and IoT integration for real-time scenario updates. Incorporating socio-cultural metrics into scenario design to improve cross-regional adaptability.

7 Conclusion

This paper explores a research methodology that leverages a scenario-driven design model for virtual simulations, supported by XR technology to facilitate immersive human-machine interaction for stakeholders, thereby enhancing design optimization capabilities. By employing this hybrid simulation method, design teams can ensure logical consistency between design concept and application scenarios throughout the research process, experiment with multiple design alternatives, and identify the optimal concept for smart cockpit design in specific scenarios. Furthermore, the integration of XR enables decision makers to comprehensively experience the performance of products and services related to the design concept, thereby reducing uncertainty risks and allowing for timely design iterations and optimizations. This paper offers an effective design methodology for automotive companies, enabling them to mitigate risks in a cost-efficient manner. Currently, the smart cockpit design in this paper remains at the conceptual stage, with significant potential for further refinement and expansion. Future research could consider the customization of smart cockpit designs for a broader range of service scenarios and incorporate more European regions and sustainability-related data to better assess and manage potential design spaces.

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