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Integration Possibilities of Logistics Process Simulation and VR Technology

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Abstract: Due to the rapidly changing market environment and the increasing complexity of processes, the simulation-based analysis of logistics processes is gaining growing significance. Simulation provides an opportunity to analyse and optimize logistics systems, as well as to conduct preliminary testing before implementation. Virtual reality (VR) can complement this by supporting design, decision-making, and training processes. The primary aim of this publication is not to present simulation modelling or VR technology in general, but rather to examine their potential applications and integration in logistics, with particular attention to synergistic benefits. The most important development directions related to these technologies have been identified. The study focuses on the integration potential of the two fields, which offers new opportunities to enhance efficiency in logistics. The research methodology is inductive, meaning the study was carried out using knowledge gained from practical experience and literature analysis. In addition to exploring and summarizing integration opportunities, the paper also presents the anticipated benefits, providing motivation for applying the solution and for further research in the field.

Keywords: Logistics; Process Development; Simulation; Virtual Reality

1 INTRODUCTION

The dynamic technological advancements of today are introducing new opportunities in the field of logistics process development. Numerous Industry 4.0 solutions have been increasingly adopted in logistics (e.g., VR, AR, Digital Twin, etc.); however, exploring the integration possibilities of these solutions and their application in logistics presents a significant challenge for logistics professionals [1-2]. The high-level visualization and interactive analysis of current and future processes are playing an increasingly important role in logistics process development, where the application of simulation modeling and VR technologies is a key factor [3-4].

It is essential to clarify the meaning of these concepts. Logistics simulation is a method capable of realistically modeling processes and systems, allowing for the evaluation of their state changes [5]. Virtual reality (VR) technology, on the other hand, is a computer-generated interactive environment that provides users with an immersive experience, enabling them to learn, work, or engage in entertainment within realistic simulated scenarios [6]. These technologies can contribute to improving the efficiency of a logistics system in various ways [7], such as through more effective employee training, faster identification of emerging issues, and providing an objective evaluation of different system variations. In this study, I applied the systematic literature review method to explore the relevant types of logistics simulation and VR technologies, as well as their development directions. One of these directions is the integration of the two fields, whose possibilities and the benefits achievable through integration are analyzed in this paper.

2 SYSTEMATIC LITERATURE REVIEW TO IDENTIFY THE RESEARCH GAP

To explore the development of the examined field, as well as to identify current research gaps and development opportunities, I applied the systematic literature review method [8]. The steps of the method are shown in Fig. 1.

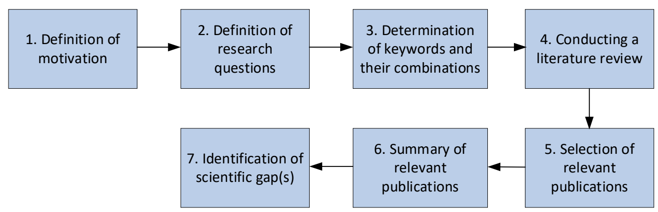

Figure 1 Steps of the Systematic Literature Review

Steps of the Systematic Literature Review:

1. ***Defining Motivation:*** Simulation modeling and VR technologies are undergoing significant transformations, and exploring their current types and integration possibilities may lead to new, previously unknown benefits.
2. ***Defining Research Questions:*** During the literature analysis of the research topic, I seek answers to the following questions:
- What are the main types and application areas of simulation modeling and VR technologies?
- What are the objectives of applying these technologies?
- What research directions can be identified?
3. ***Defining Keywords and Their Combinations:*** To answer the research questions, the focus during the definition of keywords was limited solely to the topics of logistics simulation and VR technologies; therefore, similar technologies such as augmented reality and mixed reality were not included in the scope of the search. The search keywords were as follows::
- "logistics" OR "supply chain"
- "process simulation" OR "simulation technologies"
- "VR" OR "Virtual Reality"

Keyword Search Combinations:
- ("logistics" OR "supply chain")
- ("logistics" OR "supply chain") AND ("process simulation" OR "simulation technologies")
- ("logistics" OR "supply chain") AND ("process simulation" OR "simulation technologies") AND ("VR" OR "Virtual Reality").

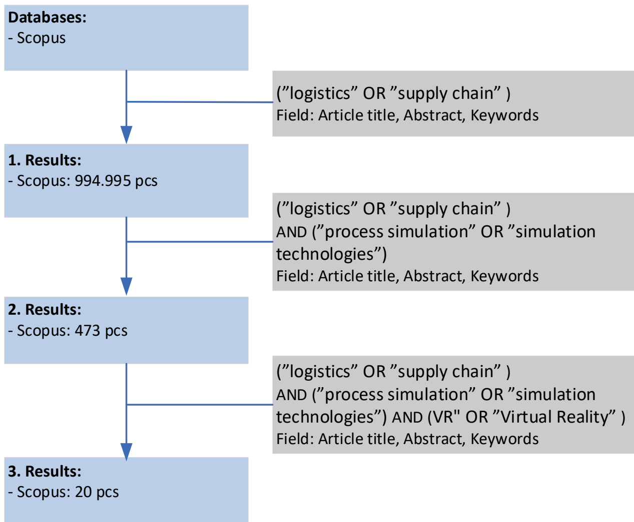

Figure 2 Process of Literature Analysis

4. ***Conducting the Literature Analysis:*** For the literature review, the Scopus database was used without any time restrictions. The main reasons for choosing this database were its recognition within the international scientific community and the fact that nearly all high-quality scientific journals are indexed by Scopus, enabling a comprehensive analysis. Using the search functions provided by the database, filters were applied simultaneously to article titles, abstracts, and keywords, as illustrated in Fig. 2. As a result of the filtering process, 473 journal articles were selected.
5. ***Selection of Relevant Publications:*** Based on the review of the abstracts of the publications resulting from the filtering process, as well as additional searches conducted on scholar.google.com, a total of 40 publications were selected for detailed analysis.
6. ***Summary of Examined Publications:*** Based on the content review of the selected publications, three key areas were summarized:

- Simulation modeling in logistics
- Application of VR technology in logistics
- Development directions of these technologies.

Simulation Modeling in Logistics:

The application possibilities of simulation modeling in logistics are clearly described by the Digital Twin concept, which can be classified into different levels of maturity. These include the Digital Model, Digital Shadow, and Digital Twin concepts [9-10]. The level of advancement depends on the way in which a bidirectional connection is established between the physical entity and the digital model (Figure 3). Additionally, it is important to note that in the case of a Digital Model, not only physical entities but also the concepts aimed at their creation can be analysed.

Digital Twin Maturity Levels:

- In the Digital Model approach, a simulation model is created based on a physical entity or a developed future concept. After analyzing the simulation, the physical entity or conceptual design is further optimized. As an example, the authors of [11] developed digital models for baggage handling systems to support the selection of optimal development alternatives.

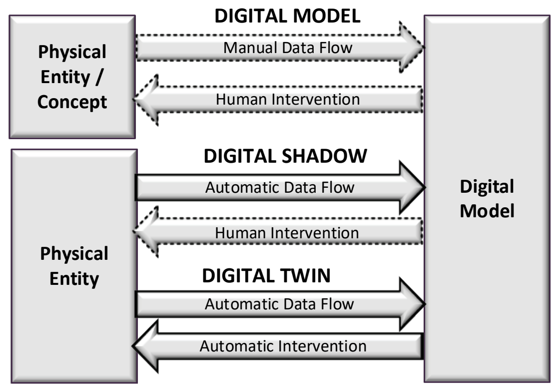

Figure 3 Digital Twin Concept

- In the case of a Digital Shadow, the simulation model automatically receives data from the physical object. After processing this data, it provides recommendations to improve the operation of the examined physical entity. The authors of [12] implemented a Digital Shadow model to enhance the efficiency of the floorball manufacturing process. The model enabled real-time monitoring of the production environment, where energy consumption and production data were collected to identify the most energy-intensive processes. Based on these insights, production plans were developed to minimize energy consumption and optimize production efficiency.
- In the case of a Digital Twin, bidirectional and automatic communication exists between the physical object and the simulation model. The authors of [13] applied the Digital Twin concept in glass lens manufacturing, where real-time data from the physical environment was processed with the support of artificial intelligence. This integration enhanced manufacturing efficiency, improved production accuracy, and reduced resource consumption.

The following key objectives of logistics simulation implementation can be distinguished [5]:

- Avoiding Design Errors: Simulation analysis conducted before the implementation of future developments helps prevent design errors. This includes avoiding inappropriate facility layouts and suboptimal selection of material handling and technological equipment.
- Comparing Design Alternatives: Simulation is applied when multiple alternatives (e.g., different layouts, processes, or types of technological equipment) exist for a development. In such cases, simulation is used to define KPI indicators that require modeling to support decision-making in alignment with the company's criteria.
- Determining Performance Limits and Capacity Requirements: Simulation modeling techniques can be used to assess the capacity needs and performance thresholds of existing systems or planned investments. This includes evaluating intermediate storage and warehouse capacities, as well as maximum production

capacity, allowing for accurate and timely definition of development phases.
- Comparing Control Strategy Variants: To achieve the optimal operation of a logistics system, different control strategies (e.g., warehouse material handling strategies, production line service strategies) can be defined. After conducting a simulation analysis, decision-making methods can be applied to select the most suitable alternative.
- Modeling Operational Disruptions and Their Mitigation: Logistics systems may encounter operational disruptions, breakdowns, and accidents. The development of scenarios for effectively managing such issues can be significantly supported by the capabilities of simulation modeling.
- Optimizing Logistics Processes: The operation of current or future logistics systems can be optimized using simulation models. For example, synthetic data generated by simulation models can be used to determine optimal production schedules, transportation routes, and layout plans.

Overall, it can be stated that these objectives can be achieved for all logistics processes through the application of customized Digital Model, Digital Shadow, or Digital Twin concepts. The implementation of a simulation model can be carried out either by developing custom software or by using frameworks (e.g., Plant Simulation, Simul8). Based on experience, the use of frameworks is prioritized due to their shorter development time requirements.

Application of VR Technology in Logistics:

Virtual reality (VR) can be classified based on different criteria, including the level of immersion and interactivity. According to the level of immersion, VR can be categorized into non-immersive, semi-immersive, and fully immersive types [14]. The fundamental difference lies in how much the user feels physically present in the virtual space [14].

Types of Virtual Reality Based on the Level of Immersion [14]:
- Non-Immersive VR: In this case, the user interacts with and controls the virtual environment through a screen, such as in the simulation model of a planned flexible manufacturing system [15].
- Semi-Immersive VR: This category includes systems that partially surround the user with a virtual environment. Examples include CAVE systems (Cave Automatic Virtual Environment), where walls, floors, and ceilings function as projection screens, as well as curved screens and projector-based systems [14].
- Fully Immersive VR: Fully immersive VR is represented by head-mounted displays (HMDs) such as Oculus Rift and HTC Vive, which provide real-time motion tracking and interactive capabilities for a fully immersive experience [16].

Based on the literature [17-19], the following levels of interactivity can be distinguished:
- Passive: The user is merely an observer of events (e.g., watching a VR movie or a simulation).
- Limited: The user can interact with the environment only by selecting predefined functions (e.g., interactive walkthrough, menu selection).
- Active: The user can freely manipulate objects in the virtual environment, which influences the outcome of the simulation (e.g., VR object manipulation, interactive simulation).
- Immersive Interactivity: Active interaction is complemented by physical sensations, including weight, texture, and force feedback, allowing the user to not only see and move objects but also feel them (e.g., haptic gloves, full-body tracking).

VR solutions can also be combined with various other technologies. The most commonly applied solutions include:
- Mixed Reality (MR) [20]: In this case, the real world and digital elements interact. MR is a combination of Augmented Reality (AR) and Virtual Reality (VR), where the user can not only see digital elements integrated into the real world but also manipulate them. In MR, digital elements appear as part of the real world, and the user can interact with them actively. Example: Using Microsoft HoloLens, the user can place virtual objects in real spaces (e.g., a virtual 3D model on a table), and these objects interact with the real environment. For instance, virtual objects do not fall off the table if a real physical object is present.
- The Metaverse [6]: The Metaverse is a shared virtual space created by integrating Virtual Reality (VR), Augmented Reality (AR), blockchain technology, and other digital innovations [6]. Its main areas of application include: virtual campuses, economic activities, art galleries gaming platforms. Examples: Decentraland, The Sandbox, and Meta's virtual spaces, where users can interact, trade, and build within persistent virtual environments.

The presented technologies and their types are summarized in Fig. 4. Since all levels of interactivity can occur across different types, their representation is omitted.

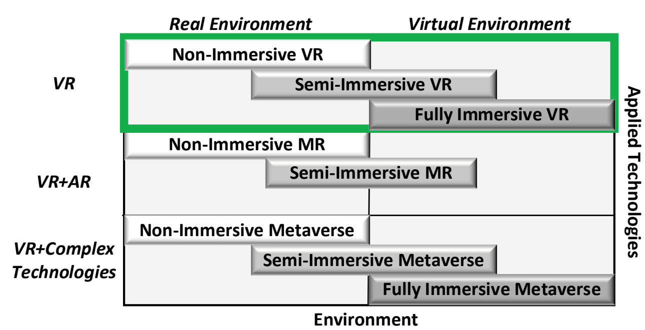

Figure 4 Types of Virtual Reality (VR)

The relevant objectives for the application of VR technology in logistics (variants marked with a green frame in Fig. 3) are as follows:
- Education and Training: Virtual reality enables the training [7, 21] and education of any logistics process. Its advantages include significantly reducing training costs and time requirements in certain cases, as well as

minimizing safety risks. Examples include training in the operation of various types of material handling equipment or the functioning of complex logistics processes. The technology can be applied in both educational institutions [22-25] and the corporate sector [26-27].
- Eliminating Design Errors: By conducting interactive examinations of designed logistics systems in a VR environment, design flaws can be identified and corrected before implementation [28]. An example would be ergonomic analysis of a specific workplace environment using VR technology.
- More Effective Handling of Operational Issues: Examining the real environment with VR technology enables rapid identification of operational issues and thus faster problem resolution [29-30]. For example, if the temperature in a warehouse exceeds the defined threshold, this can be indicated in the VR environment, allowing for a quicker response to the problem.
- Enhancing Customer Experience: VR technology allows customers to gain new experiences and additional information relevant to their processes. Examples include tracking a shipment in a VR environment or using VR in a restaurant to experience an artificial setting (e.g., a beach environment) or to access gastronomic information [31].

Overall, it can be concluded that VR technology offers numerous advantages in the field of logistics, as it enables cost-effective training, the elimination of design errors before implementation, the rapid identification of operational issues, and the enhancement of customer experience. As a result, it contributes to increased efficiency and competitiveness.

Development Directions of Simulation Modeling and VR Technologies:

Based on the literature analysis, the following development directions have been identified in the fields of simulation modeling and VR technologies:
- Technology Development: Further advancement of simulation modeling and VR technologies to create more user-friendly applications and new experience-driven functionalities. This includes real-time data integration, AI-based predictive features, and multi-user interactive capabilities.
- Expansion of Technology Applications: Research into new application areas beyond existing fields, such as education, healthcare, urban planning, and the development of logistics supply chains. This also involves conceptual planning and implementation of technologies to enhance competitive advantage, with a particular focus on sustainability and energy efficiency goals.
- Technology Integration: Exploration, conceptual planning, and implementation of integration possibilities between simulation modeling, virtual reality (VR), augmented reality (AR), and other emerging technologies such as IoT, blockchain, and artificial intelligence. This integration aims to support the more efficient modeling and management of complex and dynamic systems.
- Optimization of User Experience: Refinement of user experience and visualization capabilities in technological development, with a focus on intuitive controls, realistic graphics, and adaptive learning systems that facilitate faster adaptation and efficiency improvement.

3 INTEGRATION POSSIBILITIES OF LOGISTICS PROCESS SIMULATION AND VR

The integration possibilities of logistics process simulation and VR can be established based on the relationship between the alternatives of the four previously discussed aspects (Fig. 5). For a future logistics system concept under investigation, only the A. Digital Model and its related VR solutions can be integrated. This means that B. Digital Shadow and C. Digital Twin solutions, along with their associated VR applications, cannot be implemented. For an existing logistics system, the relationship between all Digital Twin maturity levels and VR types can be interpreted.

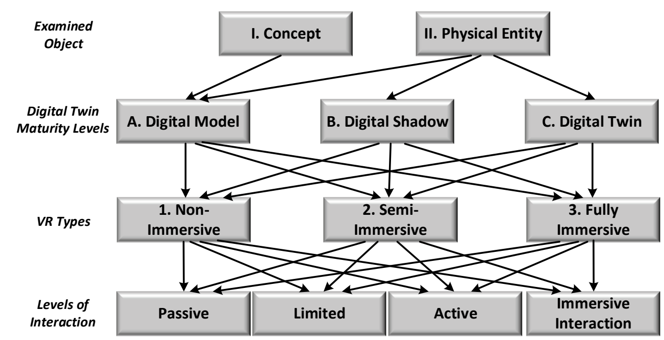

Figure 5 Integration Possibilities of Simulation Modeling and VR

Advantages Achieved Through Technology Integration:
- Improved Visualization and Intuitive Understanding: Interactive 2D/3D visualization of simulation models makes it easier to understand the examined processes.
- More Efficient Decision-Making: The ability to quickly manipulate simulated processes allows for the rapid evaluation of intervention effects, thereby reducing decision-making lead time.
- Consideration of Human Factors: In a life-size simulation model, features such as motion tracking and haptic feedback enable the assessment of worker efficiency, allowing for the optimization of working conditions before implementation.
- Faster Problem Identification and Resolution: Some design and operational issues may remain hidden in traditional simulations. However, VR applications enhance their detection (e.g., material handling obstacles, hazardous areas).
- Safer Testing Environment: Dangerous or costly processes can be examined in a safe virtual environment, reducing risks and expenses.

4 CONCLUSIONS

This paper has presented two technologies, namely simulation modeling and virtual reality (VR), along with their current types and future development directions. One of these directions is the exploration and application of integration possibilities between simulation modeling and VR technologies. Through simulation, logistics systems can be analyzed and optimized more effectively, while design errors can be identified and eliminated before implementation. By applying VR technology, visualization capabilities can be further enhanced, decision-making processes can be supported, and training processes can be made more cost-effective.

The integration of these technologies enables faster problem detection, more efficient optimization, and the creation of a safer testing environment. As a next step, concepts for implementing integration possibilities will be developed, tested, and applied in real industrial environments.

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