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Digital Design of Intralogistics Systems: Flexible and Agile Solution to Short-Cyclic Fluctuations

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***Abstract*—In times of fast-paced, fluctuating and individual markets, intralogistics systems, such as warehouses, have to adapt to the resulting volatile performance demands dynamically. Hybrid systems, in which humans and machines work together efficiently and communicate in socio-technical networks, can be the answer to manage these high-frequency markets. Hybrid systems of the future need to adapt frequently and permanent change becomes the "new normal". A one-time planning of warehousing systems upon first installation becomes obsolete. This results in the question of how to design and implement processes for future logistics systems in an agile way in order to exploit the flexibility potential of hybrid services, which represent an interface between man, machine and organization. As part of the Innovation Lab Hybrid Services in Logistics in Dortmund, Germany, a research project funded by the German Federal Ministry of Education and Research, this research proposes a new concept for digital design of intralogistics systems that is meeting the requirements of a continuous, short-cycle adjustment following the Industry 4.0 development path.**

***Keywords*—Digital design, Warehousing, Hybrid systems, Digital twin, Monitoring, Redesign, Virtualization, Virtual reality, Internet of things**

I. Introduction

The changing needs of fast-paced, fluctuating and individual markets require changes in logistics and logistics research. In times of industry 4.0 there is a rapid development towards scalable and autonomous technologies that react more flexibly to the market fluctuations but whose behavior cannot be predicted deterministically anymore. In order to exploit the flexibility potentials of these new technologies to the full extend they have to interact with each other and with human operators. Consequently, an important part of industry 4.0 is the interaction between people and machines as well as the environment. Industry 4.0 represents the fourth industrial revolution and stands for communication and networking between people, machines and objects on the basis of the Internet of Things (IoT) [1]. Industry 4.0, thus, is understood as the implementation of cyber-physical systems in the fields of production and logistics following IoT principles. Employees are supported in their work by smart assistance systems. Socio-technical systems generate new potential for the introduction of new innovations. They are based on the awareness that human work has a high impact in the innovation process. For this reason, it is particularly important to integrate humans into the planning process of systems in times of the fourth industrial revolution [2][3]. Thanks to continuous advancements in digitization, in the future people who are equipped with electronic devices will interact with technology instead of just monitoring it. As a result, social networks will arise in industry 4.0 surroundings. In these networks, the focus of attention is on people and people develop parallel to technology. Hybrid systems, in which humans and machines work together efficiently and communicate in socio-technical networks, can consequently be the answer to manage high frequency markets. In this context hybrid systems are needed, as they can cope with the continuous changes [2][4].

In this context, two basic observations aroused the motivation to deliberate on a new approach towards digital warehouse design:

- Although the realization of new warehouses still is a strategic decision and investment, its underlying planning fundamentals, such as customer demand and assortment, in times of e-commerce and highly customer-centered businesses cannot be forecasted reliably for a long-term horizon any more. As a consequence, storage and material handling technologies as well as logistic processes need to be set up as flexible and scalable as possible.
- Digitization is the main driver towards logistics solutions: cyber-physical systems increase performance adaptability on shop floor operations,

self-learning systems allow better forecasts and performance smoothening, virtual surroundings like virtual and augmented reality open new perspectives towards integration and education of staff.

Having identified both, market changes and requirements as well as solutions digitization offers to meet logistic challenges, the focus of this work on how to bring both ends together in a comprehensive approach on warehouse design emerged:

- RQ1: Which planning steps are necessary in digital design in order to be able to realize continuous and short-cycle adjustments in intralogistics systems?

In the future, real-time, continuous virtual and collaborative technology environments will become increasingly important. These environments should be designed collaboratively between man and machine [5]. In addition, increasing attention is given to automatic technologies and the human factor to improve the performance of a warehouse [6]. These developments lead to the second research question:

- RQ2: What role do planner and operator play in hybrid systems and how can their knowledge be incorporated into intralogistics planning processes?

The next chapter gives an overview of the state of the art in the area of designing intralogistics systems and derives the motivation for this exploratory study. It is followed by an overview of relevant conceptual background information for the presented concept of digital design. Afterwards, the methodological approach is presented.

II. State of the Art

Various publications including research studies and projects, doctoral dissertations and books concerning intralogistics planning methods and digital planning were examined to determine the research gap that motivated this study.

Currently, there is no universal solution for digital warehouse design. So far, only isolated solutions exist, for example in the area of supply chain management. Most solutions in the area of warehouse design can be found in transport logistics. Kitamura and Okamoto, for example, present an approach for automatic planning of milk-run routes [7]. Ellinger presents in her dissertation an agent-based concept for planning of picking systems [8] and Gath also chooses the agent-based approach for its optimization of transport logistics processes using a multi-agent system [9].

In the German research community, mainly level-based approaches to warehouse design can be found (e.g. [22], [25], and [26]). The levels break down the warehouse design problem into smaller sub problems that are solved iteratively. They usually follow the structure of determining requirements, designing processes, and selecting and dimensioning suitable technologies.

Developments in the English-speaking literature, which were examined for example in scientific publications or reviews from Gu, Goetschalckx, McGinnis [10][11], Apple [12] and Baker and Canessa [13] as well as Sharp, Goetschalckx and McGinnis [14][15] show that especially in the English-speaking research community the focus, predominantly lies on mathematical optimization in the area of warehouse design.

The examined approaches generally do not involve the interaction between humans and machines in the design process. Furthermore, scalable technologies that are controlled decentrally and act autonomously will be used increasingly in the future in order to be able to react to fluctuating market movements. Their behavior cannot be described deterministically anymore which leads to the need of new planning approaches.

Various studies have shown that VR-supported simulations can be used to qualify employees through training. Furthermore, their performance can be evaluated in the virtual environment and errors can be reduced. In particular, the integration of serious games in virtual worlds represents an innovative approach to sustainable continuing education. This is strengthened by the rapid spread to the end consumer market [16][17].

The technologies already used by companies in the areas of production, office and communication vary from manually controlled work equipment to self-controlling machines. In the areas of office and communication, digitization has been much faster in recent years than in production equipment. Investment in digital technologies has not led to average job losses or significant profits in recent years [18].

Due to demographic change, the further development of working systems is becoming increasingly important. The following chapter describes the methodological approach for this scientific elaboration.

In conclusion, currently research in warehouse design mostly focuses on analytical models that find an optimal or near optimal solution for a design problem. These approaches only seldomly include the operators experience and knowledge as well as the interaction between human and machine. VR supported planning approaches can be a solution.

III. Conceptional Background

For closing the research gap, two fundamental paradigms were identified to build the conceptual foundations of the digital design approach: hybrid services and the distribution center design process (DCDP), a level based approach to warehouse design developed by Schmidt [22] that is the base for the concept of digital design. Hybrid services describe the concept of how humans are integrated in socio-technical systems and thus are the foundation for answering the second research question presented in this paper. The DCDP presents a method that makes agile redesign of warehouses possible based on the principles of systems engineering and thus is the fundamental concept for answering the first research question. The following paragraphs describe these two paradigms in more detail.

A. *Hybrid Services*

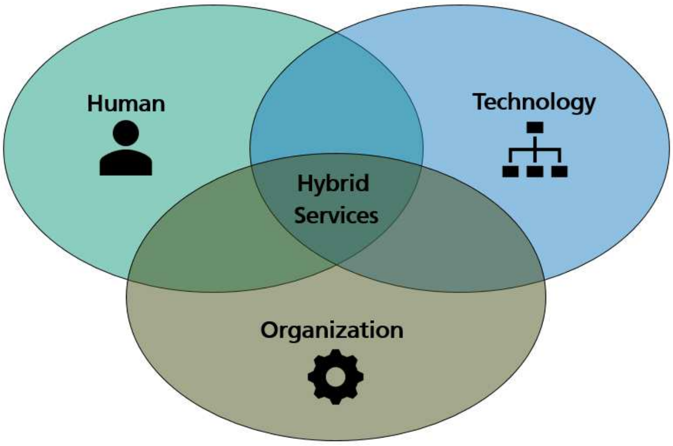

Fig. 1. Parts of Hybrid Services

Hybrid services are defined as a bundle of services comprising a product and supplementary value-added services. They are based on the combination of innovative technology, innovative software and a suitable business model to ensure the customer-oriented focus [4][19].

A holistic view of the socio-technical system is an essential basis for hybrid services. A socio-technical system is a production unit consisting of human, organizational and technological subsystems (Fig. 1). The technological subsystem limits the design possibilities of the other two subsystems. They have independent social and work psychological characteristics, which have a retroactive effect on the technological subsystem. This suggests that a solution has to be found for a structured design approach of the overall socio-technical system. Thus, the complementary design of the individual system elements and their intersections to an overall system is accorded special significance. In this overall system, the specific strengths and weaknesses of man and technology are taken into account. In this system specifically, the functional relationships or interfaces between technical, human and organizational systems are described [4][19].

The generic term Human-Technology-Interaction allows a convenient description of the socio-technical system. The term "technology" summarizes all technical facilities. This includes already existing and planned devices capable of interacting with other system actors [2][19]. With digital technologies, functions and tasks between man and machine are made possible. This configuration is regarded as a key issue for industry 4.0. In this context, intelligent assistance systems are required to cope with increased complexity of self-steering, smart technologies. In this context, assistance systems can enable more diversified work and support learning processes close to the workplace. Assistance does not mean that a person always has to tell the assistant what to do [2]. Instead, the intelligent system learns during use and can gradually adapt to specific conditions. However, the systems can limit employees' room for acting through strict process specifications. It is important to note that human work retains transparency and control over all processes and that employees therefore exercise planning, controlling, scheduling and executing activities. Thus, the important functions in enriched activities remain in human decision-making power [19].

Different models of work organization can establish the interface between people and the organization. For example, flexible and decentralized team structures are considered among them. In the case of a human-oriented organization, given room can be used to enhance activities and qualifications. In this system, tasks are not addressed to individual employees. Rather, the employees act in a self-organized, flexible and situational manner depending on the problems to be solved. Employees are thus given the freedom to make decisions and have the opportunity to find solutions on their own responsibility. The restrictions defined by management must be adhered to [19].

When looking at the interface between the organization and technology, it is important to cope with the demands of digitization. On the one hand, new technologies have to be integrated into existing workflows and processes. Not only the level of the shop floor is considered, but also other hierarchical levels. Due to the degree of automation of the technology, the organizational form is designed. Taking into account temporal and functional decoupling, alternative forms of organization such as hybrid services are made possible. Financial and human resources play a decisive role for many companies. Due to these structural obstacles, companies have to decide whether they can cope with the accompanying complexity [19].

Interaction is understood as the reciprocal interactions of actors or systems. The basis for interaction is the ability to communicate and interact.

Digitization is the optimization of existing processes by digital technologies. For this purpose, the stabilization of existing operational and work structures is essential. For this, logistically economic and socio-scientific perspectives are used – an interdisciplinary network constructed by the Innovation Lab.

B. *Distribution Center Design Process*

In his dissertation Schmidt developed a formal approach for designing intralogistics systems such as warehouses. The Distribution Center Design Process (DCDP) is a level-based planning approach and is based on the principles of systems engineering. The process is divided into two parts, each with four levels. The first part covers the functional design, in which the design task is transferred into a functional concept in the form of a top-down problem analysis. The second part deals with the physical design, which converts the concept into one or more evaluated solution proposals by a bottom-up solution synthesis [22].

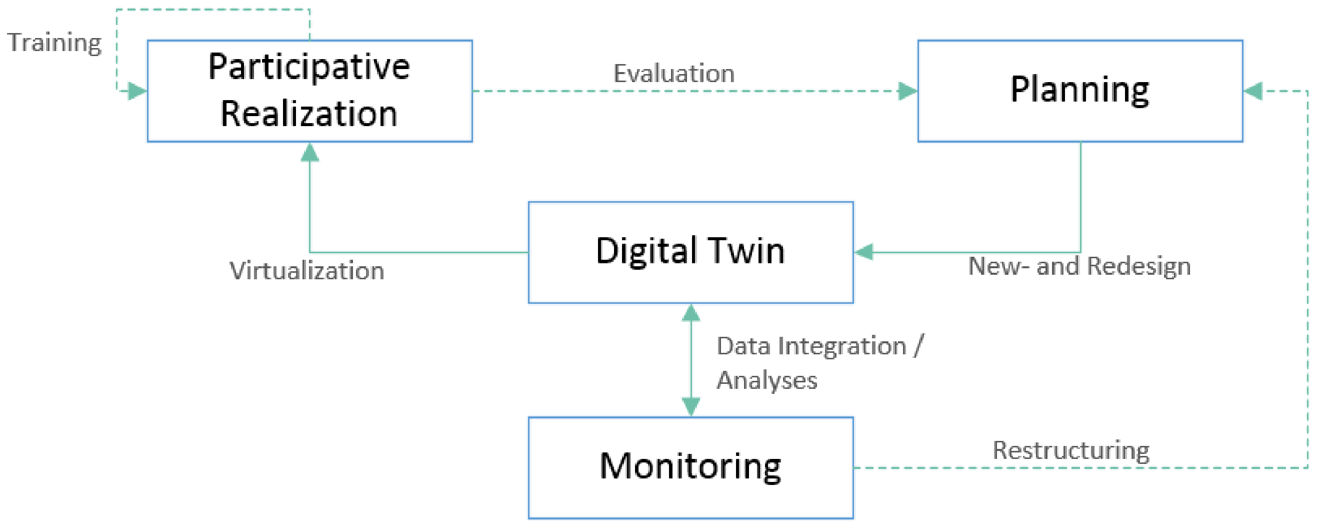

Fig. 2. The four modules of the digital design concept

The focus is on the formalization of the functional area of designing intralogistics systems, as this part has not yet been sufficiently scientifically considered. Thereby 18 services and 15 basic transformation properties of handling units are defined. These are used in the DCDP for the creation of Service Flow Networks (SFN), which are of importance to the warehouse design approach presented in this research and thus are described here [22].

SFN formally describe the functional design of a system and consist of services and their interconnections. A service is the intended transformation of incoming flows into outgoing flows. The execution of the service transforms varies basic properties of the handling unit. The creation of the SFN, which is part of the functional design, is based on the defined task objectives and the specification of the performance requirements. The services that must be provided to fulfill the requirements are then defined. The result is a hierarchical network of services that are characterized by interconnected function flows in the SFN. After the structure follows the transition from functional planning to the area of physical structure design [22].

IV. Digital Design

The state of the art has shown that there are deficits with regard to dynamic adaptation in the digital warehouse design. Based on the findings that humans need to be more involved in the design and redesign process of warehouses and that volatile markets and new technologies make new holistic design approaches necessary, the concept of digital design has arisen. It consists of four modules. The concept enables continuous and short-cycle adjustments of intralogistics systems, and supports the planner and operator of intralogistics systems and engages them in the design process.

A. *Modules*

Figure 2 shows the four modules of the digital design concept and their relations to each other, which enables a continuous adaptation of the intralogistics system as well as an increased integration and consideration of human factors in the continuous design process. In addition to the modules as components of the digital design developed in the Innovation Lab, which are presented in Fig. 2, there are interfaces to a social network and the associated smart devices to the main fields of activity of hybrid services in this paper. The presented devices will become increasingly important in the future for hybrid services and must therefore be integrated into the research approach.

The core of the digital design concept is a digital twin as a digital image of the intralogistics system including all objects. The digital twin represents the central instance for all other modules. It digitally mirrors the current state of the intralogistics system and serves as a data basis for all planning, analyzing and optimization operations in the other modules of digital design.

The forecast of the future state of the system, obtained through the digital twin, is forwarded to the monitoring system, which analyzes and observes key figures of the intralogistics system in real-time. The detailed and real-time monitoring of business processes and system statuses requires the exact representation of the model [3]. The planning system of the digital design provides decision support during the redesign of the system for the predicted new system load. Based on the new system requirements and the functional design of the intralogistics system, the planning system evaluates various candidate designs that differ in technologies and their dimensioning. The next step is for the planner to redesign the processes. The planner refers to the trigger for planning from the monitoring system. The planning system also supports the selection and dimensioning of the technology.

Following the redesign of the system, the digital twin is updated to the adjustments and the new design is evaluated in a first simulation. In case the simulation indicates that the adjustment of the system does not fit the future system load, the re-planning starts over. Otherwise, a more detailed evaluation of the redesigned system is conducted using the module of participative realization. The participative realization module has two goals. On the one hand the detailed evaluation with the support of the employees and on the other hand the qualification of the employees.

The four modules of the digital design concept are described in more detail below.

B. Monitoring

The monitoring system enables real-time requirements for action to be determined. As soon as a key figure in the forecast exceeds or falls below its limits, the monitoring system triggers the system's adaption to the new requirements [3]. The system captures data, maintains knowledge of the entire system and thus ensures continuity [5]. The system is monitored in real time, while the digital twin continuously outputs data on the current status [20]. Therefore, using upcoming technologies like RFID and real-time data capture through the Internet of Things decisions can be made quickly. The real time data analysis is the basis for a flexible and scalable logistics system in which the technologies can be adapted to changing requirements. Through a constant comparison of the current situation with target values, target/actual comparisons can be carried out.

During the monitoring process, relevant key figures must be filtered out of the operational information that the planner needs for an optimal decision [21].

C. Digital Twin

The Digital Twin can be described as a multi-physics, multi-scale, probabilistic simulation of a system. It uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its real twin [5]. Accordingly, the digital twin is a highly detailed simulation model that represents the physical environment as realistically as possible in the virtual world. The digital twin is composed of the three components, physical entities in the physical world, the virtual models in the virtual world, and the connected data. These components tie the physical and virtual worlds. It is thus the virtualization of the physical elements. Next, the physical processes are analyzed, evaluated and optimized in the virtual environment. Based on this, the processes in the physical system are optimized [20]. The virtual model reflects the planner's expectations and practical limitations. It also provides the basis for a simulation model that forecasts future states of the system based on its current state and scheduled workload. The digital twin supports the planner in iterative optimization and supports him in future planning [20].

D. Planning

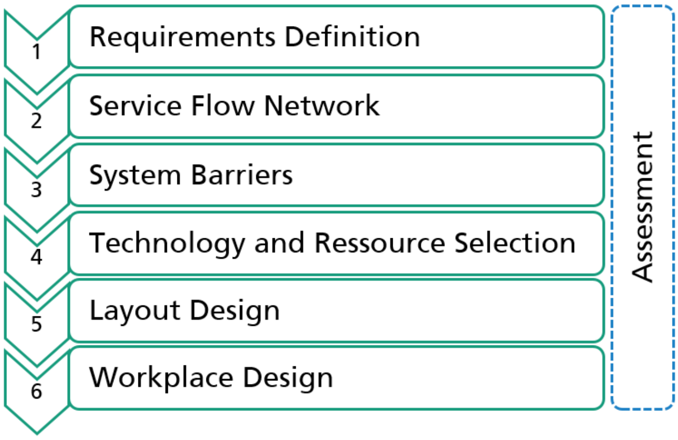

Fig. 3. 7-step planning system

Up to now, it has been possible to clearly differentiate in the cooperation between man and machine in which areas the machine is superior to man. Thus, the machine takes over more physical tasks and the human being brings in his improvisation ability and creativity. In the future, however, a development is to be expected in which machines can support people in making decisions due to their increasing autonomy. The resulting degrees of freedom in the division of labor further emphasize the importance of human beings as a model of human-centered automation. The human being acts as the conductor of the technology and no longer has to adapt to the technology, but the technology adapts to the human being [2].

Currently, the management of activities is not cost-efficient. Planning systems are needed which do not fundamentally dependent on people [5]. The need to be able to cope with changing circumstances is also growing in long-term planning [5].

Based on examined planning models in the field of logistics that are mentioned in the state of the art, it becomes clear that most of the models are level-based. The number of levels varies depending on the specific application. In most cases, the planning models start with a description of the current situation in the form of a system description or task definition. By determining capacity and performance indicators, then the design parameters of the system are defined. Afterwards the processes within the system are described. Thereafter, a selection of technology or allocation of resources takes place, from which the layout design derives at the end.

This paper suggests a planning system consisting of seven iterative steps to be followed (Fig.). The 7-step planning system is based on the planning models examined and especially the DCDP developed by Schmidt [22].

1) Requirements Definition: In the first step, requirements and goals of the design project are defined. The quantitative performance and dimension base of the logistics system for replanning or new planning must be determined. Based on this information, the planner can generate a service flow network.

2) Service Flow Network: As explained in the conceptional background, the SFN belongs to the functional part of the design process. By first conducting the functional design of a system the design space is not limited by the physical design and no design alternatives are excluded prematurely. The second step of the digital design concept starts with the creation of an initial SFN in which a superior view of services in the logistics center is carried out. The concept of digital design supports the planner through automatically creating an initial SFN based on the requirements specified on the first level and afterwards formalizes and verifies the subsequent elaboration of the SFN. This hierarchical network of services is characterized by interconnected function flows. The varification of the SFN is done by using the services' defined transformation of handling units and match the output of a service with the input of another service.

The aim of this step is the transition from functional planning to the design of the physical structure. The architecture of the services used determines the material flow. This gives the planner a holistic overview of the services required in the system.

3) System Barriers: Furthermore, in this step it is necessary to define a physical structure and process structure of the systems. For this purpose, services are allocated and several services are combined into one system. Because of the combination of single smaller systems the complexity of designing the entire system is diminished.

4) Technology and Resource Selection: This step includes a detailed examination of the material and immaterial resources as well as the process execution at the workplace. The technologies and resources are selected by exploring the design space of the individual subsystems and creating and evaluating various design alternatives [22]. With the help of this computer-aided model approach, logistics systems are designed and generated. This automatic selection reduces the planner's planning effort and gives reliable decision support for chosing a candidate design.

5) Layout Design: Layout planning is carried out between the fourth stage, technology selection and resource selection, and the workplace design in the sixth phase. In the overall planning system, the layout planning functions as an intermediate step before the workplace design. After selecting the technology to be used and allocating the resources, the elements are laid out in the warehouse before they are designed in accordance with technical working rules. In the final selection of a suitable layout, for example the utility value analysis is carried out. With the provided layouts, the planner can design the workplace.

6) Workplace Design: Based on the selected technologies and resources as well as the layout, the workstation is designed in the sixth stage. This step is strongly linked to the module of participative realization and also integrates the human factor into the planning approach. On the basis of the workplace design and within the framework of participative realization, an evaluation can be carried out by the employees.

7) Assessment: The assessment step is to be regarded as a superior level, as it is carried out at each level for control purposes. This involves a comparative assessment regarding the quality of their suitability and the target values set out in the requirements definition. It can lead to several levels being executed iteratively. The assessment guarantees on the one hand the quality of the warehouse designed by the 7-step planning system and on the other hand the integration of the planner's experience.

E. Participative Realization

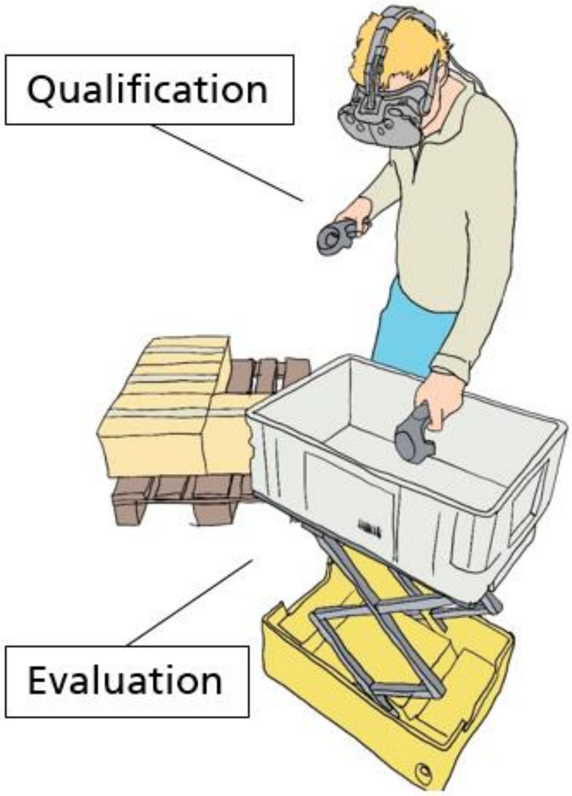

Fig. 2. Participative realization through virtual training

By executing future processes in a virtual environment before the system is implemented, weak spots of the selected candidate design can be evaluated. A further advantage of using the virtual image of the future system is the possibility for shop floor employees to be involved in the design process, to train new processes and the use of the new technologies before implementation. That way processes and technologies can be adjusted before they are set up physically and they meet with wider acceptance among the employees because they were involved in the design process. Therefore, employees are involved in ongoing planning via the virtual world [23]. The second part deals with the qualification. New processes are trained early in the virtual reality. This possibility of learning new processes decouples the integration of new employees from day-to-day operations. Thus, no foreman has to be assigned for the training of the new employees. Motivation can be increased within virtual reality through playful elements. This will accelerate and intensify the transfer of knowledge.

This results in the sensitization for virtual training. On the one hand, logistics systems must react flexibly to market changes. At the same time, the working environment must be adapted to the needs of the employees. The digital design helps shop floor employees and the planner to design their working environment. The planning results of the rescheduling can be checked for feasibility in virtual reality. Affected employees are thus involved in the meaningful workplace design and can be trained at an early stage. Virtual Training offers the possibility of training in a realistic environment.

Digitalization results in new methods of employee qualification in intralogistics. The module uses a model of the redesigned intralogistics system in virtual reality (VR). The VR model provides the opportunity to evaluate the system on a new and more detailed level. Serious games with virtual realities are used as a modern alternative to classical training methods. Virtual training is used to learn new skills to evaluate them and reduce mistakes. This possibility to experience scenarios also offers the possibility to simulate scenarios that are difficult or cost-intensive in reality. Gaming seriously combines game mechanics with appropriate learning mechanisms to increase learning success [17]. Serious Gaming achieves good usability and a positive user experience, while the effort can be classified as moderate. A correlative correlation is to be recognized, after which the usability of the user associates with the intrinsic motivation. Thus, Serious Gaming represents a modern alternative to classical training methods in intralogistics in virtual reality. This increases the motivation and learning success of the user [17].

V. Conclusion

In parallel with the rapid development of technology and organization, the transformation of the working world is accompanied by the following changes. It should be noted that the requirements and the required know-how of the employees are changing and continuous learning will become necessary in the future. In addition, new technologies offer new opportunities for learning new processes and individual training measures [4][23].

The concept of digital design that is presented in this paper makes the planning of scalable intralogistics systems possible and meets the requirements of fast-paced individual markets. It will accelerate the acceptance and introduction of new technical solutions in the area of industry 4.0. The research on the digital design concept within the Innovation Lab Hybrid Systems in Logistcs is currently at the end of the concept phase and the implementation of the modules is next.

Acknowledgment

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