Implementation of a digital twin framework in the modular housing industry

Anne Fischer
Chair of Materials Handling, Material Flow, Logistics
Technical University of Munich
Garching/Munich, Germany
anne.fischer@tum.de

Jorge Rodriguez Llorens
Chair of Materials Handling, Material Flow, Logistics
Technical University of Munich
Garching/Munich, Germany
jorge.rodriguez@tum.de

Zhen Cai
Chair of Materials Handling, Material Flow, Logistics
Technical University of Munich
Garching/Munich, Germany
zhen.cai@tum.de

Michael Wilke
Max Bögl AG
Mühlhausen, Germany
mwilke@max-boegl.de

Stephan Kessler
Chair of Materials Handling, Material Flow, Logistics
Technical University of Munich
Garching/Munich, Germany
stephan.kessler@tum.de

Johannes Fottner
Chair of Materials Handling, Material Flow, Logistics
Technical University of Munich
Garching/Munich, Germany
j.fottner@tum.de

Abstract*—The construction industry is one of the minor digitized industries, and it has been characterized by a below-average increase in productivity in recent decades. The modular housing sector copies the production system of the manufacturing industry to meet these deficits, which makes it a perfect example for evaluating Industry 4.0 technologies. This paper explores the methodology and possibilities of implementing a digital twin of a modular housing production plant to optimize its production. The proposed approach based on a Digital Twin (DT) framework consists of three consecutive parts: (1) analyzing the production system by using the Lean tool of Value-Stream Mapping extended (x-VSM) towards Discrete-Event Simulation (DES) models, (2) collecting real-time data to track and trace the system's bottleneck by using Radio-Frequency Identification Devices (RFID) as a Tracking-and-Tracing system (TaT), and (3) optimizing it by using DES. Three scenarios to eliminate waste, increase throughput, and identify the best possible TaT implementation have been simulated. The results are a 64 % inventory reduction, a 20 % faster production lead time, and the finding of the critical part to be tracked using RFID. The resulting model has shown to be a valuable instrument for understanding the different process interdependencies. Moreover, it has been used as a support tool for middle management to assess the impact of different optimization approaches quantitatively. Overall, this paper shows the implications of combining DES and TaT systems towards a DT of a modular housing production plant.

Keywords—Modular housing building, Digital Twin (DT), extended Value-Stream Mapping (x-VSM), Tracking-and-Tracing system (TaT), Radio-Frequency Identification Devices (RFID), Discrete-Event Simulation (DES)

I. INTRODUCTION

The competitive situation in the housing market calls for innovative concepts within the construction industry. In recent years, the manufacturing concepts of process standardization and modularity have been successfully transferred to the construction sector as modular buildings. Modular buildings are prefabricated buildings consisting of repeated sections called modules produced in a production facility. The installation of the modules happens on-site, where the modules are placed and stacked together to form the final building. An illustration of this process is shown in Figure 1.

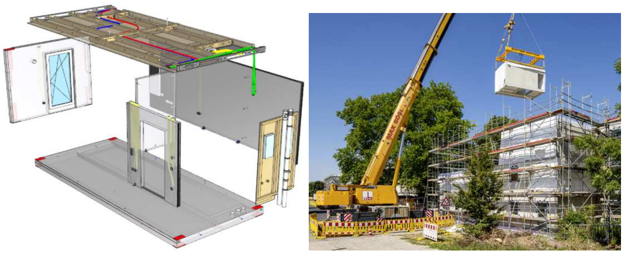


Fig. 1. Left: Module divided into its different components. Right: Stacking of the module to assemble the building. [1]

This concept offers numerous benefits to stakeholders involved in the construction process, including reducing the construction time, safety risks, whole life cost, and improved quality and productivity [2, 3]. On the contrary, some of the challenges identified by Lu and Liska [4] are the inability to make changes on-site, transportation constraints, and limited design options.

The production system used to fabricate the different modules has many similarities to traditional manufacturing systems. These similarities enable the knowledge transfer of classical Lean production theory and its methods, such as Value-Stream Mapping (VSM), and more innovative concepts like Industry 4.0 technologies, such as Tracking-and-Tracing systems (TaT) and Discrete-Event Simulations (DES) [5].

The counterpart of Industry 4.0 in the construction industry is known as Construction 4.0, and it is increasingly being mentioned in the scientific literature [6]. Its essence is the digitization and automation of the construction sector to create a digital construction site to monitor progress throughout the lifecycle of a project [7]. One well-known application in various industries is the new phenomenon of Digital Twins (DT) [8].

The use of these technologies provides a potential means to overcome some of the challenges faced by the construction industry, such as a steady decline in productivity [9]. However, the practical applications of TaT and DES in the construction sector are still limited [10, 11], as the industry has consistently shown skepticism to its adoption [12].

This paper presents how one can profit from Construction 4.0 by implementing a DT in a modular housing plant. The developed DT includes the technologies of TaT and DES and uses the Lean method VSM as a basis for its conceptual modeling. The modular housing sector is chosen as it is a parade trade of TaT and DES application due to its in-house and standardized production process.

First, this paper gives an overview of the current state of TaT, DES, and DT in the construction industry. Follow-on, it introduces the framework of the presented DT, including the three used methods that are applied in the real-life case study at a German modular housing company: (1) the extended Value Stream Map (x-VSM), (2) the TaT system, and (3) the DES model. The lessons learned from the methods are shown. In addition, three different scenarios provide potentials of the production system gained by the implemented DT.

II. LITERATURE REVIEW

In the following, the two key technologies of Industry 4.0, TaT and DES, are introduced and evaluated towards their application in the construction site. Combining both technologies, this section further illustrates DT and transfers it to the research objective of this paper.

A. *Tracking-and-Tracing system*

TaT originally refers to "methods to determine the processing or delivery status of an object within a supply chain of a production or logistics company" [13]. However, with the development of digitization in the construction industry, especially with the arrival of fleet management software, TaT is increasingly known as a working method.

Research surveys have shown that the construction manager spends a crucial amount of working hours searching for working equipment, materials, and co-workers. Reducing these hours can have an enormous impact on cost savings, showing the great potential of TaT methods in the construction industry [14, 15].

As part of Internet of Things (IoT) technologies, TaT systems in the form of sensors are used to obtain positional data of the objects tracked. As this research study is focused on an indoor production plant, only indoor location sensing technologies like radio-frequency identification devices (RFID) or Bluetooth Low Energy (Beacons) are considered. The comparative study conducted by Li and Becerik-Gerber [15] concluded that RFID is the most suitable indoor location sensing technology among eight sensing technologies.

RFID is "the projection of radio waves and signals to transmit data and conduct wireless data retrieval and storage to identify the status of workers and object contents", according to Yin et al. [16]. It consists of two components, a tag and a reader. The tag is installed onto or into the object to be identified. The reader is connected to an antenna, which receives the data via electromagnetic fields from the tag.

The real-time data obtained using RFID can be integrated with DES, where the simulation provides standard production performance, while RFID data provides actual production performance and real-time object location. By comparing the actual and the simulation results, the production planning strategy can be modified in real-time, accounting for delays or takt time variations, among others [17].

In a research study developed by Altaf et al. [17], simulation and RFID have already been used to develop control systems that serve as decision-support tools in the building sector. However, these studies have primarily considered and applied RFID technology as a localization technology, while, to our knowledge, few studies exist that have applied RFID technology for generating input data automatically for simulation modelling.

B. *Discrete-Event Simulation*

In a discrete manufacturing environment, simulation of discrete-time events is defined as "a computerised system capable of creating deterministic and stochastic simulations in real-time or near-real-time, to monitor, control and schedule parts and resources" [18]. This kind of simulation is called DES.

Research has shown that computer-based DES tools can be employed to check alternative production systems to understand their features and assist organizations with deciding to implement Lean approaches [19]. Furthermore, DES has been considered one of the most flexible analytical tools in manufacturing system design and operations [20]. Moreover, it provides insights for predicting outcomes of multiple what-if scenarios, supporting the decision-making process in any construction company [21]. Moreover, Afifi et al. [22] proved that a simulation tool helps study complex construction operations since it facilitates decision-making in construction. The interest in simulation models within the construction industry is corroborated in a survey conducted by Leite et al. [12], where 88 % of the participants described simulation as a value-adding research direction.

Despite its obvious advantages, the use of DES in the construction industry has mainly been limited to academia, and practical applications in the construction sector are still very limited [23]. Building and analyzing a DES model is still time-consuming and needs skilled professionals, the cost of which can be prohibitive to small and medium enterprises [10]. Furthermore, the limited number of construction simulation tools was also identified as a barrier to simulation adoption by Abdelmegid et al. [24].

However, as this study is carried out in a modular construction plant, its modularity and standardization facilitate the transfer of some manufacturing simulation tools. Besides, as all projects are carried out within the same production environment [25], the barrier of the long cycle time of simulation studies is not relevant anymore, as the simulation model can be reused or easily adapted for every new project.

C. *Digital Twin in construction*

DT is defined by Trauer et al. [26] as "a virtual dynamic representation of a physical system, which is connected to it over the entire lifecycle for bidirectional data exchange". This technology is an emerging concept that has become the centre of attention in the domains of manufacturing, production, and operations [27]. Besides, the advancements in Industry 4.0 concepts such as advanced data analytics and IoT connectivity have facilitated its growth in recent years [27].

According to Schleich et al. and DebRoy et al. [28, 29], building a simulation model with high levels of accuracy and integrating real-time data is the core constituent of a DT. This work is particularly interesting for this research study, where a representation of the physical system is built using DES, and a potential real-time integration using RFID technology is analyzed.

In the context of construction, DTs are a new phenomenon. There is little or no consensus among researchers and practitioners of how DT processes can support design and construction [8]. However, a common goal seen so far across the field of DTs in the manufacturing sector is the idea of real-time simulation instead of deterministic models. DT can learn and monitor simultaneously, facilitating decision-making [9] to make processes significantly leaner based on well-informed and reliable "what-if" scenario assessments [7].

However, several challenges regarding data integration and data security still exist in the current applications. Furthermore, the DT models require people with the right skills to construct them, many funds, and the latest technologies with higher computational power to develop them successfully [30].

D. *Research gap and objectives*

Overall, the research review identifies a gap in the integration of DTs to support the construction industry with decision-making by using TaT for production performance tracking and running DES for optimization studies. Therefore, our objectives and its linked research questions subsequently are defined as follows:

1) Provide insights on how a DT can be applied in the construction sector: *Which general framework is needed to simplify the integration of a DT?*

2) Model and implement a DT framework, combining VSM, TaT, and DES: *How can a DT be integrated into a real-use case, and which problems are faced?*

3) Explore the effectiveness of the DT developed on a modular housing production plant and show that simulation can be used as an effective decision-support tool for middle management in the modular construction industry: *Why is the implementation of a DT worthy?*

III. METHODOLOGY

The research study is carried out in collaboration with an industry partner, maxmodul, a subsidiary of the German construction company Max Bögl Group, who provides the production process within the modular house building sector. More details about the methodology and results can be found in the master's thesis by Rodriguez Llorens [31] (a co-author of this paper).

A. *Framework*

The proposed approach extends the framework presented by Fischer et al. [32], see Figure 2.

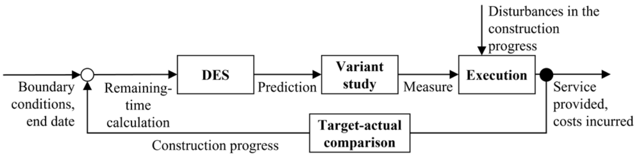


Fig. 2. Cybernetic control loop for a DT including the update of DES models by integrating data collected during execution [32,33]

The main idea is that the DT is integrated into the planning and production system like a cybernetic control loop to provide the decision-making experts with updated information and solutions continuously. This loop is fed by an initial setup of the system itself gathered by the Lean method of VSM. Then, a DES model is conducted based on this setup, followed by a parameter study. Finally, if the system diverges, the collected (real-time) data helps update the DES model to optimize it.

B. *Value-Stream Mapping*

The project study started with the data collection process of the production plant of the industry partner. The plant was visited several times to gain a complete understanding of the modular housing manufacturing process. The data collection tips for process mapping according to VSM described by Rother and Shook [33] were followed during these visits.

The modules produced by the industry partner consist of a floor and different types of walls, depending on the module type. They are all assembled within the same facility. A simplified material flow diagram is shown in Figure 3. The facility consists of four main processes: the shell construction line and the concreting station (blue square), the intermediate buffer, ceiling, and double-wall stations (green square), and the final assembly line (orange square).

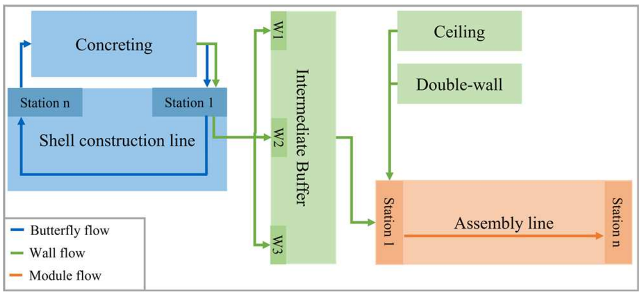
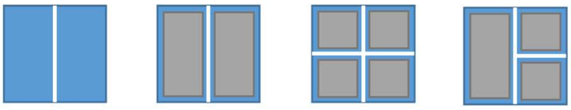


Fig. 3. Simplified material flow of the four main production process: butterfly flow in the shell construction line and the concreting station (blue square), wall flow in the intermediate buffer, ceiling, and double-wall stations (green square) and the assembly line (orange square)

The shell construction line is a flow shop line, where five different wall types are prepared for concreting. In this process, formwork and reinforcement bars are installed. For this entire line, a special transportation casing called butterfly is needed. The butterflies move from station to station containing the walls that are later to be concreted. A schematic representation of an empty butterfly is shown in Figure 4. Each butterfly may contain from two to up to four walls of the same type depending on the wall type.



Empty butterfly **Concreted butterfly type I** **Concreted butterfly type II** **Concreted butterfly type III**

Fig. 4. The four different possible butterfly states, f.l.t.r.: empty, two walls of the same type, 4 walls of the same type, 3 walls but only 2 of the same type

The prepared butterflies are transported to the concreting station using a portal crane from the shell construction line. The concreting station consists of four compartments, and in each compartment, up to five butterflies can be concreted at a time. In the current state, only two of the four compartments are used. After a specific curing time, the concreted walls are lifted from the butterfly and then stored in an intermediate buffer until they are pulled into the assembly line. On the other side, the empty butterfly is transported back to the first station of the shell construction line, closing the cycle, as shown in Figure 3.

Parallel to this process, the ceiling and the double-wall are produced in an independent facility and then transported to this production plant. In the case of the double-wall, it must undergo an installation process in a particular station of the production plant. From there, it is transported to the assembly line, where the different wall types are mounted together. The end-product is a finished module, which is then stored in an exterior storage location until it is transported to the construction site.

Apart from gathering production times, machine and inventory data, expert interviews with employees from the company were conducted to properly understand the information flow and to prepare the ground for the subsequent VSM and simulation model. The extended Value-Stream Map (x-VSM) proposed by Bait et al. [18] was implemented to integrate the collection process for both tools optimally. They add, for example, crane movements and shifts patterns to the data collection process of a traditional VSM, facilitating the posterior simulation modelling.

The x-VSM was drawn by hand as recommended by Rother and Shook [33]. However, to properly visualize the value stream in this project study, a diagramming and vector graphics application, Microsoft Visio, was used to obtain a digital version of the x-VSM. Furthermore, due to the complex nature of the analyzed production process, a static tool like x-VSM is not sufficient to quantify potential optimization measures, creating a need for a tool that can quantitatively evaluate different dynamic scenarios, such as DES. This need had already been outlined in different research studies performed by Abdulmalek and Rajgopal [34] and Donatelli and Harris [35].

C. Tracking-and-Tracing system

As a result of the VSM study, the double-wall is assumed to be the system's bottleneck. Therefore, it is chosen as a suitable candidate for implementing the TaT system to quantify this assumption. The measuring setup for the TaT system of the pilot project is shown in Figure 5. It is realized according to Borrmann und Günthner [36]. In total, ten RFID tags (1) and two antennas (2a, 2b), with a coverage distance of two meters, were available. The antennas are connected to a multi-reader from Impinj, which transmits the data to a computer (3).

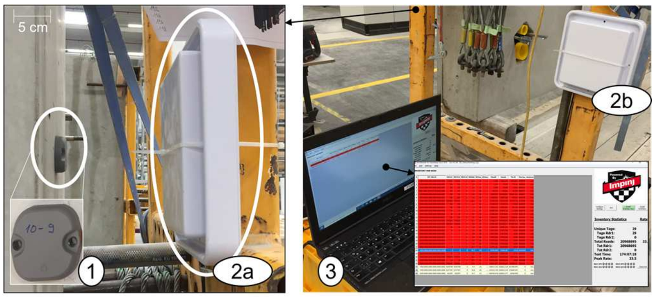


Fig. 5. Measuring setup for the TaT experiment. Left: An antenna (2a) facing a RFID tag (1) attached to a double-wall. Right: An antenna (2b) connected to a reader that is connected to a computer (3).

The TaT was installed on-site, with both antennas mounted close to the double-wall station. The objective was to track the processing time of each double-wall produced, without interfering in the actual production. One antenna was installed at the station's entry, facing the double-wall as shown in Figure 5, and one at the buffer situated just after the station, following the same principle. The walls were equipped on both sides with RFID tags so the antennas can read the information independently of the way the operators transported the walls into the station. Once a double-wall leaves the station, the operators were instructed to remove the RFID tags and reinstall them in another non-processed double-wall.

The raw data obtained is transmitted to the computer via the reader. The processing time is then determined as the difference between the first timestamp measured by the exit antenna minus the first timestamp measured by the entrance antenna.

D. Discrete-Event Simulation model

The dynamics of the production process analyzed in this study are characterized by discrete events such as the arrival or departure of a job or the initiation and completion of a manufacturing task; consequently, DES is a suitable simulation method. The steps described in the workflow by Kudlich are implemented to develop a DES model: system analysis, modelling, implementation, simulation, and evaluation [37].

The first two steps are covered by the physical plant description and the x-VSM. The Tecnomatix Plant Simulation material flow simulation software developed by Siemens PLM Software was used for the third step (implementation). Tecnomatix Plant Simulation software provides the DES and statistical analysis capabilities needed to optimize material handling, logistics, or machine utilization and is one of the key players in this segment. The iterative process of verification and validation with middle management occurs while implementing the computer model. Finally, for simulation and evaluation, three different experiments were carried out within the Tecnomatix Plant Simulation environment using the validated model to provide optimization insights for middle management:

1) *Scenario I* is about a doubling of the production capacity of the model's concreting station. The shell construction line is currently working on a two-shift arrangement, whereas concreting and assembly work on a one-shift basis. The reason behind it is that the concreting station works at half capacity using only two out of four concreting compartments. This simulation scenario modulates the concreting station to operate the four compartments in a two-shift pattern to scale production output.

2) *Scenario II* is about inventory reduction using the number of butterflies as an input parameter. To achieve this inventory reduction, the simulation is used to model and evaluate the performance of the production plant as a function of the number of butterflies used. Several scenarios varying the number of butterflies are then analyzed.

3) *Scenario III* is about collecting the real-time data using RFID technology used as an input for the model to analyze a double-wall station bottleneck and investigate a potential first implementation of a DT in the production plant.

IV. RESULTS

A. *Value-Stream Mapping*

Figure 6 shows the x-VSM of the physical production plant. For every process the cycle time, the processing time, and the number of shifts was collected. The cycle time is the elapsed time between two units leaving the process. In this x-VSM, it corresponds to the maximum cycle time of the stations included in each process. The processing time is the actual working time needed to process each unit. It may differ from the cycle time in each station if two or more operators are working in parallel in a station. In this x-VSM, it is the sum of the processing times in every station for each process. The number of shifts is the number of shift patterns each process.

We identified the following three reasons for the failure of the experiment: Firstly, four RFID tags were not removed from the finished double-walls, so they continued their way through the assembly line and ended up lost inside a finished module. Secondly, the TaT system used had a storage capacity of 20,005 data points, meaning that the data points were automatically removed from the system after this number was reached. Thus, the stored data points had to be manually copied within a specific time frame. Thirdly, a new measurement trial was not possible within the time frame of this research study. Combining these factors made it impossible to collect a representative dataset of RFID measurements for use in this research study and no deeper analysis can be made.

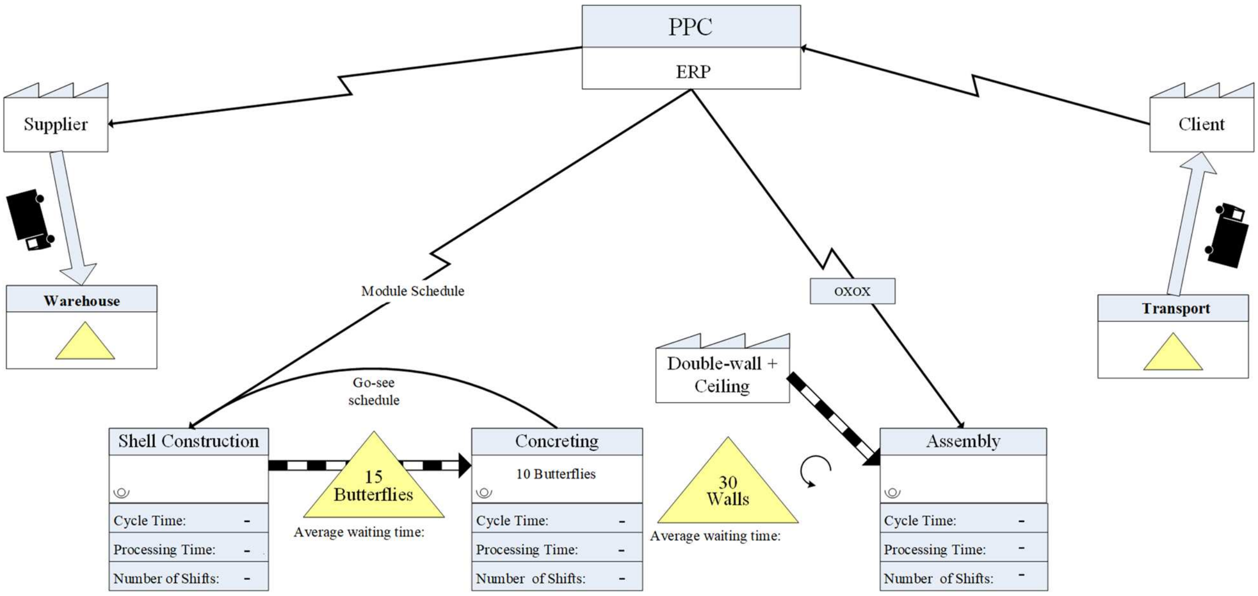


Fig. 6. High-level x-VSM of the entire production process. For reasons of secrecy, only the relevant data for this research study is presented.

The center block contains the production, planning, and control (PPC) controlled using an enterprise resource planning (ERP) tool. The thick black and white striped arrows indicate a push process of the material flow between the lines, whereas the anticlockwise arrow indicates a pull process. The "OXOX" shows a scheduling process.

B. *Tracking-and-Tracing system*

In one of the plant visits, the RFID tags were installed onto the walls in the double-wall station to gain more information about the station's processing and idle times. Due to the nature of the modular production plant, where a double-wall takes at least two hours to be processed, the measurement time was set to 14 days.

As shown in Table I only four data points were collected during this time. Ideally, this RFID experiment provides a dataset of 40 processing times (ten working days and four double-walls produced in each shift) and gives a first impression of the processing times variability.

TABLE I. COLLECTED PROCESSING TIMES OF THE DOUBLE-WALL STATION IN THE RFID EXPERIMENT

Module number	***1***	***2***	***3***	***4***
Processing times [hours]	3	2	4	6

For future experiments, the loss of trackers can be solved by fixing the antenna to the station and placing the trackers onto the portal crane that transports the double walls instead of placing them onto the double-wall itself. An antenna with a higher coverage distance is required to increase the experiment's robustness substantially. Instead of RFID, active Bluetooth tags can be tested as they are able to transmit more information.

Nevertheless, the insights provided on how the solve the issues will serve as a basis for implementing TaT systems in future research projects at this production plant.

C. *Discrete-Event Simulation model*

IMPLEMENTATION AND VALIDATION OF THE SIMULATION

The implementation process of a DES model consists of the programming part and the validation process. The first process to be programmed and validated is the shell construction line combined with the concreting station (blue square in Figure 3), as it is also the basis for the rest of the processes. The shell construction line is a simple flow line, and it was modelled using the deterministic processing times provided by the middle management as an input. The inventory between the shell construction line and the concreting station is tracked for the concreting station.

The blue line in Figure 7 shows the evolution of the inventory in the concreting buffer using 31 butterflies during a simulation runtime of 15 days.

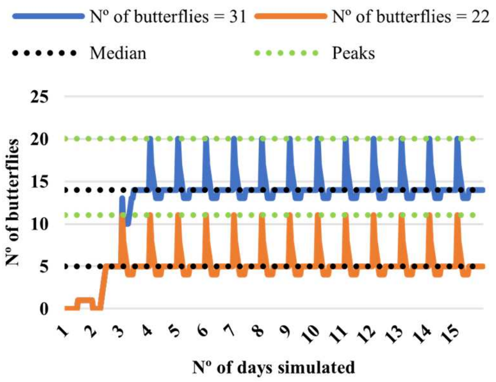


Fig. 7. Evolution of the butterfly inventory using 31 (reference model) and 21 butterflies (optimization scenario II) between the shell construction line and the concreting process, based on the simulated days

After reaching a stationary state on day 4, the inventory ranges from 13 to 20 butterflies, with a median of 14 butterflies in inventory. The sudden fluctuations observed in Figure 7 occur when butterflies leave the concreting station in lots of 10, producing the peaks at 20 butterflies. This peak is quickly compensated for, as the concreting is refilled again, and the butterflies are pushed back onto the shell construction line.

When walking through the shop floor, one expects to see 14 butterflies in the inventory (median value in Figure 7), which is very close to the 15 butterflies observed in the VSM in Figure 6, and so both the shell construction line and the concreting process were validated.

After programming and validating both processes with middle management, the intermediate buffer between production and assembly and the double-wall station is programmed (green square in Figure 3). The box plot in Figure 8 showing the different buffer occupancies is used to validate the model with the x-VSM data performed in Figure 6.

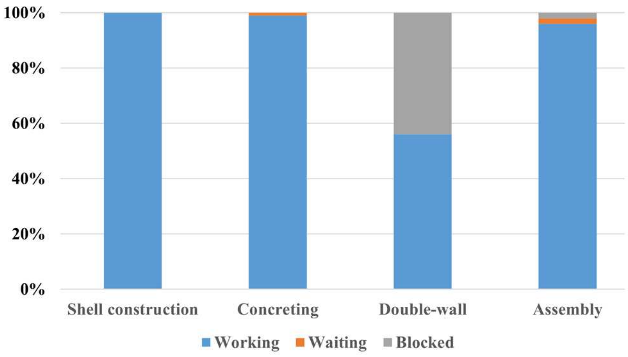


Fig. 8. Validated workload diagram of the production plant with a focus on the four main production lines of the process. The ceiling was not included as it is not processed in this plant.

The box plot shows the frequency distribution for each wall type in the buffer during the entire simulation runtime. The sum of the medians for each wall type equals roughly 30 walls, which is the amount represented in the xVSM.

Ultimately the assembly (orange square in Figure 3) is added to the model. A workload diagram represented in Figure 9 is used and presented to middle management for validation. For each line, the workload is divided into three states: working, waiting, and blocked, and is represented as a percentage of time each line is in the corresponding state. In this state, production runs smoothly, with the double-wall station being empty or blocked almost 50 % of the time. This result corresponds exactly to the current operation of the production plant, so the assembly line was also validated.

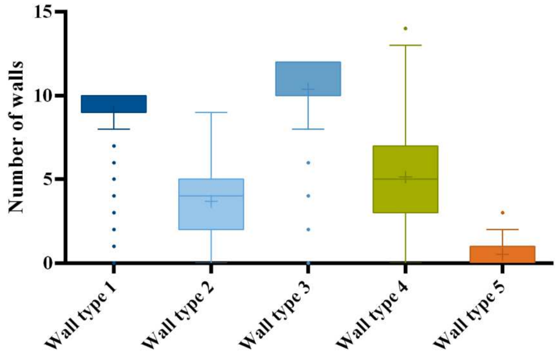


Fig. 9. Boxplot diagram of the intermediate buffer occupancy (number of walls) for each wall type (1-5) to validate the simulation model

Finally, the total process lead time and waiting times are calculated, as presented in Table II. The total production lead time is 6.5 days, denoting that a module takes on average 6.5 days from the production of the first butterfly for that module and until the final module leaves the plant. In this case, the waiting time includes both waiting in the intermediate buffer and in the concreting station, totaling 2.7 days.

TABLE II. VALIDATED VALUES FOR THE REFERENCE MODEL

Validation values	
Average production lead time	*Average waiting time*
6.5 days	2.7 days

Throughput analysis of the number of modules produced per day was presented to middle management to validate the entire simulation model. The number of modules produced in the reference model equaled the duration of the shift divided by the cycle time and is used relatively for comparison in the next section. Ultimately, the model was validated by the middle management and serves as a reference model for the following sections.

SCENARIO I: DOUBLING THE PRODUCTION CAPACITY OF THE CONCRETING STATION

The concreting station is simulated to work at full capacity in the production scaling experiment to see how the plant copes with increasingly large projects. The capacity increase for the concreting station and the shift to a two-shift pattern is implemented in Plant Simulation to evaluate its effects on production lead and waiting times and module throughput. Table III shows average production lead and waiting times and module throughput compared to the reference model performance.

TABLE III. VALUES FOR THE UPSCALED MODEL

Upscaled model vs. Reference model		
Average production lead time	*Average waiting time*	*Throughput*
-29 %	-19 %	+57 %

The production lead time is reduced to 4.6 days (29 % reduction), due to the change to a double-shift pattern. Consequently, the average waiting time is also reduced by 19 %. Furthermore, due to the capacity increase, the module throughput is increased by 57 % modules per day, demonstrating that the production plant can deal with increasing demand in the modular housing sector by producing modules faster and leaner.

SCENARIO II: INVENTORY REDUCTION

In the inventory reduction experiment, the optimal number of butterflies in the system is analyzed. Inventory as a source of waste as defined by Ohno [38], is reduced, thus also cutting production lead and waiting times. The experiments and results are only focused on the production performance and do not consider any economic considerations, e.g., workers' wages, revenues, or energy costs.

Figure 10 shows this analysis for the validated previously reference model. The average production lead time and waiting time as a function of the number of butterflies is depicted in the primary vertical axis. The secondary vertical axis is the percentage idle time for Station 1 of the shell construction line. This metric is an indicator of the continuous flow of the shell construction line and is incorporated in the analysis after consultation with the middle management. An idle time of zero percent indicates continuous flow, whereas an idle time above zero signifies a disruption of the flow.

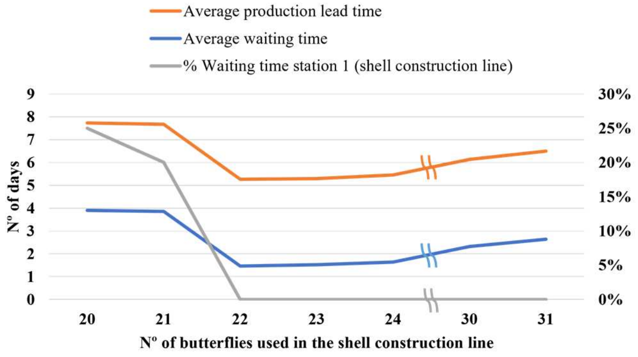


Fig. 10. Primary vertical axis: Average production lead and waiting time of the shell construction and concreting process in days, according to the number of butterflies used. Secondary vertical axis: Percentage of idle time in station 1 of the shell construction line as a function of the number of butterflies used.

Consequently, the objective is not only to minimize the waiting time but also to keep the percentage of idle time at Station 1 at zero percent, indicating continuous flow. This objective is achieved at 22 butterflies, where the idle time is 10 % and the waiting time is minimized at 1.5 days. By setting the number of butterflies at 22, the inventory of this scenario is plotted and compared to the reference model inventory in Figure 7 (orange line). The development pattern of the inventory is equivalent in both states; nevertheless, the inventory median is reduced from 14 to 5, a 64 % reduction, with a corresponding peak reduction from 20 to 11.

These optimization scenarios show substantial improvement in terms of median inventory, with a 64 % inventory reduction in the reference model, demonstrating the effectiveness of the butterfly analysis. Reducing unnecessary inventory makes the production process leaner and reduces the production lead and waiting times, providing a capability to respond faster to customer demands. As stated by Rother and Shook [33], the shorter the production lead time, the shorter is the time between paying for material supplies and getting paid for products made from those materials.

Therefore, it can be concluded that both scenarios represent substantial improvements in almost every metric, demonstrating the benefits of using DES for optimizing the production plant.

SCENARIO III: DIGITAL TWIN-BOTTLENECK ANALYSIS USING RFID DATA

Finally, the objective was to use the RFID data as an input for the DES model, following the presented DT framework in Figure 2. However, as previously mentioned, the data collection of the RFID trackers was problematic throughout the entire research study, mainly due to loss of trackers in the measuring process and a need for manual data update because of limited storage space, which complicated the integration of the data in the DES model. Thus, the DES model is manually updated to perform quantitative bottleneck analysis, and real-time data integration is limited to a qualitative assessment.

The double-wall processing time is set to two hours in the validated reference model. Nevertheless, expert interviews on-site and the little data gathered in the RFID experiment in Table I showed that the real processing time might fluctuate strongly, disrupting the production flow. Therefore, different processing times are simulated, and the results are plotted in the workload diagram displayed in Figure 11, which shows that a wide distribution of the double-wall processing time may indeed disrupt production.

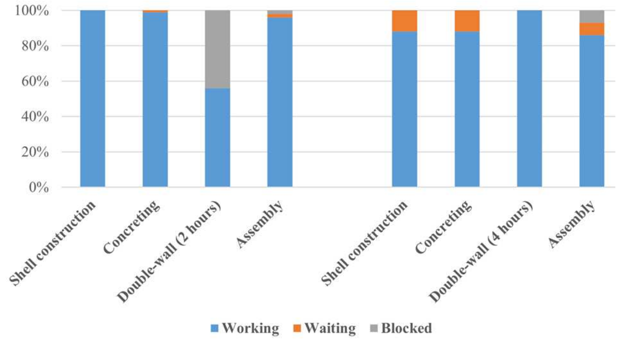


Fig. 11. Workload diagram for the four main production processes: shell construction, concreting, double-wall and assembly. The diagram is plotted for two different processing times for the double-wall station: 2 hours (left, reference model) and 4 hours (right, bottleneck scenario).

With a production time between three and four hours, the double-wall becomes the bottleneck of the system, delaying the entire production, thus making the double-wall an ideal candidate for real-time data integration. Being able to rely on real-time data provided by RFID trackers to predict the future state of the station can side-step critical flow disruptions. Chriti [15] and Schneller [14] conducted the same possibilities when showing the upsides of implementing RFID technology in the construction sector.

Besides, by integrating the real-time process data into the simulation, the model can update the production schedule automatically achieving a bidirectional data exchange between the simulation model and the physical system [39].

Thus, implementing a DT increases the robustness of the entire production system in terms of the variability of the double-wall stations' process time. This idea is corroborated by Parrot and Warshaw, who also identified the ability to predict the future state of an object and early anomalies detection as the main advantage of a DT application [40].

V. CONCLUSIONS

The DT framework has been used in a modular housing production plant using a x-VSM as a conceptual model, RFID for real-time data collection and DES for simulation. Even though a DT has not been implemented because of several problems with RFID data, relevant insights have been gathered in each of the intermediate steps.

A DES model of the production plant has been successfully implemented in Plant Simulation. During this process, x-VSM - as a Lean technique - has been used effectively as a conceptual model for the simulation. The resulting simulation model has shown itself to be a useful decision-support tool for middle management to quantitatively assess the different scenarios. Three experiments have been simulated and different performance indicators have been used to track improvements. The results of this assessment include a potential 53 % increase in throughput, a 64 % inventory reduction, and a bottleneck analysis of the double-wall what demonstrates the benefits of implementing DES in a modular building plant.

The bottleneck analysis also served to identify the double-wall station as a suitable candidate for implementing RFID technology. The analysis shows that using a bidirectional data exchange between the plant and the model to manage the production schedule enabling a predictive control of the system's bottleneck. However, the experiment for gathering real-time data failed due to lack of resources and the loss of trackers.

As a perspective for further research projects, guidance is given on using Bluetooth technology combined with a more robust experiment setup. This setup prepares the ground for real-time data integration into the DES model to create a DT of the double-wall station. This DT then marks an important step before creating a DT for the entire production plant.

ACKNOWLEDGEMENT

This research was funded by the German Federal Ministry of Education and Research within the "Building 4.0." research project.

REFERENCES

[1] maxmodul, "The room module - an industrial building system," [Online]. Available: https://www.maxmodul.de/en/maxmodul/room-module (accessed: Jan. 29 2022).

[2] W. Pan and C. Goodier, "House-Building Business Models and Off-Site Construction Take-Up," Journal of Architectural Engineering, vol. 18, no. 2, pp. 84–93, 2012, doi: 10.1061/(ASCE)AE.1943-5568.0000058.

[3] X. Zhai, R. Reed, and A. Mills, "Factors impeding the offsite production of housing construction in China: an investigation of current practice," Construction Management and Economics, vol. 32, 1-2, pp. 40–52, 2014, doi: 10.1080/01446193.2013.787491.

[4] N. Lu and R. W. Liska, "Designers' and General Contractors' Perceptions of Offsite Construction Techniques in the United State Construction Industry," International Journal of Construction Education and Research, vol. 4, no. 3, pp. 177–188, 2008, doi: 10.1080/15578770802494565.

[5] F. Correa, "Integrating Industry 4.0 Associated Technologies into Automated and Traditional Construction," in Proceedings of the 37th International Symposium on Automation and Robotics in Construction (ISARC), Kitakyushu, Japan, 2020.

[6] B. García de Soto, I. Agustí-Juan, S. Joss, and J. Hunhevicz, "Implications of Construction 4.0 to the workforce and organizational structures," International Journal of Construction Management, 2019, doi: 10.1080/15623599.2019.1616414.

[7] M. El Jazzar, C. Schranz, H. Urban, H. Nassereddine, "Construction 4.0: The 4th Generation Revolution, 2017," Frontiers in Built Environment, vol. 7, 2021, doi: 10.3389/fbuil.2021.671408.

[8] R. Sacks, I. Brilakis, E. Pikas, H. S. Xie, and M. Girolami, "Construction with digital twin information systems," DCE, vol. 1, 2020, doi: 10.1017/dce.2020.16.

[9] McKinsey & Company, "Modular construction: From projects to products," 2019. [Online]. Available: https://www.mckinsey.com/business-functions/operations/our-insights/modular-construction-from-projects-to-products (accessed: May 04 2022).

[10] J. Erikshammar, W. Lu, L. Stehn, and T. Olofsson, "Discrete event simulation enhanced value stream mapping: an industrialized construction case study," Lean Construction Journal, vol. 10, pp. 47–65, 2013. [Online]. Available: http://www.leanconstruction.org/lcj/journal-papers/2013-issue (accessed 04 May 2022)

[11] C. Danjou et al., "Industry 4.0 in Construction Site Logistics: A Comparative Analysis of Research and Practice," The Journal of Modern Project Management, vol. 7, no. 4, 2020.

[12] F. Leite, Y.K. Cho, A.H. Behzadan, and S. Lee, "Visualization, Information Modeling, and Simulation: Grand Challenges in the Construction Industry," Journal of Computing in Civil Engineering, vol. 30, no. 6, p. 4016035, 2016, doi: 10.1061/(ASCE)CP.1943-5487.0000604.

[13] W. Krieger, Informationsmanagement in der Logistik [Information management in logistics]. Wiesbaden, Germany: Gabler Verlag, 1995.

[14] M. Schneller, Modell zur Verbesserung der Lebensarbeitsgestaltung von Baustellen-Führungskräften [Model for the improvement of the life work organization of construction site executives]. Wiesbaden, Germany: Springer Fachmedien Wiesbaden, 2015.

[15] M. Chriti, "Aufnahme des zeitlichen Arbeitsaufwandes und Ermittlung von Stundenaufwandswerten des technischen Führungspersonals bei Bauvorhaben im Bereich Tiefbau/Infrastrukturbau [Recording of the time spent on work and determination of hourly expenditure values of the technical management personnel in construction projects in the field of civil engineering/infrastructure construction]," Dissertation. Wien, Austria: Technical University of Wien, 2015.

[16] S. Y. Yin, H. P. Tserng, J. C. Wang, and S. C. Tsai, "Developing a precast production management system using RFID technology," Automation in Construction, vol. 18, no. 5, pp. 677–691, 2009, doi: 10.1016/J.AUTCON.2009.02.004.

[17] M. S. Altaf, H. Liu, M. Al-Hussein, and H. Yu, "Online simulation modeling of prefabricated wall panel production using RFID system," in Online simulation modeling of prefabricated wall panel production using RFID system, Huntington Beach, CA, USA, 2015, pp. 3379–3390.

[18] S. Bait, A. Di Pietro, and M. M. Schiraldi, "Waste Reduction in Production Processes through Simulation and VSM," Sustainability, vol. 12, no. 8, p. 3291, 2020, doi: 10.3390/su12083291.

[19] I. D. Tommelein and S. N. Tucker, "Discrete-Event Simulation of Lean Construction Processes," in 5th Annual Conference of the International Group for Lean Construction, 1997. [Online]. Available: http://www.iglc.net/papers/details/25 (accessed: May 04 2022).

[20] W. Xia and J. Sun, "Simulation guided value stream mapping and lean improvement: A case study of a tubular machining facility," JIEM, vol. 6, no. 2, 2013, doi: 10.3926/jiem.532.

[21] J. S. Goulding, F. Pour Rahimian, M. Arif, and M. D. Sharp, “New offsite production and business models in construction: priorities for the future research agenda,” Architectural Engineering and Design Management, vol. 11, no. 3, pp. 163–184, 2015, doi: 10.1080/17452007.2014.891501.

[22] M. Afifi, M. Al-Hussein, S. Abourizk, A. Fotouh, and A. Bouferguene, “Discrete and Continuous Simulation Approach to Optimize the Productivity of Modular Construction Element,” in Proceedings of the 33rd International Symposium on Automation and Robotics in Construction (ISARC). Auburn, AL, USA, 2016.

[23] W. Lu, T. Olofsson, and A. Segersted, Eds., “Application of discrete event simulation and CONWIP on inventory control,” in Proceedings of the CIB W78 2010. Cairo, Egypt: 27th International Conference, 16-18 November 2010.

[24] M. A. Abdelmegid, V. A. González, M. Poshdar, M. O’Sullivan, C. G. Walker, and F. Ying, “Barriers to adopting simulation modelling in construction industry,” Automation in Construction, vol. 111, p. 103046, 2020, doi: 10.1016/j.autcon.2019.103046.

[25] S. Mostafa, N. Chileshe, and T. Abdelhamid, “Lean and agile integration within offsite construction using discrete event simulation,” CI, vol. 16, no. 4, pp. 483–525, 2016, doi: 10.1108/CI-09-2014-0043.

[26] J. Trauer, S. Schweigert-Recksiek, C. Engel, K. Spreitzer, and M. Zimmermann, “What is a digital twin? Definitions and insights from an industrial case study in technical product development,” in Proceedings of the Design Society: DESIGN Conference , vol. 1, pp. 757 – 766, 2020, doi: https://doi.org/10.1017/dsd.2020.15.

[27] A. Fuller, Z. Fan, C. Day, and C. Barlow, “Digital Twin: Enabling Technologies, Challenges and Open Research,” IEEE Access, vol. 8, pp. 108952–108971, 2020, doi: 10.1109/ACCESS.2020.2998358.

[28] B. Schleich, N. Anwer, L. Mathieu, and S. Wartzack, “Shaping the digital twin for design and production engineering,” CIRP Annals, vol. 66, no. 1, pp. 141–144, 2017, doi: 10.1016/j.cirp.2017.04.040.

[29] T. DebRoy, W. Zhang, J. Turner, and S. S. Babu, “Building digital twins of 3D printing machines,” Scripta Materialia, vol. 135, pp. 119–124, 2017, doi: 10.1016/j.scriptamat.2016.12.005.

[30] H. Feng, Q. Chen, and B. Garcia de Soto, “Application of digital twin technologies in construction: an overview of opportunities and challenges,” in Proceedings of the 38th International Symposium on Automation and Robotics in Construction (ISARC). Dubai, UAE, 2021.

[31] J. Rodriguez Llorens, Holistic Optimization of a Modular Building Production Plant using Discrete-Event Simulation. Master’s Thesis. Munich, Germany: Technical University of Munich, 2021.

[32] A. Fischer, M. Liang, V. Orschlet, H. Bi, S. Kessler, and J. Fottner, “Detecting Equipment Activities by Using Machine Learning Algorithms,” in 17th IFAC Symposium on Information Control Problems in Manufacturing, 2021.

[33] M. Rother, J. Shook, and J. Womack, Learning to see: Value-stream mapping to create value and eliminate muda, 20th ed. Boston: The Lean Enterprise Institute, 1999.

[34] F. A. Abdulmalek and J. Rajgopal, “Analyzing the benefits of lean manufacturing and value stream mapping via simulation: A process sector case study,” International Journal of Production Economics, vol. 107, no. 1, pp. 223–236, 2007, doi: 10.1016/j.ijpe.2006.09.009.

[35] A.J. Donatelli and G.A, Harris, “Combining Value Stream Mapping and Discrete Event Simulation,” in Proceedings of the Huntsville Simulation Conference, 2001.

[36] W. A. Günthner and Borrmann A., Eds., Digitale Baustelle - innovativer Planen, effizienter Ausführen. Werkzeuge und Methoden für das Bauen im 21. Jahrhundert [Digital construction site - more innovative planning, more efficient execution. Tools and methods for construction in the 21st century]. Heidelberg, Germany: Springer Verlag, 2011.

[37] T. Kudlich, Optimierung von Materialflußsystemen mit Hilfe der Ablaufsimulation [Optimization of material flow systems with the help of flow simulation]. Dissertation. Munich, Germany: Technical University of Munich, 2000.

[38] T. Ohno, Toyota production system: Beyond large-scale production. Cambridge Mass: Productivity Press, 1988.

[39] L. Yilmaz, W. Chan, I. Moon, t. Roeder, C. Macal, and M. Rossetti, Eds., “Online simulation modeling of prefabricated wall panel production using RFID system,” in IEEE, 2015.

[40] A. Parrott and L. Warshaw, “Industry 4.0 and the digital twin. Manufacturing meets its match,” 2017. [Online]. Available: https://www2.deloitte.com/us/en/insights/focus/industry-4-0/digital-twin-technology-smart-factory.html (accessed: May 04 2022)