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OPTIMIZING THE AUTOMATION IN CONSTRUCTION SITE LOGISTICS: PROBLEMS AND PROPSED MODELL LIBRARY FOR MATERIALS FLOW SIMULATION

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ABSTRACT

The construction industry is currently facing challenges such as skilled labor shortages, limited automation, and inadequate digitalization, particularly for small and medium-sized enterprises (SME), amidst rising interest rates and decreasing subsidies for builders. To address these challenges, a simulation model library for construction is being established. The Plant Simulation System is used to map construction site systems with various model components, enabling digital simulation of the environment and supply chains. Customized simulation parameters are used to simulate specific construction requirements. This paper describes the use of masonry robots and transportation in wall and floor construction and their impact on site performance. The simulation model library REMUS is important for digitalizing construction sites, allowing for the assessment of innovative systems before construction and estimation of investment returns. Simulations can be used to evaluate investments and future concepts.

1 INTRODUCTION

The construction industry is a significant economic factor in Germany, accounting for 6% of the overall gross value added in 2023. Notably, a high proportion of SMEs operate within the industry, with only 13.1% of companies employing more than 200 individuals in 2022. Since 2009, the number of employees in the construction industry has continuously increased and currently stands at 928 thousand (KfW 2024; Statista 2022).

The construction industry is expected to face a significant shortage of skilled workers in the coming years. This shortage is likely to result in wage increases, project delays, increased construction costs, and reduced profitability. Additionally, rising interest rates will make it more challenging to finance construction projects (DIW Berlin 2023; KfW 2024; Statista 2024).

SMEs are particularly vulnerable to cost and efficiency pressures and must focus on maintaining competitiveness. As with other industries, the construction sector is increasingly pressured to streamline its processes. Despite the prevalence of manual labor, automation is not yet common in construction, unlike in other fields. In Germany, SMEs in building and solid construction have not yet established connections with automation system providers.

There is still a lack of comprehensive digitization and networking, even on construction sites (Schrage et al. 2023). Experience from other sectors has shown that SMEs, in particular, can benefit greatly from digitalization and automation processes. Therefore, companies in the construction industry could also increase their competitiveness through digitalization. According to recent studies, the digitization of the construction industry is important to increase its productivity (Infra-Bau 2023; PricewaterhouseCoopers 2024).

This publication presents the REMUS simulation model library, which includes components for automated construction sites. These components facilitate the quick setup of a simulation model, taking into account typical framework conditions. As a result, various simulation experiments can be conducted before and during the construction phase to optimize supply chains.

2 CONSTRUCTION SITE SIMULATION – STATUS AND CHALLENGES

Experienced employees currently oversee control and processes on construction sites. However, digital and automated applications are not yet widely available. A continuous exchange of data and information is essential for efficient construction processes (Infra-Bau 2023; PricewaterhouseCoopers 2024).
It is crucial for the future of the construction industry to embrace digitalization. CAD systems can support design, while Building Information Modeling (BIM) can facilitate networked planning, construction, and management. However, optimizing supply chains to improve processes is often limited to specific applications (Scherer and Schapke 2014a; Scherer and Schapke 2014b).
Process simulations allow concepts, systems and material flows to be tested at a very early planning stage. They are a widely used tool in industry. Software systems with model libraries are available that allow simulation experts to quickly create simulation models (Wenzel 2018).
These Simulations are seldom utilized in construction due to a lack of knowledge and time to set up meaningful models and carry out simulation studies. Constructing a simulation model for construction sites and conducting simulation studies can be challenging for companies in the construction industry due to the lack of resources and application knowledge. Model modules and libraries are often taken from industrial applications and may not comprehensively represent the specific requirements of the construction site (Donhauser 2020).

Additionally, acquiring a simulation tool can be a costly investment, and it requires employee training. In the future, process simulation of supply chains will be used on the construction site. For this purpose, a simulation model library REMUS with standardized model components will be created and made available. This will make it possible to simulate, analyze and optimize workflows and processes on the construction site. The model components facilitate and accelerate the model structure.

2.1 Initial Situation

The construction industry is undergoing structural change due to a number of factors, including a shortage of skilled labor, fluctuating demand for commercial real estate, a backlog of investment in social housing, and rising interest rates (Statista 2022, 2024; Statistisches Bundesamt 2019). Quick responses are needed to adapt to the changing demand for real estate, especially in the private sector. Investments that were made during the boom years without proper scrutiny must now be reviewed and assessed for profitability before being approved. For companies in the construction industry, conducting simulation studies and managing construction sites can be challenging. There is a cost associated with the simulation system. The creation of simulation models is currently poorly supported. Basic components are available that need to be modified and customized with control strategies. This requires extensive knowledge and the use of simulation experts. Close coordination between design experts and simulation experts determines the success of the simulation study. Model libraries, such as those that exist for specific industrial applications, support, and accelerate model development.

Therefore, the REMUS simulation model library is to be developed for mapping the construction site in simulation models for logistics and supply chain simulation. It should contain components of an automated construction site environment. These model components should be flexibly adaptable to the circumstances. It should be possible to map requirement clusters. It should be easy to use and extendable.

2.2 Automation in the Construction Industry

SMEs face significant cost and efficiency pressures. To remain competitive, they must identify potential savings and adapt to new technologies. Automation is a proven method for generating cost savings and improving efficiency. The construction industry can benefit from approaches, processes, and systems that have been successful in the manufacturing industry (BauMaster 2024; Infra-Bau 2023). Digitalization and automation processes can be particularly advantageous for medium-sized companies, as demonstrated by other industries (Infra-Bau 2023). Robot use in the construction industry is being extensively researched in the USA and Japan, in addition to Germany. Japan is driving forward digitalization and robotization projects in building construction with the participation of construction companies, manufacturers, research institutes, and government authorities. If Germany wants to maintain its digital expertise, it must conduct appropriate research in this area (BWI-Bau 2013).

2.3 Challenges

The goal of the RoMuLuS project is to develop an autonomous system for the construction of wall segments that can independently produce the masonry of a floor. For this purpose, the necessary information from the CAD system and BIM will be transferred to different actors. They organize the site equipment with all machines and components. It is important to organize the processes on the construction site. This includes adapting the supply chain and logistics processes, which must be dimensioned, checked and optimized in advance using simulations. The corresponding model components are to be made available in a simulation model library. These are different automated masonry systems, transport vehicles, storage and transfer areas. The construction site environment is characterized by variable environmental factors such as uneven terrain, delays, and weather conditions. These should disrupt the optimal logistics process in the digital model. Corresponding effects, impacts and resulting response options are to be mapped and response options are to be determined. The library is specifically focused on automated masonry robots their system components and requirements.

2.4 Masonry Robots on the Construction Site

High-precision robotic systems have been utilized and developed in the industry for a significant period. The use of these systems in SMEs has become more prevalent due to the decrease in prices for industrial robots over the last decade, which has facilitated technology transfer.

In the context of using robotic systems in structural engineering, various application scenarios can be distinguished. In production halls, segments for wooden houses are already being prefabricated fully automatically and assembled on-site (Hartmann and Galandi 2020; MaschinenMarkt 2022). The Construction Factories system comprises various robot systems designed to automate different construction tasks (Bock and Linner 2016). A robot designed for wire pulling shows potential for automating significant portions of the masonry building construction process (Figure 1-1) (Mattern et al. 2016). Contour Crafting utilizes an extrusion process similar to 3D printing to construct building geometries from cement (Figure 1-2) (Deutsche Bauzeitung 2021). The SAM-Semi-Automated Masonry wall system comprises a conveying technology and a mobile robotic arm (Figure 1-3) (Construction Robotics 2021). Masonry construction on-site has the potential to personalize and automate logistical processes. The masonry robot HADRIAN X constructs structures on-site from a truck's loading area (Figure 1-4) (FBR 2023). The BauBot is a mobile and remotely controlled robot capable of performing various operations, including gripping, drilling, painting, welding, and 3D printing (Figure 1-5) (Baubot 2024).

Figure 1: Various robotics systems for construction sites

2.5 Digital Representation

In the past, the construction industry was slower to adopt new technologies compared to other sectors. However, recently there has been a shift towards digital transformation, and the construction industry has been quick to grasp the opportunities and benefits of new technologies in the pre-construction, construction, and facility management phases. These digital technologies are intended to strengthen established business processes by integrating state-of-the-art technologies (Scherer and Schapke 2014b; Scherer and Schapke 2014a).

The current research focus is on BIM, which should be utilized in all construction product phases to map and support the entire life cycle. Digital twins have gained a lot of attention in the construction industry for their ability to improve safety, assess project risks, and facilitate collaboration between stakeholders. Digital transformation is having a profound impact on the pre-construction, construction, and facility management sectors and is currently under intense scrutiny (Naji et al. 2024).

A specific BIM application example presents the use of discrete-event simulation in construction site logistics. The planning is based on BIM, resulting in a 4D BIM model that includes project-specific information, geometry data, deadlines, costs, and properties. The use of simulation to validate planning scenarios and check restrictions and sequences is described. The simulation model, based on AnyLogic, is utilized to control construction site logistics and determine performance data for material flow and storage technology in advance. While more extensive planning of logistics processes on the construction site is not yet possible, this approach allows for efficient and effective planning (Stolipin et al. 2020).

As part of the Mefisto research project, a BIM-based management system was developed to handle construction projects. The system includes a digital simulation of construction site set-up and operation, allowing for movement analyses, collision checks, space requirements, and transport routes to be mapped (Scherer and Schapke 2014a).

The building block box SimBauLog is a component of the Tecnomatix Plant Simulation software, developed as part of the Mefisto research project. It contains geometric elements of building models, bills of quantities, schedule models, and other relevant information. The simulation allows for the modelling of construction site processes, enabling the comparison and evaluation of logistical concepts, strategy variants, and construction methods (Plant Simulation 2022).

2.6 Problem Definition

VDI Guideline 3633 defines simulation as the reproduction of a system's dynamic processes in an experimental model to obtain findings that can be applied to reality (VDI 3633 Bl.1 2014). Material flow simulation provides the opportunity to map logistical processes, depict various scenarios, analyze their behavior, and carry out optimizations. Simulations have been widely used in industry and trade to test plans and concepts for new production and logistics systems, and to evaluate modifications if necessary (Gutenschwager et al. 2017).

These simulations are not commonly used in construction, especially for representing supply chain processes, which are complex due to the lack of standardized model components (Borrmann et al. 2011). Small and medium-sized enterprises (SMEs) often lack the resources to purchase simulation systems or employ simulation experts (Wenzel 2018).

The objective of this paper is to create a simulation of an autonomous system for erecting wall segments. The model should focus on adapting logistical processes. The simulation should represent the automated production of a complete masonry floor using JIS bricks of the correct type and dimensions delivered to the masonry robot. The supply chain of building materials should be represented using various innovative means of transportation. The necessary materials, including connecting material and bricks, are readily available in supermarkets and are supplied flexibly. Logistical entities, such as drones, AGVs, and autonomous tugger trains, pick up the materials and bring them together in the correct sequence for the robot. This reduces the mass that the robot needs to move and optimizes the space required on the construction site.

The construction site processes will be realistically mapped using a simulation model based on Tecnomatix Plant Simulation. Activity-oriented simulations will be conducted, which are discrete in nature. A change of state of model components requires a certain period of time. It is characterized by a start event (VDI 3633 2018).

The simulation model includes basic modules for mapping material and information flow, resources, and movable material flow objects. These modules can be specified more precisely using attributes. Predefined or individual methods can be used to adapt the behavior of the components to the construction site environment and its requirements.

These model components are combined to create simulation models that depict various construction site scenarios. It is crucial to precisely determine the degree of abstraction to create an image of the real system with reduced complexity. This improves understanding of the system while reducing the effort required for data collection and runtime. In addition to modeling, defining the simulation parameters is also necessary. In industrial environments, it is important to consider processing times, malfunction times, and cycle times, as well as set-up processes and malfunctions. In construction site environments, it is necessary to take into account additional exogenous parameters. The model should integrate alternative system components, and the resulting scenarios should be evaluated through various simulation experiments. This will lead to a better understanding of the processes and procedures on the construction site.

As part of the RoMuLuS research project, the exact planning of the masonry and the derivation of the required bricks will be carried out. This is crucial for a demand-oriented supply of the construction site. The simulated development of a material supply concept makes it possible to determine the number and sequence of bricks required, as well as the need for partial bricks. A material flow simulation can define optimal processes for the use of one or more robots, taking into account the limited mobility of the robot. The transport devices and their transport frequency are also taken into account. Simulation-based investigations can be used to efficiently identify potential strengths and weaknesses of the supply concepts in order to design the system for the preferred variant at an early stage.

3 SIMULATION

The simulation system Plant Simulation from SimPlan AG is used for the simulation in the construction site environment. Plant Simulation is a standard software used to simulate logistics and production processes as well as business processes (Plant Simulation 2023).

3.1 Simulation Model Library REMUS

A simulation model library named REMUS is being created for simulation studies in construction (Figure 2). It includes model elements that represent specific components on the construction site. These elements can be flexibly adapted and expanded. The model modules are designed to be abstract and parameterizable.

The simulation model library contains various model elements for mapping the operational level in a later simulation model of the construction site. The operational level is represented by modules and objects. Modules are categorized into physical and logical ones, while objects are classified into physical objects and information objects. In the simulation model library REMUS, the physical modules are further divided into stationary and mobile modules.

Stationary modules execute an object change and consume time (VDI 3633 Bl.1 2014). The model library includes masonry walls, material supply, a construction crane, stone storage, stone supermarkets, the source of loaded stone pallets, and a sink for empty pallets.

Mobile modules can cause a change in location or position (VDI 3633 Bl.1 2014). The masonry robot is stored in various variants in this area, along with the conveyor systems. The stone transporter, forklift, and truck are provided, along with **logical modules** for controlling processes, system states, and framework conditions. These modules include robot movement, transport control, and load sensors.

Objects can be **physical** or **informational**, such as the various variants of stones and the orderly provided stone pallets.

The **information objects** for this task include the work plan, environment, framework, energy, and maintenance.

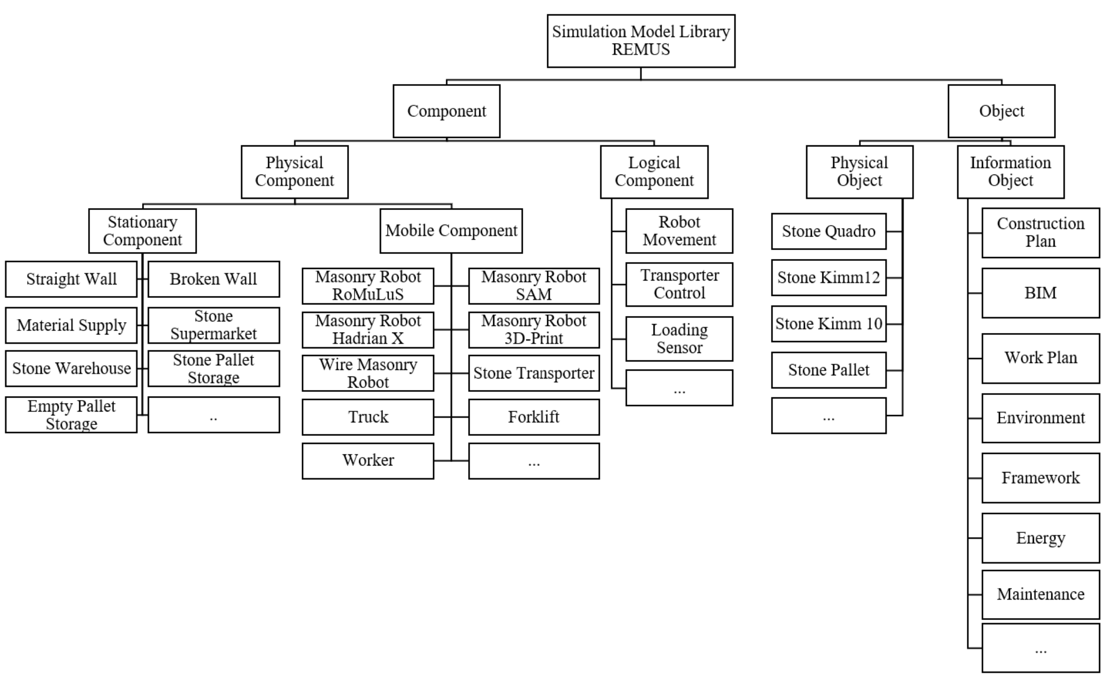

Figure 2: Simulation model library REMUS

3.2 Framework Conditions

The simulation components are utilized to configure simulation models for construction sites. Prior to creating the simulation model and conducting the simulation experiment, a requirement cluster is established with the key parameters of the construction sites. These parameters should be variably selectable in the simulation experiments. The implementation is based on relevant standards or guidelines, as long as they are available or can be transferred from similar areas or applications. The information objects for this task include the work plan, environment, weather, energy, and maintenance.

Environment and Location: Construction sites present various conditions. The transportation vehicles operate in unpredictable and constantly changing environments, requiring resilience to weather and resistance to temperature fluctuations (ISO 20653 2023). The representation is achieved through simulation technology, which includes disturbances and maintenance times. The simulation system enables the integration of flexible disruption events, such as heavy rain, snow/ice, and temperature peaks, which are configured here for representation.

Technological Requirements: Environment perception occurs through sensors, and interactions with environmental factors must be taken into account. This fragment describes the importance of adaptability to light conditions through advanced imaging and detection technologies, as well as the necessity for precise localization systems that can adaptively adjust to constantly changing environments. Additionally, intelligent control systems are deemed essential for autonomous operations.

Safety: To ensure safe human-machine collaboration, it is necessary to establish secure working practices. This involves integrating safety mechanisms for accident prevention based on the Austrian Carta for construction site safety (AUVA 2024). These mechanisms include physical emergency stop switches or protection against unauthorized access, as well as safety protocols, instructions, and orientations. The digitalization of construction sites also requires protective measures in data transmission to prevent unauthorized access and manipulation. Operational security measures must be implemented to secure access to workplaces. It is important to comply with legal and professional regulations for tools and auxiliary equipment, such as scaffolding. The use of transportation equipment such as forklifts, cranes, conveyor belts, and grippers requires proper training and orientation, as well as adherence to applicable safety measures. It is mandatory to wear or use general and personal protective devices in hazardous areas, and to secure fall edges and floor openings. The corresponding road traffic regulations and guidelines must be followed to meet the requirements (IEC 61508-1 2010). Currently, safety devices for worker protection are not included in the simulation of a fully automated construction site. The assumption is that no workers are present in areas where machines are operating. If necessary, constraints should be added to represent the presence of workers.

Integration and Flexibility: The aim is to consistently integrate existing construction processes and systems. Model use cases should be easily transferable to a wide variety of construction projects. Standardization of interfaces between systems and the use of common data formats for exchange is recommended. The simulation system provides functionalities to transfer data from other systems, including text files, object files, and Excel tables.

Energy and operating time: Efficient energy supply and utilization of the construction site must be ensured, including the use of autonomous power sources. Long-term operational capability for extended construction projects should be considered during the project planning stage. Performance data for the machines in different operating states is specified in the simulation components and can be evaluated. Additionally, the transition times between different operating states are recorded and evaluated over time.

Material and tool handling: Ergonomic principles should be considered on the construction site, particularly in avoiding heavy physical and static muscle work and ensuring ergonomic tool design. The impact of uneven terrain can be addressed in process simulation by reducing travel speeds and increasing disruptions. Poor ergonomic design of workstations can result in longer downtimes and reduced working speeds for workers.

Maintenance and repair: Wear and damage caused by environmental influences and working conditions require preventive maintenance and servicing of all components. This applies in particular to highly automated devices. For maintenance and repairs, these are transferred to an easily accessible environment. Maintenance can be specified individually in the simulation components with intervals and durations (in the faults tab). Planned maintenance can be calculated with fixed intervals depending on the operating time. Repairs are initiated randomly with varying probabilities and durations. This data is recorded during simulation experiments for evaluation.

Regulatory compliance: A construction site must comply with various regulations and safety standards, which are mandatory. Automated devices must also comply with the assigned regulations of the construction site; otherwise, they may be shut down. Control systems can be used to map out the regulations. Restrictions can be specified to stop robot movements when workers enter the work area or similar.

Communication and collaboration: Communication interfaces between operators, supervisors, and automated devices must be designed with care and robustness due to the potential for danger. A fail-safe for wireless communication and defined rest positions in the event of system faults should be included. System faults can be set via the settings on the components. Depending on the occurrence, the device can be programmed to stop or move to certain positions, which are then used as the starting position for subsequent activities.

Costs and profitability: From a business perspective, it is important to monitor the costs and profitability of automation projects. Only solutions that guarantee profitability in the foreseeable future are viable. The module description specifies costs for individual simulation components, including investment costs, depreciation period, and operating costs. This allows for the determination of corresponding costs for individual time types. This enables the calculation of the profitability of both the entire system and its individual components.

The framework considers the necessary time allocation for faults, repairs, maintenance, and costs. Any limitations based on safety regulations, risk assessments, and other factors can be addressed through customizable methods.

3.3 Simulation Model

The REMUS model library's model elements can be connected to simulation models based on their internal process logic and logical linking possibilities. The model is parameterized with corresponding data and information. During simulation experiments, the model can be subjected to various scenarios and system loads.

The simulation system implements new simulation models by selecting model components and arranging them according to the assembly structure. Material flows are drawn between the involved components. Controllers and processing strategies must be determined for the affected model components by connecting the controllers, thus adapting the model to the site conditions.

The **verification** phase checks the model creation. The model processes must meet expectations. Animation is utilized to control the logical processes. Therefore, logistical procedures in the loaded and unloaded model are simulated. The behavior should depend on the system parameters (VDI 3633 Bl.1 2014).

During the **validation** process, the relationship between the model and reality is examined. If necessary, the model must be refined if abstraction is not permissible. This is accomplished by comparing the input/output data with the actual operating data. In the case of a new, planned system, expert discussions are used for this purpose. The quality of the model significantly impacts the results and, therefore, the planned system (VDI 3633 Bl.1 2014).

3.4 Simulation Experiments

The simulation experiment depicts the construction of a straight masonry wall of a predetermined height (Figure 3). The simulation model includes the following simulation elements: Stationary building blocks include masonry walls, material supply, and stone storage. The mobile building blocks consist of a masonry robot, stone transporter, truck, and forklift. Logical building blocks are implemented for controlling the physical building blocks. The physical objects listed are Quadro stone, Kimm12 stone, Kimm10 stone, and stone palette. Various information objects are required to integrate the framework conditions.

The bricks required for construction are delivered to the site by a truck according to a pre-defined delivery schedule. The delivery plan specifies the delivery time and the loading scheme of the stone pallets, which are loaded in the order of installation. Upon arrival, the truck is unloaded, and the pallets are transported to the stone storage area using a forklift. The pallets are lifted also by a construction crane into a stone storage area in the building, according to a selectable priority regulation. From there, the stone transporter drives the pallets to the delivery place at the robot. The robot then removes the individual stones in the specified order and positions them on the masonry wall. The application of mortar is done through a dipping station on the robot and is currently considered an additional processing time component. The robot operates dynamically at the construction level, creating the wall according to the given criteria.

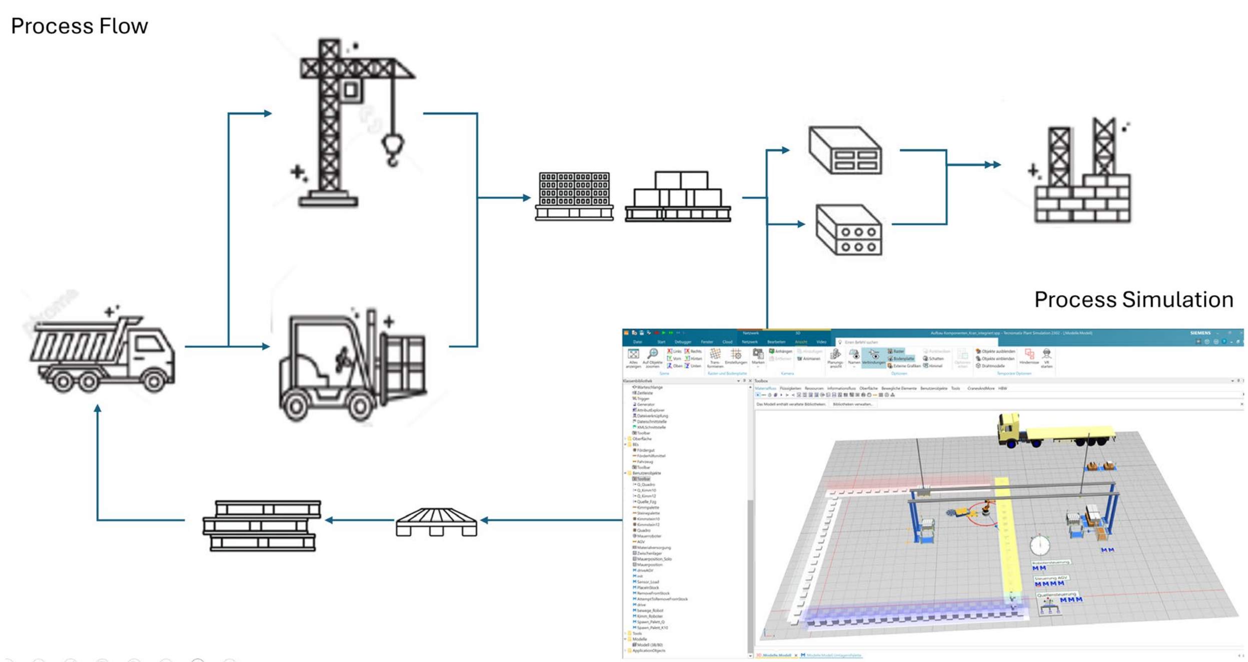

Figure 3: Process flow and simulation model of the construction site

The simulation runs illustrate the basic functionality of the construction site environment. First experiments analyze different supply concepts and their effects on buffer space and supply of construction robots. There is a direct correlation between the delivery frequency and the buffer space required to ensure a consistent supply of goods to the site. In addition, key performance indicators (KPIs) are recorded and evaluated. Costs and assets are linked, and changes can be made by adding additional assets or improving existing ones. In the current application, a bricklaying robot, an automated guided vehicle (AGV) and a truck are sufficient. However, as the wall size increases, additional AGVs are required. The raw material requirement depends primarily on the number of bricklaying robots. After a certain output, the AGVs become a bottleneck and need to be supplemented. The energy consumption and resource use of each system component is evaluated, with low resource use proving to be beneficial for energy efficiency, as the systems operate within an optimal load range. The material used, sand-lime brick, correlates predictably with resource use and performance. Coordinating these models increases output by eliminating waiting times for parts, deliveries, or machine operations. Changes in workload affect overall system performance until bottlenecks occur in various components. Work conditions can lead to unplanned process interruptions and reduced overall performance. Simulation experiments effectively model jobsite processes. KPIs are used to evaluate and assess various aspects, including interdependencies. The REMUS simulation database maps and optimizes key aspects of a future-oriented construction site.

4 RESULTS

The REMUS simulation model library allows for the quick construction of simulation models for construction sites. It enables the direct insertion of significant model components that can be easily parameterized to reflect the construction environment. Component replacement is also possible at a fast pace. This approach provides valuable insights that can be applied to real-life scenarios at an early stage. Simulation components, such as the wall robot, can be easily adapted to various requirement clusters and successively integrated. This library model is crucial in simulating construction project sequences. It encompasses various scenarios and parameters, such as weather, resource availability, and workforce. Virtual tests and optimizations reduce the risks and costs of errors during the construction phase. Different scenarios can be quickly tested to understand the impacts of changes. Overall, the simulation model library improves the efficiency, quality, and profitability of construction projects while enhancing the success and satisfaction of all involved parties.

5 CONCLUSION

The experiments so far demonstrate the functionality of the REMUS simulation model database. Further components need to be added in order to be able to comprehensively model a wide range of topics on the construction site. The introduction of additional KPIs enables the optimization of processes and assets on the construction site. In this way, the economic efficiency of the site environment can be comprehensively examined, evaluated and improved at an early stage.

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