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A COMBINED DIGITAL TWIN AND LOCATION-BASED MANAGEMENT SYSTEM

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ABSTRACT

As the coordination of resources' flow during location-based construction is complex due to limited space and simultaneous movements, management systems have been extended by adding a control stage to handle deviations from the initial schedule. However, a suitable information system has yet to be established. Therefore, a combined digital twin and location-based management system was developed. The digital twin concept relies on continuous, real-time data collection to provide information about the project's status. The combination of both methods facilitates effective, data-based production planning of the resources' flow over time and space. The proposed system offers the ability to proactively manage real-time information for ongoing location-based work through discrete event simulation. For improved understanding among stakeholders, the simulated processes are visualised in a 4D game engine. In an exploratory study, the system's effectiveness was demonstrated by using literature-based changes in productivity rates during the construction of finishing work in a high-rise building. The discrete event simulation results indicate that by ordering reasonable actions in response to construction deviations, a high level of resource efficiency can be maintained. This highlights the importance of using real-time data in location-based construction projects.

KEYWORDS

Digital Twin Construction, Discrete Event Simulation, Location-Based Management System, 4D Process Visualisation.

INTRODUCTION

As many different interacting trades are involved in the construction phase, appropriate coordination before and during the works is essential for successful sequences (Trebbe et al. 2015). A well-organised planning phase, which includes all stakeholders, before the construction start helps to reduce subsequent conflicts. However, during construction, unexpected issues arise, such as delays or disruptions, that lead to process deviations. Process deviations refer to any changes during production that deviate from the initial planned schedule and may cause time-space conflicts on site. During time-space conflicts, at least two activities must be executed simultaneously at the same location, which impedes continuous workflows (Akinci et al. 2002). The location-based management system is an approach used for efficiently planning trades' workflows to avoid clashes between participants. In comparison to previous location-based methods, the location-based management system extends the planning process by a controlling stage during construction. Currently, the control process is enabled by weekly

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planning meetings according to the Last Planner System® (LPS) (Seppänen et al. 2015). However, for efficient planning within weekly meetings and for managing ongoing construction works, reliable information regarding current site conditions and processes are required. Insufficient communication and information exchange among trades is a prevalent issue in current construction practice (Dallasega et al. 2018), which hinders efficient construction work and results in wasted time for staff. The digital twin concept can remedy these shortcomings, as it aims to provide data-based status information in real-time. It is crucial to use the information gained to proactively manage ongoing works through modelling and simulation while considering Lean Construction principles (Jiang et al. 2021). This approach is called digital twin construction (DTC) (Sacks et al. 2020). One essential aspect of digital twins is the appropriate visualisation in an intuitive and understandable manner (Rogagae et al. 2022).

In this paper a combined digital twin and location-based management system was developed (DTLMS) as an advanced method. By integrating DTC, the location-based management system benefits from continuous, real-time information regarding ongoing construction processes. Real-time knowledge can enable data-driven management of trades' workflows and more efficient construction execution. In a previous study, the authors demonstrated how machine learning classification can be used to extract reliable, stochastic activity durations from real-time data and calibrate a discrete event simulation (DES) model (Jungmann et al. 2022). This paper focuses on the usage of gained information in a DES to ensure efficient construction by investigating possible what-if scenarios. To support the planning, a 4D process visualisation tool was added to the system. The simulated construction processes are illustrated in a game engine for improved communication among stakeholders in planning meetings. The paper presents the DTLMS as a business process model and notation (BPMN) and aims to demonstrate efficient project planning according to process deviations in a case study. The paper is structured as follows: The following section presents a theoretical framework of the topics location-based management system, DES, and DTC. Next, the developed DTLMS is described by a BPMN followed by the application of the developed DTLMS approach on a finishing works case study. The final section summarises the findings, limitations, and future research.

THEORETICAL FRAMEWORK

Modelling and simulation is an effective method for supporting construction planning and control (Altaf et al. 2018) by efficiently testing different scenarios and their estimated impacts. DES has proven its usefulness in supporting the decision-making process in location-based production flow research (Brodetskaia et al. 2013) by investigating construction processes and resource allocations (Liu et al. 2015). DES can be used prior to the start of construction to determine the master schedule and during construction to generate and investigate control actions. To produce reliable simulations of process flows, DES requires meaningful input parameters that represent current productivity rates from the construction site. Therefore, it is essential to receive data about production processes during the construction phase to update input parameters according to current site conditions. To this end, a digital twin is required, which offers reliable data-based information in a timely manner. It is important to ensure that data-driven information integration adds value to production management (Dave et al. 2016). Real-time data enable the determination of reliable activity durations, which can be used within DES to plan location-based resource flows based on the simulation results. The results of the DES need to be visualised to enhance the understanding of the sequences and their impact on time, space, and resources. Traditional 2D plans are often difficult to understand in short meetings, but 4D visualisations enable a superior visual project representation (Crowther and Ajayi 2021). The different approaches – Location-based management system, DES, DTC, and

4D visualisation – complement each other and exploit the potential benefits of the combined system.

Location-Based Management System

Location-based management methods focus on the flow of resources across different work zones provided by a location breakdown structure (LBS) of the construction site to support the planning process by considering time and space. Due to the adjustment of resource allocations, productivity rates of different trades become similar. Thus, continuous resource workflows over locations can be achieved and waste can be minimised (Seppänen et al. 2014). This method is particularly useful for repetitive construction works, but planning the distribution of resources over time and locations while avoiding idle time remains a major challenge (Ungureanu et al. 2019). A technique within location-based management systems is to delay the start of activities at the first location to consider a sufficient time buffer between tasks (Seppänen et al. 2014). For lean production planning, control, and the location-based management system, it is essential to visualise problems as early as possible (Seppänen et al. 2015). Within location-based management systems, flowline diagrams – a visual representation of crews' movement over time on the X axis and over locations on the Y axis – are used as 2D visualisations. A recent study demonstrated that a significant amount of time is wasted during mechanical, electrical, and plumbing work due to communication issues among workers caused by insufficient plans and schedules, as 2D plans are often confusing and unsuitable (Görsch et al. 2022). 4D models add a time dimension to digital 3D models, such as a BIM model, making them more intuitive for providing an overview and identifying project conflicts. Research has shown that 4D visualisations significantly improve the planning process and project reliability by facilitating collaboration among project partners (Crowther and Ajayi 2021). Hence, there is a need for research on 4D visualisation based on schedule simulation and automated progress monitoring (olde Scholtenhuis et al. 2016).

The location-based management system strives to manage deviations as early as possible to adapt trades' productivity rates in scheduling to prevent any time-space conflicts or adverse impacts on the construction execution. Changes in resource allocations could be applied as control actions (Seppänen et al. 2015). The LPS is a Lean Construction method that proposes weekly lookahead meetings to control current processes on a construction site (Ballard 2000). Therefore, location-based management system and LPS complement each other to improve production management during construction works (Kenley and Seppänen 2010). However, approaches for information flow between these two systems and its appropriate usage are needed. Thus far, discussions in lookahead meetings regarding changes in construction sequences have been based on separate, paper-based project documentations (olde Scholtenhuis et al. 2016) or the subjective experiences of different stakeholders who are often unwilling to compromise due to financial concerns (Ballard and Tommelein 2021), rather than site data (Hartmann 2021).

Discrete Event Simulation

DES enables the simulation of real-world events in a virtual environment. The effects of management-decisions and what-if scenarios can be modelled and investigated in a cost-effective and risk-free way (Wainer 2009). In recent years, DES has been increasingly employed in lean construction research (Shou et al. 2019) as a suitable method for handling the management of complex construction interactions by dividing the schedule into discrete events (AbouRizk 2010; Martinez 2010). DES simulates a list of separated events over time and the system's state changes according to the occurrence of discrete events. The simulation is proceeded according to a provided activity duration, which can be either deterministic or stochastic. Based on the activity duration, required resources are seized. If the required resources are already seized for another activity, the activity has to wait in a queue until the resources are released. Hence, DES enables the description of the resources' flow in a system. DES functions as an input-output transformer by taking input parameters and outputting process durations and resource usage. While the potential of DES is acknowledged in the construction sector, its usage is limited due to a lack of meaningful input data (Abdelmegid et al. 2020), resulting in unrealistic outputs (Abbasi et al. 2020). Nevertheless, Shou et al. (2019) provided a systematic review of DES application in lean construction research.

DIGITAL TWIN CONSTRUCTION

For the usage of a digital twin, it is essential to determine its purpose beforehand (Brilakis et al. 2019) as digital twin models have to be used for a target service (Jiang et al. 2021). In general, it can be stated that a digital twin for the construction phase consists of three elements: a physical system, a digital model, and its bidirectional data, information, and knowledge exchange (Tao et al. 2019). Real-time data are collected using different technologies, such as sensors or cameras, on the physical asset and sent via the internet to an Internet of Things (IoT) platform, where the data are accessible from everywhere. The collected data are analysed by artificial intelligence to gain information about current conditions. This provides reliable project status information (PSI) and the digital model, the digital twin, can be updated according to the physical system and knowledge is created by comparing the PSI with the as-designed building and the as-planned process. This results in project status knowledge (PSK). Precise PSI and PSK enable the use of the digital twin for data-driven simulation of ongoing construction works. The DTC paradigm is a mode to apply the digital twin concept for proactive management of production processes by considering lean construction principles (Sacks et al. 2020). In general, enormous positive potential is anticipated for the digital twin concept (Delgado and Oyedele 2021). However, the digital twin concept is still seldom applied in the building sector, especially in the construction phase (Sacks et al. 2020), although digital twins can promote smart construction. The implementation of digital twins in the construction industry is very complex, as many interacting resources move continuously on large-scale sites influenced by uncontrollable uncertainties. Therefore, there is an urgent need to develop common frameworks and demonstrate use cases for digital twins in the construction sector (Jiang et al. 2021; Pregnolato et al. 2022).

COMBINED DIGITAL TWIN AND LOCATION-BASED MANAGEMENT SYSTEM

A BPMN for the application of DTLMS by DES was developed (Figure 1). Before construction begins, a BIM file for the intended building is modelled. The BIM file is used to derive the required activities. The construction site can be structured into different zones according to a LBS so that for each zone information about required material amounts is available. By having different zones, the activities are structured in a work breakdown structure (WBS) for the management of the different tasks. Hence, due to the structuring into a WBS and LBS there is a final list of events, which is modelled in a DES. The productivity rates, which represent the activity durations, are derived of a historic database based on data collection from previous projects. Additionally, the number of resources needs to be stated. Within the DES, different options can be compared based on automatically calculated key performance indicators (KPIs). The following KPIs were determined: total construction duration, resource efficiency for the trades (i.e. the active time divided by the total time the trade is on site from the first day until the last day of work), idle days on the separate locations (i.e. the duration when construction works are not finished in a zone, but no works are executed in this zone), and total personnel costs for resources (the duration resources are on site multiplied by personal costs per day). It is aimed at achieving continuous workflows for all trades and avoiding time-space conflicts. If decision-makers decide on a construction option, the master schedule for long-term execution is stated. The before construction start available information from the BIM model, databases, and simulations builds the basis for creating the master schedule.

According to the master schedule, construction starts and sequences are executed. During construction, data collection technologies automatically collect real-time raw data and store it on an IoT platform. The data are analysed by artificial intelligence to determine the as-built and as-performed status, the PSI. E.g. time lapsed images can be taken and analysed by deep learning to track progress at certain intervals or sensors attached to the workers can provide data that are analysed by machine learning classifiers to track works. The PSI is used for control in comparison to the initial planning information. If deviations from the initial planning are detected, the productivity rates can be updated and stored in a database for use in following construction projects. Furthermore, this updated information can be input into DES to investigate realistic short-term what-if scenarios. The results offer the basis for managing ongoing works in the weekly lookahead meetings. Within these weekly meetings, it is aimed to maintain equal productivity rates for all trades to avoid idle time. If there is an urgent case, an earlier intervention than weekly is possible. The whole procedure is based on the plan-do-study-act (PDSA) cycle for continuous improvement of management processes. Due to the continuous data collection and the control actions, it is aimed to learn about processes and apply these gained findings for further improvement of the production sequence. This process must be repeated until all works are completed.

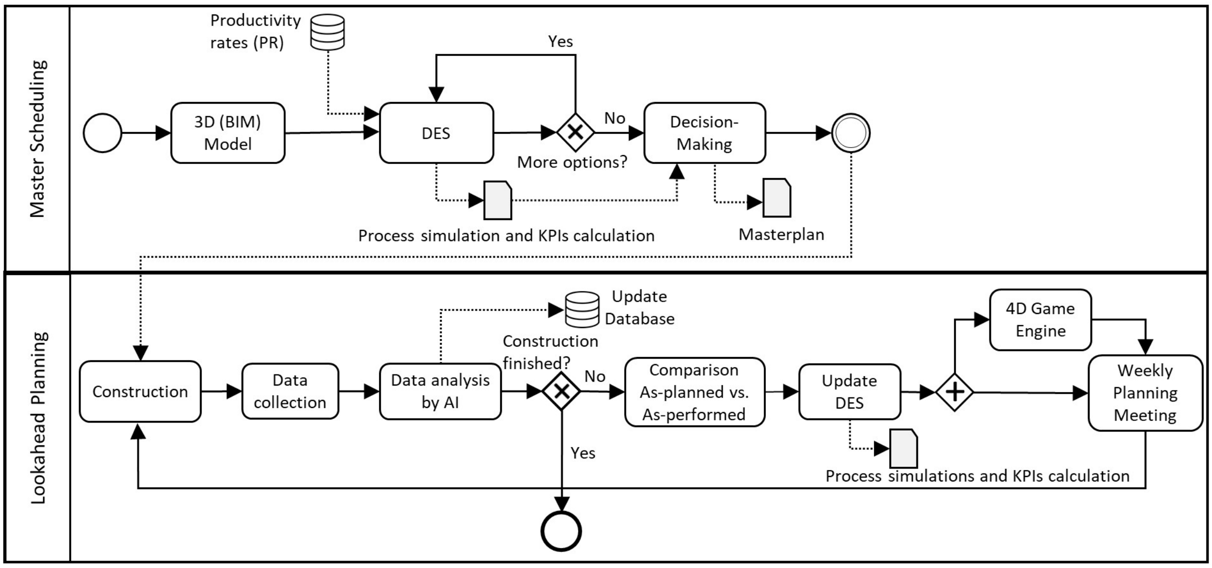

Figure 1: BPMN for a combined digital twin and location-based management system

A developed Digital Twin-platform, which is based on the game engine Unity, visualises the simulated processes of the trades. The BIM model as an IFC file is converted to a Unity file using a Python script to retain the geometry and metadata for import onto the platform. The start and end times for each process resulting from the DES are provided to the game engine as a JSON file. The information is interpolated to enable continuous process visualisations of the discrete events on the Digital Twin-platform. A colour is assigned to each trade and the construction site is divided into different zones. The zones are coloured according to the period during which an activity is executed by the trade. A Gantt chart timeline presents the activities at the bottom, which proceeds when the play button is clicked. Additionally, navigating back and forth is possible to investigate a situation in detail for better comprehension. By using a split screen, it is possible to compare the processes of different options next to each other.

DEMONSTRATION SITE

The demonstration site for the application of the developed system is a high-rise building in Gothenburg, Sweden. The future hotel and office building will have a total floor area of around 30,000 m². The floor area for each of the 27 floors ranges between 960 and 1,400 m². As most of the floors have similar floor plans, the finishing works will be executed in a similar sequence across all floors. The simulation of labour-driven operations executed by human resources, such as finishing works, is especially important, as the coordination is riskier due to the simultaneous execution by different trades (Bokor et al. 2019). A case study found that only 27% of the working time during equipment installation works is value adding and recommended research to minimise the wasting time (Görsch et al. 2022). Because finishing works are repetitive, it is possible to continuously learn from completed works and use the PSI and PSK for DTC management of ongoing works. The 16th floor, which will be used as a hotel, has a size of 1,200 m² and was chosen for an exemplary investigation (Figure 2).

Within this study, the execution of the following finishing activities by different trades was investigated: dry wall first side, wall installation of ventilation, plumbing, and electricity, dry wall second side, dry wall ceiling, painting, floor, and doors (Figure 2). The works are executed consecutively for each location by the following trades: dry constructor, heating, ventilation and air conditioning (HVAC), plumbing, electrician, painter, floor layer, and carpenter. Some activities require teams of two workers for the execution.

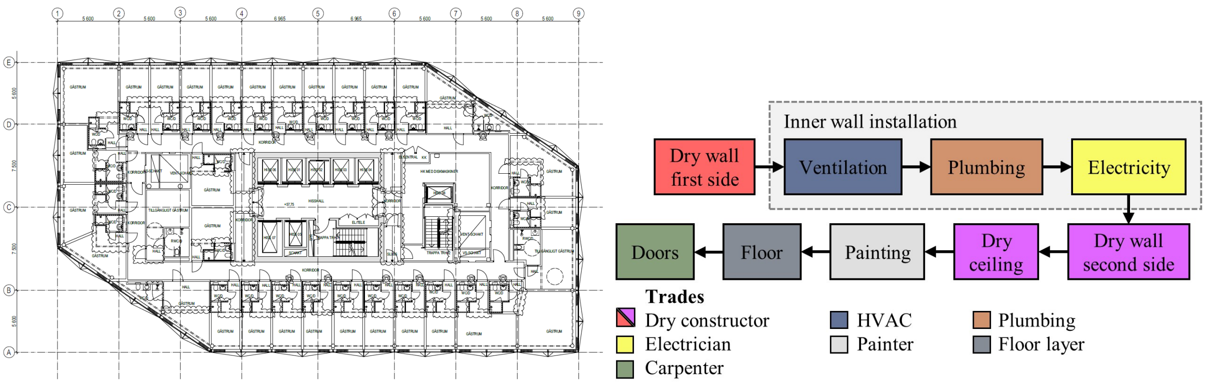

Figure 2: Floor plan 16th floor and process of finishing activities

APPLICATION

The execution of the finishing works for the 16th floor was modelled in a DES in R according to the process in Figure *2*. The whole floor was divided into three zones of similar sizes. Due to the floor plan, the material quantities and the zone sizes differ slightly. According to the LBS and the WBS, there are 24 tasks as the dry wall work on the second side and the dry ceiling work were combined into one task. The productivity rates for each activity were derived from the construction company's provided schedule and the material quantities were gathered from the BIM file. The resulting activity durations were rounded up into whole days so that there would be a time buffer for the case processes proceeded more slowly than initially planned. If a higher number of resources is used, the execution of the activity is faster, however, at some point, there is a turning point and more resources hinder the execution (Ng et al. 2013). Therefore, a constraint of five simultaneous executed works of one trade in a zone was specified. To avoid time-space conflicts, subsequent activities can only begin after the previous activities are completed.

The stated KPIs were forecasted automatically in the DES to compare three different options. The two main principles of synchronisation – similar productivity rates among trades – and pacing – continuous process of activities across the zones – for location-based scheduling were integrated. As production management is especially complicated, if a trade returns to the same location (Brodetskaia et al. 2013), for the mounting of the second dry wall side and the ceiling, a second crew of dry wall constructors was introduced. Hence, one crew can focus on the mounting of the first dry wall side and the second team can work on the second side of the dry wall and on the ceiling. Thus, the whole sequence can be repeated subsequently on different floors. Option 1 is the initial planning before construction starts. Within Option 2, changed productivity rates during execution are considered, but no control actions are performed. Option 3 assumes the application of the DTLMS and the changed productivity rates are stated, followed by control actions to handle the deviations from initial planning. The results for the three options according to the DES are listed in Table 1.

Table 1: DES results for different options

	Option 1	**Option 2**	**Option3**
Duration [days]	52	52	48
Efficiency trades [%]	100	100	100
Idle days on site	21	32	19
Personnel costs [€]	125,300	110,400	109,200

In Option 1, the resource allocations were adjusted before start to achieve continuous flows for each trade without any idle time. Therefore, the start of the plumbing trade was delayed by one day. Figure 3 presents the usage of the different zones. This results in an efficiency of 100% for all trades. Six floor layers working in two-person teams are commissioned and no idle time occurs, but the three zones are not occupied continuously. During construction, 21 days occur when no work is executed in one of the three locations, although the works have not been finished in the respective zone. In the first zone, there is almost no idle time, only the delayed start of the plumbing trade, but in the second and third zones, some several short-term interruptions occur. However, such short interruptions can also function as buffers, if a trade proceeds slower than expected. Option 1 results in a construction duration of 52 days and leads to personal costs of around 125,328€.

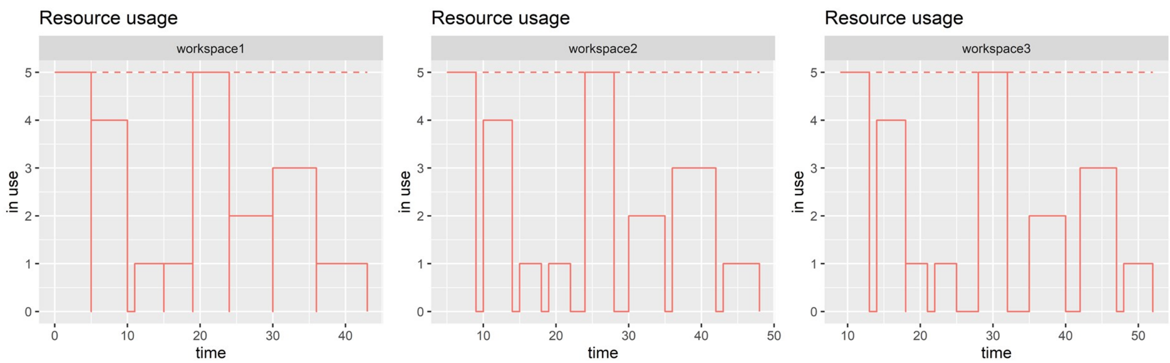

Figure 3: Option 1 - Zone usage

Option 2, the initial planning was based on Option 1, but a deviation in the actual productivity rate for the dry walls was assumed. The updated productivity rates were based on a study that investigated the productivity rates for dry wall work in a similar construction project in Sweden (Brosque et al. 2020), as no site measurements were possible. The mounting of the second side of the dry walls was faster in the construction company's assumptions, but the field investigation revealed that the construction of the first side was faster. The productivity rate for the first side changed from 0.200 h/m² to 0.106 h/m² and for the second side from 0.165 h/m² to 0.140 h/m². However, within Option 2, no change from the initial planning was made and the start date of the different activities was not amended. As the drywall work are executed faster, there is no change in the end date. Personnel costs fall slightly to around 110,400€ as the staff is required on fewer working days. No change in the efficiency of the different trades is observed, but the zones were used inefficiently as the duration of the idle periods increased as presented in Figure 4. On 32 days, no work was executed in one of the three zones, although the work in that zone was not completed. This is an idle time increase of more than 50% in comparison to Option 1. As the productivity rates for the first dry constructor team was faster, idle times occurs that sums up for all three zones. Additionally, the idle periods are of longer durations.

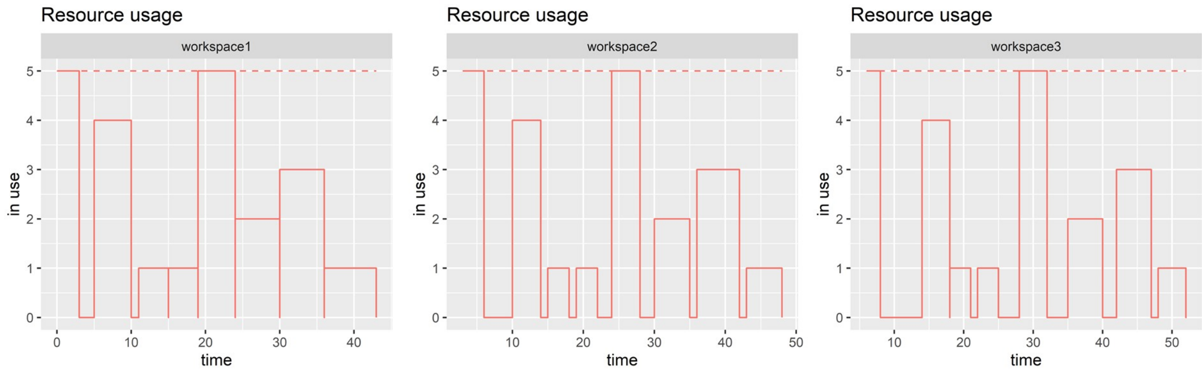

Figure 4: Option 2 – Zone usage

Within Option 3, it was assumed that the DTLMS was applied and the deviation of the productivity rates was stated by the digital twin concept. Subsequently, the gained PSI and PSK were used to adjust the initial planning and scheduling after the first week. On the one hand, the start dates for the following activities were brought forward. On the other hand, due to the faster productivity rate for the dry wall construction on the first side, another HVAC team was introduced to achieve a similar PR. As only a small deviation occurs for the mounting of the second dry wall side, this does not significantly affect the execution due to the simulation in whole days. Option 3 resulted in an estimated construction duration of 48 days. This is four days less than initially scheduled and the efficiency of 100% could be kept for all trades. Additionally, the idle days on the construction site were reduced to 19 days, an improvement of around 10% compared to option 1 and of more than 40% compared to Option 2. Figure 5 displays that the idle days were minimised and no idle days occurred in the first zone. The costs declined by around 15% to around 109,214€ compared to Option 1.

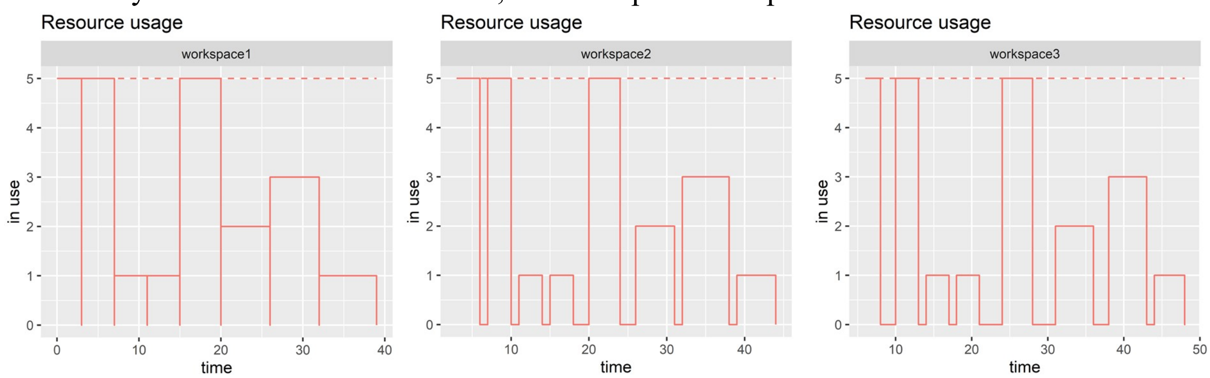

Figure 5: Option 3 – Zone usage

An image of the 4D process visualisation tool is presented in Figure 6. By clicking on arrow buttons, the different options can be selected. While the processes simulated for Option 1 are on the left side, the processes for Option 2 are visualised on the right side. The three zones are coloured differently depending on the activity performed and a Gantt chart provides an activity overview. Thus, the differences can be detected. By applying the developed approach, the impact of the construction execution can be improved in comparison to the initial planning. In all three options, a theoretical resource efficiency of 100% can be achieved. But in Option 3, the zones are used much more efficiently, as around 40% fewer idle days occur. Furthermore, the personnel costs could be reduced. If considering a larger case study and all floors of the investigated building, the positive impacts would increase even more.

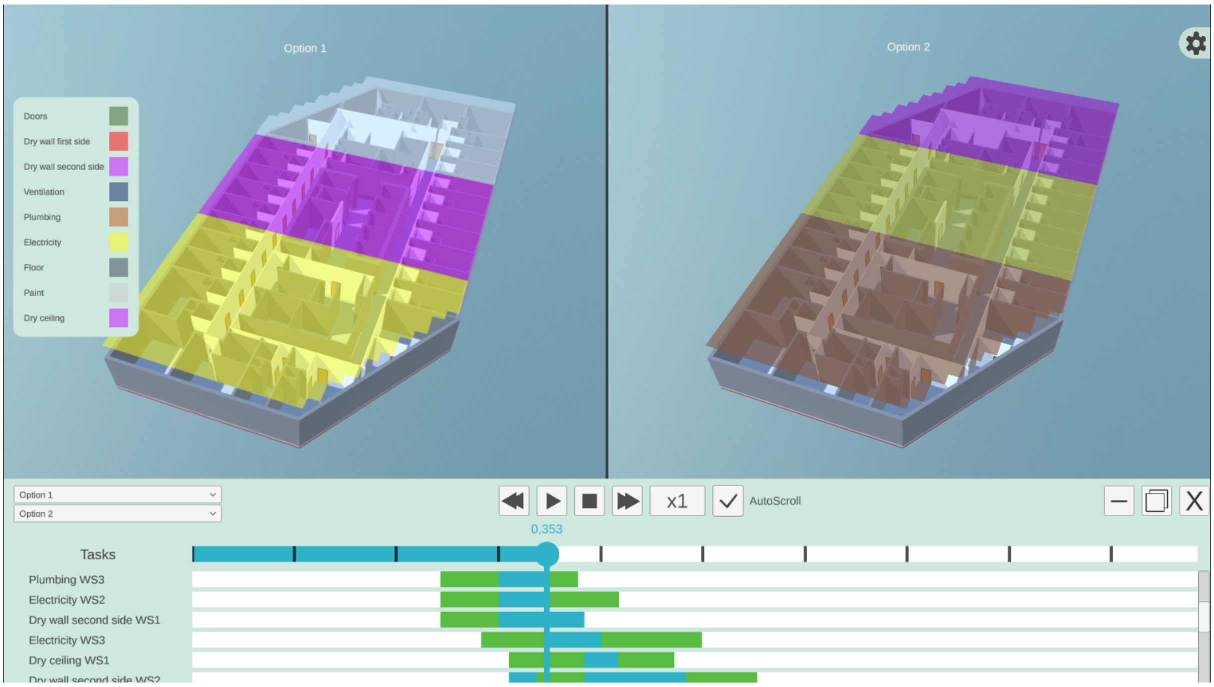

Figure 6: DES-based 4D process visualisations

CONCLUSIONS

The DTLMS presents a systematic approach for using real-time data during construction works for project management in consideration of Lean Construction. The paper provided evidence that using gained PSI and PSK can enhance the management of ongoing construction processes by ensuring continuous workflows and high efficiency during finishing works. However, in real projects, an efficiency of 100% remains a theoretical maximum (Ungureanu et al. 2019). Deviations from the initial master schedule should not necessarily represent an obstacle, but can also offer an opportunity to learn and improve ongoing processes. In the case study, it was possible to improve the estimated KPIs resulting in shorter durations, lower costs, and less idle time due to the intervention. The reason is the faster execution of dry wall work, which is uncommon in construction, as slower productivity rates are more frequently reported during production control (Seppänen et al. 2014). Nonetheless, this paper emphasises the need for real-time data-based construction control and, if necessary, control actions for handling deviations to hinder adverse impacts and shift away from subjective decision-making. The 4D visualisation assists due to an improved presentation of construction sequences and helps to identify conflicts in a timely manner. The extension of conventional 2D methods by the 4D process visualisation enhances the basis for discussion in weekly planning meetings. For successful management and execution, a common information basis and understanding of processes is required among all stakeholders, which also strengthens confidence.

A major limitation of this study was the use of literature-based measurements instead of data-based findings. The analysis of real-time data to gain reliable information for stochastic simulation was presented in a previous work (Jungmann et al. 2022). The focus of this paper was on the application of simulation for enabling control actions according to a literature-based deviation. Other than dry wall work, the productivity rates of different activities will vary from initial assumptions during construction. Hence, the investigation of an extended, more complex construction process will be expedient. Additionally, future research has to investigate the gap between the intended performance and the real performance, which will unavoidably differ. Future research should also consider the material deliveries via real-time data-based information in the DES to consider further uncertainties during construction. Furthermore, the game engine visualisations will be extended to a dashboard to enable information provision regarding past works.

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