Proceedings of the 2021 Winter Simulation Conference
S. Kim, B. Feng, K. Smith, S. Masoud, Z. Zheng, C. Szabo and M. Loper, eds.

EVALUATING SUPPLY- AND REVERSE LOGISTICS ALTERNATIVES IN BUILDING CONSTRUCTION USING SIMULATION

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ABSTRACT

Building construction is a one-of-a kind production with complexity caused by interdependencies between logistical- and construction-operation processes. Especially the finishing phase involves numerous trades who install a wide variety of materials and have to share logistical resources. Traditional planning approaches based on analytical tools and experience gained from historical data fall short in providing the support needed to evaluate different logistical strategies. Therefore, the present work aims at developing a user-friendly simulation model that considers both material supply and waste removal through a third-party logistics partner (TPLP). The process interdependencies are investigated using data from a real hotel building project. A kitting solution is evaluated as an alternative, using consolidation centers to reduce material handling on site. Comparing the supply- and reverse logistics of these alternatives, kitting appears to be more costly however the model does not capture potential improvements in performance of construction operations and coordination of processes.

1 INTRODUCTION

Projects in building construction are usually complex, unique, and challenged by interdependencies between individuals and processes involved (Arbulu and Ballard 2004). Construction project planning has to consider multiple objectives and must be customized to each project (Berner et al. 2013; Voigtmann and Bargstädt 2010). The goal is to achieve an efficient allocation of available resources to provide a temporally feasible and robust project schedule while minimizing risks and uncertainties (Berner et al. 2013). To manage the complexity of a project, in-depth planning including consideration of logistical processes is required to ensure smooth material flow, to support productive deployment of personnel and equipment, and to avoid cost overruns and delays (Wenzel and Laroque 2013). Matching supply with demand on site is a common challenge for logistical processes as both vary throughout the duration of construction. A mismatch will cause inefficiencies, increasing cost and delay (Arbulu and Ballard 2004).

The problem is especially of concern for the finishing phase of a construction project. Boennert and Blömke (2006) stated that in this phase 30% of the work time is spent on logistics such as transportation, searching for materials, rearranging materials, and cleaning up. They estimate that 10% of the total work time could be saved by better logistics planning. Moreover, Lindén and Josephson (2013) stated that costs could be reduced by approximately 20% if material handling is organized by a logistics plan that is executed by a third-party logistics partner (TPLP).

978-1-6654-3311-2/21/$31.00 ©2021 IEEE

To study this complex system, it is necessary to consider the challenges stemming from the interdependence between logistical- and construction-operation processes. Agapiou et al. (1998) already noted that planning from a logistical point of view can contribute to productivity enhancements. The savings from well-planned logistics quickly compensate for potentially-required additional effort and costs (El Moussaoui et al. 2021). Challenges also arise when making modeling choices. As project size and complexity increase, and problems require multi-objective optimization, analytical tools may not offer closed-form solutions (Feine et al. 2016). However, optimizing only a part of a problem can be counterproductive (Voigtmann and Bargstädt 2010). In this context, simulation can support the understanding of interdependencies and planning processes by making it possible to analyze a construction project in detail (AbouRizk 2010). Considering these challenges, we focus here on the interplay between logistical and construction-operation processes and use simulation to study the project production system, aiming to improve resource allocation and use in order to increase value delivery while eliminating waste.

This paper proceeds with a review of the literature to identify characteristics and simulation approaches in building construction. Next, we present the underlying conceptual model including the processes for both logistics and construction operations. Then, we describe the implementation of the simulation model. Using case-study data, we compare the logistics system of a real building construction project to an alternative approach using kitting. Finally, we discuss the findings and offer conclusions to this work.

2 LITERATURE REVIEW

2.1 Characteristics in Building Construction

The complexity of construction projects derives, among other factors, from extensive reliance on subcontracting (El Moussaoui et al. 2021). This results in fragmentation and high specialization across project participants, who typically are brought together just for one specific project (Arbulu and Ballard 2004; Wegelius-Lehtonen 2001). It also derives from the close connection between logistical- and construction-operations processes that therefore need to be tightly coordinated (Berner et al. 2013).

Construction operations are characterized by involvement of a many of trades, especially in the finishing phase of a project (Voigtmann and Bargstädt 2008). The different trades' tasks are constrained in precedence and in availability and sharing of required resources (personnel, equipment, and space), as well as by performance objectives such as the desire for continuity in resource use. Especially in this phase, it is common to combine certain activities in order to create repetitive operations. These are then performed unit by unit by the same crew within a certain time window (Behzadan et al. 2015; Dlouhy et al. 2019).

Construction logistics is all too often regarded as an independent function but it lends essential support to construction operations (Feine et al. 2016). The handoff between logistics and construction operations takes place at the installation work face (Voigtmann 2014). Construction logistics is responsible for planning and controlling resources including equipment, material, and possibly also employees, as well as information throughout the construction process (Tischer et al. 2013). The goal of supply logistics is to ensure the delivery of the right product in the right quality in the right amount to the right place at the right time, also referred to as the "5R"s of logistics (Hamzeh et al. 2007). The unavoidable counterpart of supply logistics is disposal logistics (aka. reverse logistics), which starts on site. Its goal is to free up site space (a constrained resource, essential to operations) while following sustainability practices (avoiding waste, in a broad sense). Concerns for sustainability have led to increasing interest in studying waste generated by the construction industry (e.g., Hosseini et al. 2015).

Disposal logistics starts at the "receding edge" of operations (Salem et al. 2018). A lack of rules regarding cleaning can lead to disorder and possibly unsafe working conditions (Thomas et al. 2005). Lipsmeier and Ghabel (1999) noted that efficient construction planning, resulting in high productivity, increases the waste generated per time unit. One disposal logistics practice, e.g., is to have a logistics service partner provide multiple bins to separate waste. The partner has to manage the separation of materials according to the available recycling practices and to organize both the central collection as well as the final disposal according to those practices and legal provisions (Tischer et al. 2013). Lu et al. (2006) simulated the steps of steel and timber waste generation, handling, and removal from a construction site focusing on resources needed for the waste sorting processes of these two different waste fractions.

During the finishing phase, the variety of materials and waste fractions is particularly high. It is common for materials to be delivered separately by trade using relatively small trucks or trucks that combine materials for delivery at multiple sites (Voigtmann and Bargstädt 2008). To reduce the number of trucks, the use of so-called "logistics centers" is gaining interest from general contractors (El Moussaoui et al. 2021). A logistics center represents a consolidation point for material suppliers, where resources are pooled to deliver materials to different sites thus minimizing the requisite number of trucks, packaging, and handling on site (Thomas et al. 2005; Mossman 2007). Consolidation centers can reduce the effort of on-site logistics and improve its overall quality, e.g., by offering information and tracking services, kitting, damage control, or e-commerce (Hamzeh et al. 2007). Despite the value that consolidation centers can deliver, they are not yet widely used in the construction industry (Hsu et al. 2018; El Moussaoui et al. 2021).

2.2 Simulation in Building Construction

A survey conducted by Leite et al. (2016) indicated that 88% of construction industry participants described simulation as a value-adding research direction. Simulation is characterized by a computer-based representation of the construction system that is investigated under different sets of parameters to understand the behavior of the system (AbouRizk 2010; Feine et al. 2016). In the past, several research studies have applied simulation tools in order to investigate different factors that influence building construction and to achieve improvements of construction processes. The following paragraphs summarize the most significant studies regarding the present research.

Weber (2007) aimed at developing a digital tool to support managers involved in implementing logistical strategies. He used the software enterprise dynamics (Fa. INCONTROL GmbH) to model logistical processes including material delivery to the construction site, potential material storage, and distribution to installation locations. Quantities of required materials were obtained from the 3D-CAD-model of the planned hotel building and subsequently linked to construction operations. Schedules were used in the simulation to determine transportation timing and destination of material. Construction operations were not investigated, as the main objective of the study was to dimension offloading zones and transportation means in the early planning stage.

Bamana et al. (2019) applied lean practices to logistical processes regarding material supplies, material storage, and lifts to installation locations. Construction operations were implemented only to determine the quantity and timing of materials required on site and at the work face. The impact of certain lean methods (e.g., prefabrication, 5S, and JIT) was studied for a six-story wooden building in Canada using the software Simio. Even though they considered only the erection phase of the project, the detailed modeling of transportation, storage, and movement of workers pertaining to both logistics and trades provided a reasonably accurate understanding of important logistical processes.

Kugler (2012) aimed at providing a tool with a high degree of automation in data acquisition and a simple user interface that can be applied to various building construction projects. He concentrated on direct production logistical processes, but neglected all kinds of procurement and disposal logistics (Voigtmann 2014). To validate his software prototype, CiSmo, he applied the agent-based simulation model to two real projects, a passive tract housing project and a senior center with three floors.

Voigtmann's (2014) study is possibly the most relevant to the present work. Her objective was to provide a simulation-based planning tool that considers all project participants and resource constraints to evaluate the impact of different scheduling variants and logistical strategies within a dynamic production environment. She implemented a constrained-based simulation approach using the modular STS block to investigate logistical processes during the finishing phase and tested it on a multi-story office building. Construction operations were implemented by a constraint-based model based on predecessor-successor relationships and resource requirements. The logistical processes started at the point of material supply and ended at the point of material installation. Though she mentioned that disposal tasks have to be considered to get a more complete understanding of the onsite logistics, she assumed that material would be delivered in the exact amount needed and neglected material waste, that is, disposal logistics were not considered.

3 RESEARCH OBJECTIVE

To the authors' knowledge, the literature on simulation for building construction does not refer to models that consider both supply tasks and disposal tasks (i.e., disposing waste or handling surplus material on site) while focusing on available logistical resources which are shared as needed to support operations. Thus, to augment the literature, the presented simulation includes the material and waste flow that is coordinated by a TPLP. We used a modularized approach to enable future use of the model on multiple construction sites in order to ease adoption within the construction industry. Furthermore, a supply approach using kitting is investigated as an alternative supply system to eliminate multiple material handlings on site.

4 CONCEPTUAL MODEL

A conceptual model must present a simplified description of the real system, independent of the simulation software used (Poshdar et al. 2016). Even though the construction industry is characterized by projects, each one realized in a unique environment and influencing factors like location, required tasks, or available worker skills are project-specific, the logic of internal processes referring to building can be transferrable across projects (Tommelein et al. 1994; Behzadan et al. 2015). Accordingly, while our work is based on the logistical- and construction-operations processes of a real hotel building project, to achieve wider use of the model, the layout and the processes have been generalized for use when modeling similar hotel and office buildings.

4.1 Construction-Operation Processes

The represented building has multiple upper floors that are designed in a repetitive way using approximately the same layout. Hence, each floor with this layout is referred to as a "standard floor." Each standard floor is zoned into several units, so-called "working areas" or "takt areas," which represent a combination of several rooms and the corresponding part of the hallway. Takt areas characteristically require similar resources regarding material types and quantities and worker skills needed in construction operations.

Construction operations are performed repeatedly by trade workers, takt area by takt area, potentially by multiple crews per trade. Crews are organized within a so-called "Parade of Trades" or "train of trades" where each wagon represents a set of tasks performed within one week in one takt area (Tommelein 2020). The sequence of the wagons (i.e., the process) is described in the construction schedule. Therefore, the schedule gives a structured overview of which tasks are performed per week and takt area throughout a given construction phase. The order of the tasks must be followed due to strict predecessor-successor relationships or otherwise agreed-upon sequencing. Hence, material requirements per week can be calculated based on the schedule and the material requirements per task, for both the entire project and all takt areas separately. The logistical processes can be planned based on these calculations.

Every Monday crews move to their next takt area according to the schedule. They start to work if all predecessor tasks are finished and if all requisite materials are available within the working space, delivered on pallets. During the execution of tasks, emptied pallets are centrally collected within the takt area. At the end of each task, the workers consolidate potential surplus material onto one or multiple pallets. Trade workers use the vertical transportation means to get to their working floor in the morning, during breaks, and at the end of their work day.

4.2 Logistical Processes

Logistical processes are performed by a TPLP, hired by the general contractor, so that the trades can fully concentrate on construction tasks and their productivity. The TPLP receives the schedule and the required materials per wagon in order to support the construction operations. TPLP employees are responsible for both supply and disposal tasks. Transportation of materials and waste is carried out by one employee using one of several of the potential transportation and disposal means.

At least one such transportation means is available on the outside of the building (on the ground floor) and inside the building (on each standard floor), specified at the start of a simulation run. Horizontal transportation means are assigned to a floor and to specific parking areas (Figure 1) during idle times as per the 5S lean method. Additionally, vertical transportation means (referred to as "elevator") are located along the façade and inside the building. These means handle both workers traveling up and down. Once transportation using an elevator is finished, the elevator remains at its position until the next transportation is requested. Furthermore, there are no intermediate stops between the original floor and the destination floor during a transportation. An indoor elevator is used to complete disposal tasks whereas a freight elevator is used to transport materials. All elevators are available for transportations of the people.

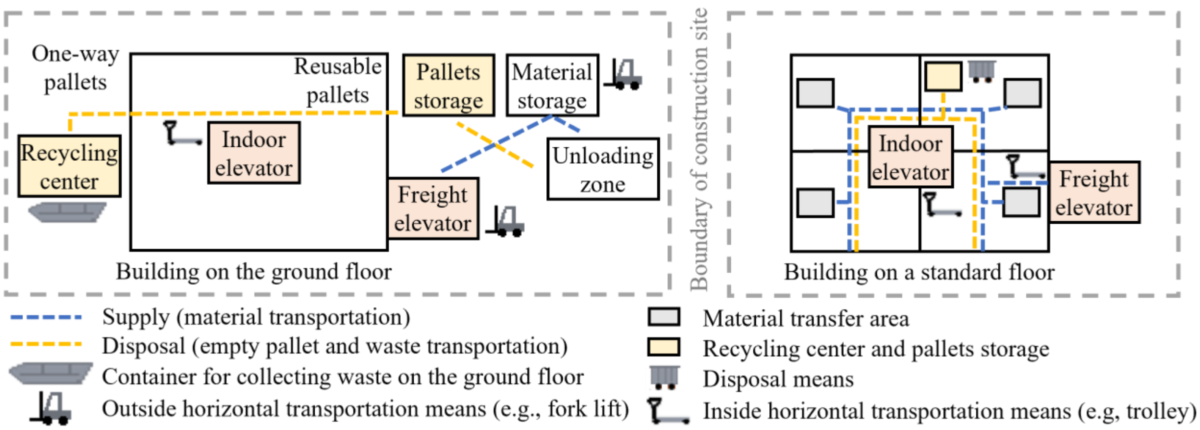

Figure 1: Example site map including parking areas for transportation and disposal means.

Following the schedule, material orders are summarized per week and per trade according to construction operations, assuming one supplier per trade. Required materials, loaded on handling units, are delivered to the site for each trade separately in the preceding week. The trucks are unloaded by a TPLP employee, one handling unit at a time, and placed in the temporary material storage (staging) area on the ground floor. After having unloaded the materials intended for this construction project, the employee loads empty pallets, if any, on the truck (Figure 2). The TPLP delivers materials from the material storage to each takt area according to the requirements for each wagon scheduled in the next week. Construction operations within one wagon do not always require an integral multiple of the material units contained in one standard handling unit. However, the materials can usually be ordered only in entire loaded handling units. Therefore, without prior kitting services, the amount of material supplied to the construction site doesn't always exactly match the demand for the following week, leaving excess.

It is common practice to divide handling units delivered to site based on the exact amount of material that will be needed in each takt area, however that may or may not be practical. For example, handling plasterboard takes a lot of effort (boards are heavy and easily damaged) ; for that reason handling units are not separated on the ground floor, but only entire pallets are transported from the material storage to selected takt areas. The result is material left over after crews have finished their task, leaving surplus material in takt areas. In contrast, other materials, for example materials delivered in bags like gypsum filler, typically are transported only by the number of bags needed in each takt area. Handling units are separated at the material storage on the ground floor by transferring the required number of bags on another pallet that is then transported to the takt area. This leads to partly-filled handling units in the material storage on the ground floor. The separation of handling units on the ground floor and the multiple handling of surplus material in takt areas may be regarded as non-value adding following the lean construction philosophy (Bajjou et al. 2017) but tradeoffs need to be made.

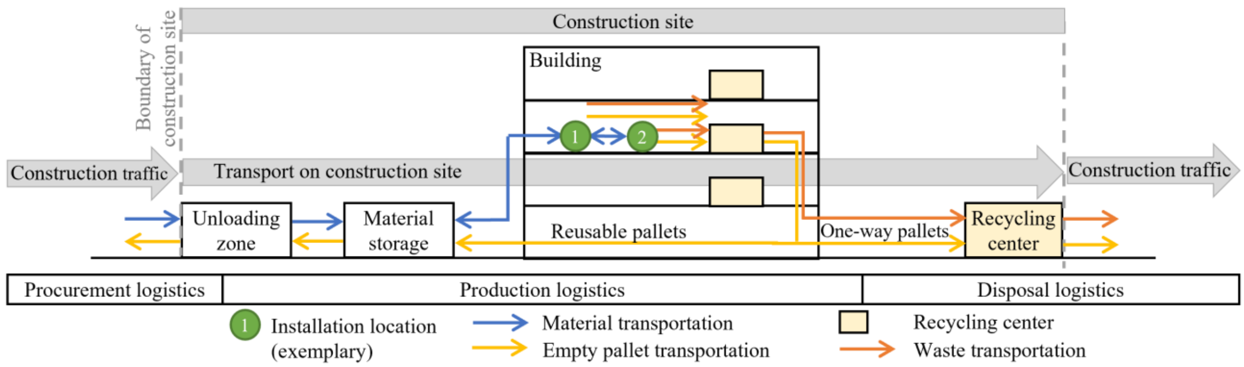

Figure 2: Logistical processes based on Voigtmann (2014) and Boenert and Bloemke (2003).

As soon as a trade has finished their operation, it notifies the TPLP in case there is surplus material left in the takt area. An TPLP employee then checks where the material is required in the following week and potentially determines the next destination of the surplus material according to the following priority rules: 1) Same takt area, 2) Subsequent takt area on the same floor, 3) Any takt area on the same floor, 4) Any takt area on a subsequent floor, 5) Any takt area, 6) Material storage on ground floor. In case there is already a partly-filled handling unit of the same material stored in the material storage, the employee consolidates both by transferring material units onto the already stored handling unit until the new delivered handling unit is empty or until the maximum capacity of the stored handling unit is reached. Any pallets emptied in this transfer are appropriately handled.

For many materials, some percentage of waste is expected in the course of their use. This waste is collected daily by one employee per floor. On each floor, there is one bin per required waste fraction. For each disposal means (bins or containers), there is a defined maximum filling level at which a it has to be emptied. This level tends to be below the full capacity of the disposal means, because one cannot expect it to get 100% filled, there are always some air pockets. Moreover, overly-full disposal means are difficult to handle, as material could fall out during transportation. If a bin is full enough, the employee empties the bin into the corresponding container on the ground floor and continues the collection process upon return to the floor. If a container is filled to its determined level after emptying the bin, the employee requests an exchange of the container.

Similar to the handling of waste, empty pallets on each floor are centrally collected daily by one employee. Reaching a previously-determined number of empty pallets stored per floor, the employee transports them to the ground floor and either disposes one-way pallets in the container for wood recycling or stages reusable pallets next to the material storage area until they can be loaded on a truck and removed from the site.

5 IMPLEMENTATION

The model is implemented using the standard simulation software Plant Simulation version 15.1.0 provided by SimPlan AG (Siemens 2019). As Pitsch (2011) stated, the use of standard simulation software can benefit the construction industry as the numerous factors that influence such work can be modeled by them. The Simulation Toolkit Shipbuilding (STS) of Plant Simulation has already been used by multiple construction researchers. However, Bargstädt and Feine (2015) question whether STS is indeed to be regarded as standard software due to the customizations made in modeling. The present study aimed at model development using only using standard elements.

5.1 Modularization

A modularized approach has been used for implementation. The standard floors and the takt areas have been modeled as so-called replicable networks. Moreover, the distances, positions, and the spatial arrangement of the considered elements are connected to variables whereby the simulation model can be adapted towards multiple construction sites without great programming effort. The model is implemented to be usable by people who are not particularly familiar with the Plant Simulation software. Therefore, the input and output data are managed through tables saved in the format of MS Excel and parameters are set using a graphical user interface.

Required inputs are: site-specific data referring to the environment and layout of the project, construction task-specific data describing operations, company-specific data such as characteristics of available logistical resources, and construction technology-related data, e.g., with regard to possible supply strategies. The latter two may not be readily available when conducting a simulation in a company for the first time, but once the data are collected, they can be reused in future projects (Feine et al. 2016).

Table 1: Input data set prior to all simulation runs.

Construction site-specific	**Construction task-specific**	**Company-specific**
- Layout of the ground floor and of standard floors (e.g., positions of takt areas or elevators in relation to each other) - Building characteristics (e.g., number of standard floors and takt areas, floor height)	- Construction schedule - Material requirements per task - Labor expenses per task - Anticipated waste fractions	- Materials (e.g., size, waste fraction) - Handling units (e.g., size, reusability) - Potential horizontal and vertical transportation means (e.g., speed) - Potential disposal means (e.g., capacity) - Trucks supplying material and exchanging containers (e.g., loading time)

For each simulation run, the user can set the desired parameters (e.g., number and kind of transportation and disposal means) by selecting from the potential options previously-specified as input data. After having specified input data and parameters, the simulation model computes its layout and starts the simulation. Stakeholders who perceive simulations as a “black box” may undervalue the opportunities provided by simulation and lack trust in its results (Behzadan et al. 2015). To counter this perception, the implemented simulation interface graphically depicts the logistical processes in order to increase intuitive understanding of the calculated results. After each simulation run, statistics are automatically exported and visualized within an MS Excel Sheet, so that users can readily evaluate the simulation run results.

5.2 Simulation Logic

Figure 3 presents the overall logic of the simulation model. Construction material and waste are controlled by material and disposal managers that are triggered by certain events. If the event causes a management action, the manager assigns a new task to the task control of the transportation means that is required to execute the task. Each kind of the considered transportation means has a central task management function that assigns requests to a certain vehicle depending on the task and the position of the available transportation means. If a vehicle is assigned to a task, it requests a TPLP employee from the personnel manager. TPLP employees are on standby for tasks on the ground floor. However, they can start a new task immediately after having finished a task on a standard floor. That is, the TPLP personnel manager assigns requested tasks to the employee who is nearest to the position of the requesting transportation means. The personnel manager for the trades controls movement of the workers at the beginning and end of the work day and breaks.

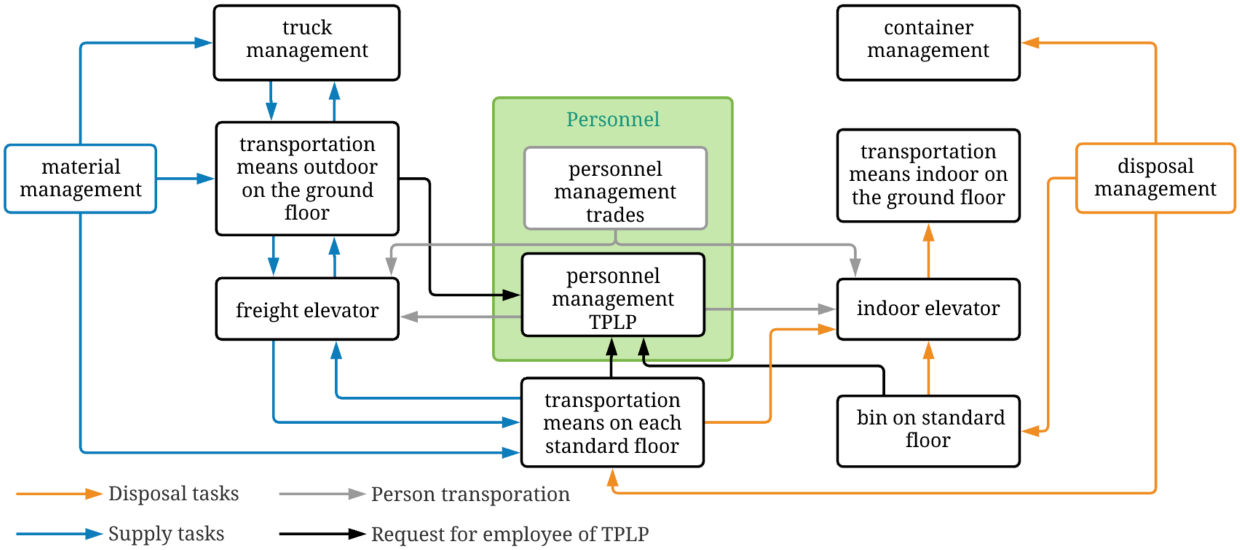

Figure 3: Simulation logic.

Moreover, transportation means can request other transportation means, e.g., if a truck arrives, it requests one of the outdoor transportation means in order to be unloaded. Likewise, the personnel manager may request an elevator to get to another floor. The material flow is controlled by destination labels that are attached to each handling unit. The same applies to employees who are moving within the simulation.

During a simulation run, the movements and tasks are recorded for all transportation and disposal means, and for all people. As a result, the evaluation of a simulated alternative is not limited to previously-defined measures, such as utilization or overall logistical hours, but can be based on more detail referring to specific task elements. Weekly statistics such as the number of handling units supplied, number of unloaded trucks, or maximum occupied storage area at the end of each week are recorded as well.

6 CASE STUDY

The case study was conducted for a hotel building with six standard floors, each one zoned in six takt areas. The takt areas include multiple rooms and the corresponding part of the hallway. The investigated construction phase begins right after completion of the shell and ends before final cleaning takes place. The trades considered in this study are called area-dependent trades as their material and labor expenses are calculated based on gross floor area. In contrast, trades responsible for technical building equipment use special transportation means (e.g., a special crane or screed mixer and pumps) and therefore were not included in the study. The schedule, the labor expenses per task, and the material requirements per wagon are imported into the simulation model. The material requirements have been calculated in detail, based on material units, for all dry building tasks, e.g., plasterboard, profiles, or gypsum filler. The remaining materials, such as doors or floor covering, were provided based on partial handling units that also allows for an accurate representation of the material flow as material is always transported by handling unit. A detailed overview of all considered trades and materials are listed in Table 5-1 in Gschwendtner (2021). The characteristics of the available transportation means were adapted from Dengler (2020). To allow for a flexible design of the construction layout, these durations have been split into multiple sub-processes. The remaining data was obtained through research by the first author in cooperation with the industry partner.

6.1 Parameter Setting

To formulate the basic scenario, the researchers interviewed employees of the industry partner regarding current material handling practices. The supply of materials to the construction site is restricted to the delivery of entire handling units. For further transportation on site, materials have been clustered into two categories: handling units that can be divided in the material storage area (e.g., paint buckets) and those that cannot (e.g., plasterboard). The alternative scenario relies on kitting at a consolidation center. Thereby, materials are not directly supplied to the construction site but to an external consolidation center where the handling units are divided and kitted according to the delivery list of each takt area for the subsequent week. On the scheduled days of delivery, the materials are sent to the site without a limitation of trade materials per truck. At the site, the handling units are transported to the corresponding takt area without further effort in the material storage area. Furthermore, there is no more handling of surplus material.

6.2 Results

Comparison of the two scenarios shows that by using consolidation centers (off-site kitting) the number of trucks that supply material to the construction site was reduced by 34% whereas the number of handling units delivered increased by 10% (Figure 4). These results stem from the following modeling assumptions and resulting model behavior: (1) In the basic scenario, the material requirements are consolidated over all takt areas. For example, if a takt area requires 10% of the material loaded on a standard handling unit, only one pallet is supplied to the site for materials that are allowed to be separated on site. This results in nine separation activities in the material storage area to deliver the material to ten takt areas. In the kitting scenario, they are not consolidated and ten handling units are supplied to the construction site. (2) The orders to the site are not reduced by surplus material in the takt areas. In the basic scenario for material that is not allowed to be separated in the material storage, the TPLP employee reduces the initially-calculated material requirements per week by the expected amount of surplus material per week per takt area. In the kitting scenario for the same type of material, there is no surplus material as all initially-calculated material requirements are supplied to the construction site. This creates a kind of regularity and stability in the process, but the simulation shows that more storage area is needed to transitionally store the supplied handling units in the kitting scenario compared to the basic scenario. This raises a challenge as site space is a scarce resource, especially in the urban environment.

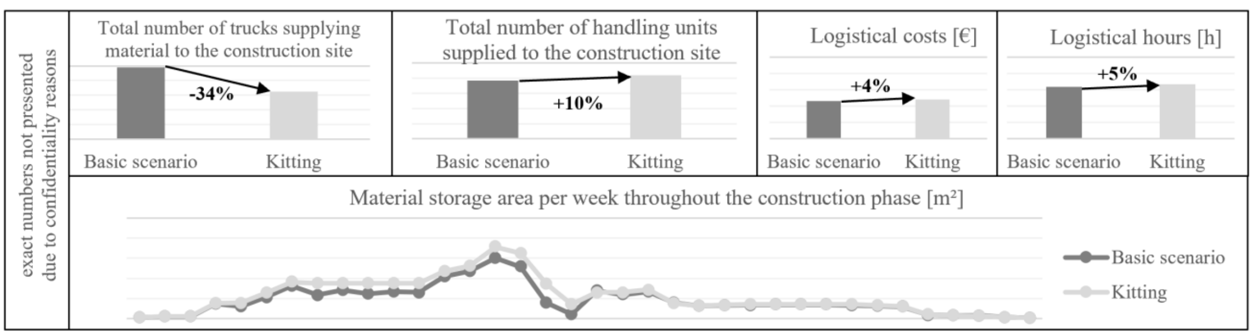

Figure 4: Results of simulation of logistics approaches with and without kitting.

To further evaluate the impact of kitting, logistical costs and hours have to be compared. The main point of study is the tradeoff between the greater effort caused by more supplied handling units and the reduced effort through the elimination of separating in the material storage and handling of surplus material. Based on data from the industry partner, Figure 4 shows that the reduced effort in this case does not offset the additional expense of the additional supplied handling units. Instead of decreasing, the logistical costs have been increased by 4% and the logistical hours by 5%.

7 DISCUSSION

Based on the presented assumptions and simulation modeling with the specific data provided by the industry partner, the kitting scenario is not favorable: it could not enhance the performance due to the increased number of handling units supplied to the construction site. Note however, in practice kitting has already been proven to enhance the construction process (Construction Excellence 2004). It reduces the amount of surplus material on site and the effort for (re)locating materials both in the material storage area and in the takt areas. Hence, on-site material management is enhanced as deliveries match the material requirements per takt area. The coordinated material flow leads to improvement in reliability regarding deliveries as all materials on site have a defined end destination. In turn, this decreases the number of tasks that fail due to lack of material and thus increases the number of timely task completions (see Figure 9 in Construction Excellence 2004). An extension of the model should include modeling elements to study the impact of materials supply on the performance of construction operations and process coordination.

The kitting approach could be improved by combining materials required by takt area in standard containers or on carts (e.g., see Figure 2 in Heinonen and Seppänen 2016). This would decrease the effort for handling units supplied to the site by reducing them in number while still benefitting from the on-site elimination of separation in the material storage area and handling of surplus material. It could further be improved by implementing a JIT delivery strategy. By directly supplying materials to the takt areas without temporarily storing them on the ground floor, the need for storage there could be significantly reduced.

As for the simulation software we selected, created to model manufacturing material flows, we were able to adapt the provided elements to the one-of-a-kind environment of the building construction industry. We modeled missing elements such as elevators by combining standard elements. The modularized programming environment allowed for the implementation of a model that is adaptable to multiple construction sites sharing the internal mechanisms within logistical- and construction-operations processes. Using the provided interface elements to software like MS Excel and the programmable graphical user interface, the resulting model can be run by people who are not particularly familiar with the software specifications. Moreover, the software allows for customized statistical evaluations enabled by standard elements. The evaluation is not restricted to predefined metrics but each part of the simulated model can be analyzed in detail to gain deep understanding of the processes. The modular implementation allows for extension in multiple directions such as construction scheduling or operational construction control. With the latter, we mean, e.g., addressing the complex control problem pertaining to the use of elevators (e.g., Ioannou and Martinez 1996) in a manner more sophisticated than what is currently modeled.

8 CONCLUSIONS

The presented simulation model uses a modularized approach, adaptable to other construction sites settings that have similar characteristics with regard to the material and waste flow on site. The selected software allows for a user-friendly implementation of the model for both data input and statistics output. The model considers all logistical processes including supply and disposal tasks in the finishing phase of a building construction project. Additionally, the interdependence of logistical- and construction-operation processes was modeled, though this could be further fleshed out.

Simulation using data from a real hotel building project helped to verify the functionality of the implemented model and to investigate two alternative supply strategies. Compared to the basic scenario, which reflected the current practice, the proposed kitting scenario was able to reduce the amount of material surplus and rehandling. However, as modeled, it resulted in an increase in the number of handling units supplied to the construction site. Nevertheless, previous findings with regard to the improvement of task completion motivate further investigation of the kitting approach. In future, the simulation model should be applied to additional construction projects in order to improve the input data quality regarding company-specific data and to potentially extend the model to address additional planning objectives.

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