Development and Analysis of Process Simulation in Building Construction

Entwicklung und Analyse von Prozesssimulation im Hochbau

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Abstract

Building construction is known for its one-of-a kind production and its complexity caused by high interdependencies of logistical and construction processes. Especially in the outfitting phase, there is a high diversity of trades involved who require a wide variety of materials and have to share logistical resources. Traditional planning approaches based on analytical tools and experience values gained from historical project data reach their limits at evaluating different logistical strategies. Therefore, the present work aims at the development of a user-friendly simulation model which considers the entire material and waste management through a third-party logistics partner in addition to interdependencies between logistical and construction processes on a building construction site in the finishing phase. The simulation model is designed in a modular approach to achieve adaptability to multiple construction projects using repetitive layouts in their building design. The simulation model is implemented using a standard software and verified on a real hotel building project. Within a parameter study, multiple logistical factors are varied, and a kitting solution is evaluated as an alternative supply system to eliminate multiple material handlings on site.

Kurzfassung

Der Hochbau ist bekannt für seine Unikatbauwerke und seine Komplexität, die durch hohe Abhängigkeiten von logistischen und baulichen Prozessen entsteht. Insbesondere in der Ausbauphase ist eine hohe Vielfalt an Gewerken beteiligt, die unterschiedlichste Materialien benötigen und sich logistische Ressourcen teilen. Traditionelle Planungsansätze, die auf analytischen Werkzeugen und Erfahrungswerten aus historischen Projektdaten basieren, stoßen bei der Bewertung unterschiedlicher logistischer Strategien an ihre Grenzen. Ziel der vorliegenden Arbeit ist daher die Entwicklung eines anwenderfreundlichen Simulationsmodells, das das gesamte Material- und Abfallmanagement durch einen externen Logistikpartners sowie die Interdependenzen zwischen Logistik- und Bauprozessen auf einer Hochbaustelle im Ausbau berücksichtigt. Das Simulationsmodell ist modular aufgebaut, um die Anpassungsfähigkeit an mehrere Bauprojekte mit sich wiederholenden Grundrissen in der Gebäudeplanung zu erreichen. Das Simulationsmodell wird mit Hilfe einer Standardsoftware implementiert und an einem realen Hotelbauprojekt verifiziert. Im Rahmen einer Parameterstudie werden mehrere logistische Faktoren variiert und eine Kommissionierlösung als alternatives Versorgungssystem evaluiert, um mehrfachen Materialumschlag auf der Baustelle zu vermeiden.

Vorwort

Die vorliegende Arbeit entstand unter der wissenschaftlichen und inhaltlichen Anleitung von Anne Fischer, wissenschaftlicher Mitarbeiter am Lehrstuhl für Fördertechnik Materialfluss Logistik (fml) der Technischen Universität München.

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Ort, Datum

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List of Abbreviations

Abbreviation	Meaning
3D	Three-Dimensional
BIM	Building Information Modeling
CAD	Computer-Aided Design
FIFO	First-in-first-out
GUI	Graphical User Interface
JIT	Just-in time
LPS	Last Planner System
SPS	Special Purpose Simulation
STS	Simulation Toolkit Shipbuilding
TPLP	Third-Party Logistics Provider
TM	Transportation Means
VDI	Verein Deutscher Ingenieure

List of Symbols

Symbol	Unit	Meaning
i	[-]	Takt area
n	[-]	Number of employees performing a task
n_{floor}	[-]	Number of employees who work on a certain floor
c	[-]	Max. capacity of persons using an elevator simultaneously
r	[%]	Ratio of employees spending break on the ground floor
t_{unit}	[time]	Processing time per unit
t_{task}	[time]	Total processing time per task
$t_{unitCalc}$	[time]	Calculated processing time per material unit
$t_{remaining}$	[time]	Remaining working time of a day
x	[-]	Number of units
$x_{processCalc}$	[-]	Number of material units to be processed
$x_{handling}$	[-]	Number of material units within a handling unit
$x_{process}$	[-]	Number of required material units

1 Introduction

1.1 Initial Situation and Motivation

Simulation is a tool which can help to support planning processes, to deeply understand processes, identify bottlenecks in advance, and increase planning quality by quantitively analyzing future projects.

In the manufacturing industry, simulation is already widespread and a well-accepted tool [Wen-2013]. Managers were able to significantly reduce waste in their processes such as unnecessary material handling or poor coordination processes by implementing new methods. In the construction industry, the level of waste is still very high as 57% of the processes on a construction site can be regarded as waste [Bla-2008; cited from Tri-2014]. To be able to eliminate waste, simulation also gains interest within the construction industry. 88% of the respondents of a survey conducted by *Leite et al.* regard simulation as a promising research within the next decade [Lei-2016]. Also, the industry partner of this project emphasizes the need for digital tools that can support planning processes.

However, a simulation model cannot be simply transferred from a manufacturing environment to construction projects as they differ from manufacturing in certain points. In building construction, each building and each construction site is unique. Moreover, the production itself differs. In construction, there is an on-site production whereas in manufacturing the products are usually produced within company-owned buildings. Additionally, the effort to coordinate people, resources, and processes is considerable high resulting in high complexity. [Baj-2017]

This especially applies to the outfitting phase of a project due to the great variety of trades involved, the shared logistical resources, and the resulting high coordination effort [Kön-2007]. The finishing trades represent the largest part (about 36%) of the construction volume in building industry in Germany in 2019 [BBR-2020]. Therefore, the finishing phase is a highly relevant phase in a construction project.

However, *Boennert and Blömke* stated that in the finishing phase 30 % of the working time is spent for construction logistics such as transportations, searching for materials, rearranging materials, clearance, and others. They estimate that 10 % of the total working time could be saved as insufficient logistics planning is a major cause for disturbances within construction processes [Boe-2006; cited from Voi-2008].

Moreover, *Lindén and Josephson* stated that costs could be reduced by approximately 20% if material handling is organized by a logistics plan which is executed by a third-party logistics partner [Lin-2013].

To get a sophisticated solution of this highly complex system, it is necessary to consider the interdependencies between logistics and construction processes. It has already been detected early that planning from a logistical point of view can contribute to productivity enhancements [Aga-1998]. Nevertheless, a partial optimization can be counterproductive [Voi-2010]. Analytical tools and traditional planning methods based on experiences of the managers and historical data from previous projects cannot solve these multidimensional problems.

1.2 Objectives of Research

To address the abovementioned issues, this work aims at developing a simulation tool that is suitable to support planning processes within building construction, emphasizing logistical aspects. Thereby, all the logistical process on site are considered – from the point of material supply to the point of disposal of waste and empty pallets. Additionally, the relevant aspects from construction processes regarding logistical processes are included in the scope of this work to take account of the interdependencies between logistical processes and construction processes. The visualization of the construction processes itself is not part of this work.

To enhance the use as a planning tool, the simulation model aims at a modular implementation to be able to use the model for multiple projects without great programming effort. The user interface should be designed user-friendly in order to provide the tool for users without extensive training in the simulation software. The effort to generate and import required input data should be reduced as much as possible under the aspect that no direct data connection to further digital tools has been available. Moreover, the most relevant statistics should be presented automatically in order to provide quantitative measures of the future project. Therefore, managers can make decisions based on data obtained from the virtual future project rather than historical data and experiences. These measures concentrate on logistical aspects in relation to supply, utilization, and cost, rather than on construction duration.

Lastly, the impact of logistical parameters, such as kind of transportation means, logistical personnel, or supply strategy, should be analyzed, based on the data of a real project conducted by the industry partner of this work.

1.3 General Approach

Conducting a simulation follows certain defined steps, see Figure 1-1.

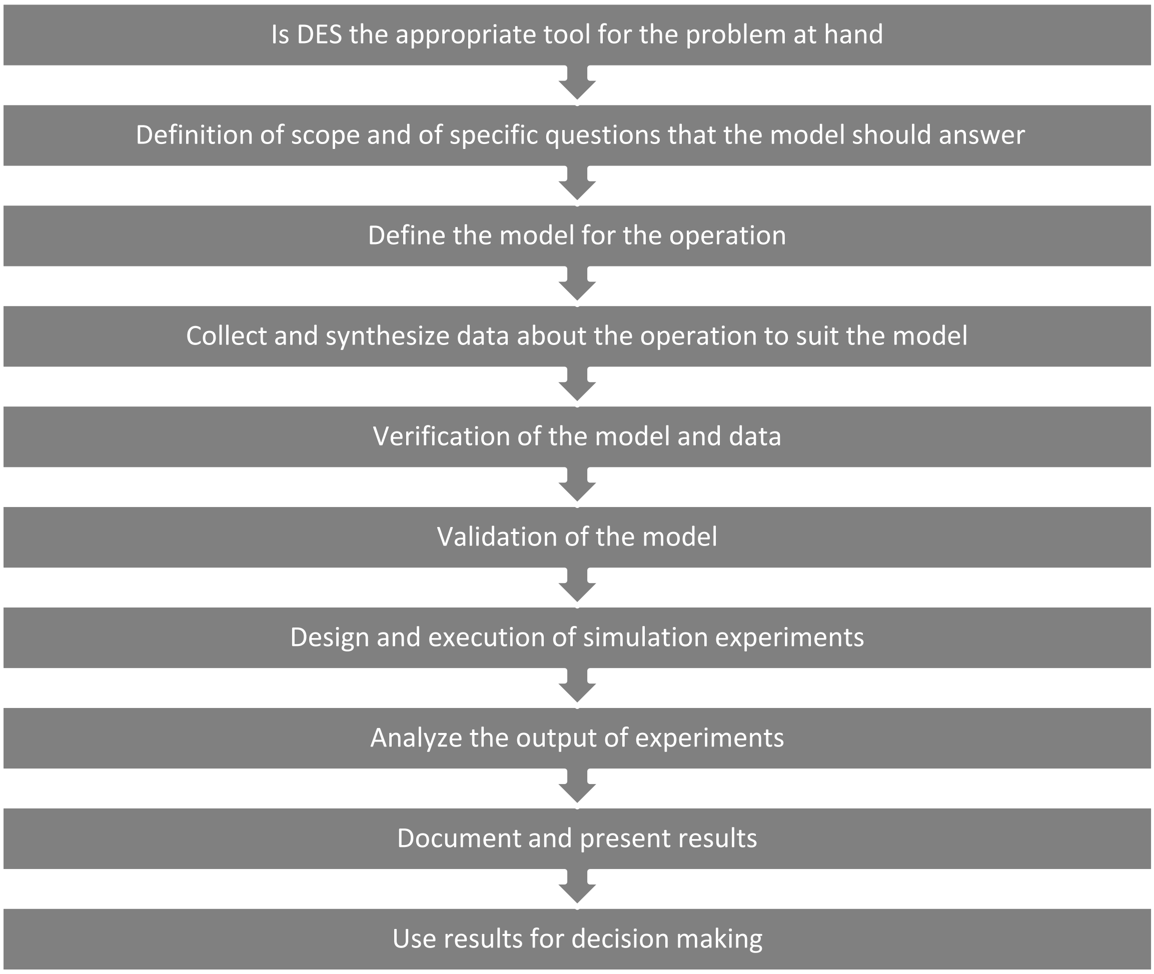


Figure 1-1: Framework based on Martinez [Mar-2010]

In chapter 2, relevant literature and research is presented regarding general characteristics and optimization trends within building construction, including planning processes. Afterwards, the conceptual model of the present work is described in chapter 3, including the considered processes and certain requirements that have been elaborated. The implementation of the defined model is described in chapter 4, followed by a parameter study of certain logistical parameters based on the data obtained from a real building construction project in chapter 5. Chapter 6 discusses the results of the parameter study and the general application of the implemented simulation model. In chapter 7, this work is concluded, and possible further research areas are shortly mentioned.

2 Review of Literature and Research

2.1 Building Construction

Processes within building construction are associated with unique characteristics which are described in the following chapter. Furthermore, current planning objectives, practices, and challenges are investigated. Finally, various aspects regarding lean construction and supportive digital tools are summarized to show recent optimization approaches within building construction.

2.1.1 Characteristics

Construction is defined as a “complex logistic system of people, machinery, tools, and materials” [Ber-2013]. In contrary to other industries, the product itself, the building, is immobile and the workstations, the trade employees, move through the building to complete their tasks [Bal-2012]. The construction industry is characterized by so-called one-of-a-kind projects which are realized within a unique environment [Tom-1999]. Even if the logic of building can be transferred across several projects, influencing factors like location, required tasks, or available worker skills are exclusive for each project [Beh-2015].

The organizational complexity of construction projects derives, among other things, from the orientation towards subcontracting [Mou-2021]. This results in a great fragmentation and high specialization across the involved participants, which are often only combined to carry out one specific project [Arb-2004; Weg-2001]. Another factor increasing complexity is the close connection between construction and logistical processes, needing a high degree of coordination due to strong interferences [Ber-2013].

Construction processes are characterized by a high variety of trades involved, especially in the finishing phase [Ber-2013; Voi-2008]. The different tasks are highly interrelated and constrained to a certain order of precedence, to the availability of required resources (personnel, equipment, and space), and to a desired level of resource continuity. Especially in the finishing phase, the execution is organized by combining certain activities to repetitive sets. The repetitive operations are performed unit by unit by the same crew within a certain time window. [Sri-2008; Beh-2015]

2.1.2 Construction Logistics

Construction logistics is regarded as an independent function and as a basis for construction processes [Fei-2016]. The point of transfer between logistics and construction activities is defined at the installation location [Voi-2014]. Construction logistics is responsible for planning, operating, and controlling all resources (equipment, material, and employees) and all related information throughout the entire construction process [Sam-2013; Tis-2013]. The main goal is to ensure the delivery of the right product in the right quality in the right amount to the right place at the right point of time, also referred to as the "5R"s of logistics [Ham-2007].

In general, three different areas can be defined with regard to the material flow (see Figure 2-1): procurement logistics reaching from procurement tasks to the supply of materials to the site, production or site logistics including all tasks related to material handling, storing, and allocating at the construction site, and finally disposal logistics describing the disposal and recycling of waste [Ran-2005; Tis-2013; Voi-2014]. Additionally, information logistics is necessary to ensure a smooth and continuous material flow [Sam-2013].

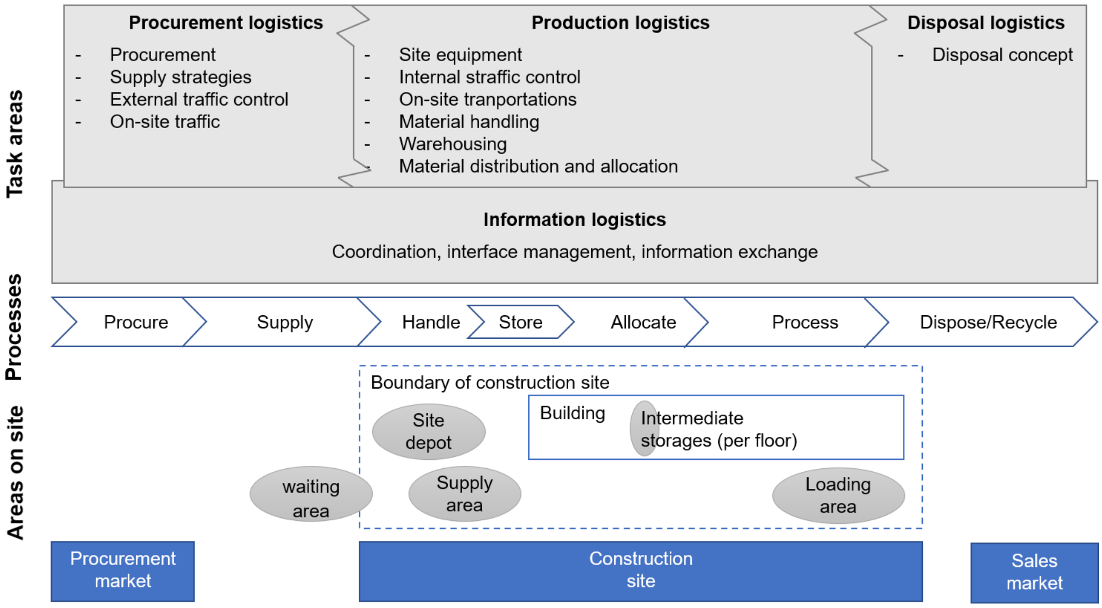


Figure 2-1: Areas of construction logistics [Voi-2014]

Procurement logistics

Materials are supplied to the site in response to orders placed by those responsible at the construction site. To ensure a timely arrival corresponding to the construction schedule, supplies to the construction site have to be planned carefully, also considering the overall supply chain, traffic patterns and transportation permits [Tom-1999; Vri-

2000]. The degree of coordination effort needed depends on the size and the phase of the construction project and the amount of logistical equipment at site [Mou-2021]. During outfitting, the diversity of required materials is particularly high. It is common that materials are delivered separately per trade by relatively small trucks or trucks that combine supplies across multiple sites [Voi-2008]. To reduce the number of trucks, the installation of so-called “logistics centers” gains more and more interest among general contractors [Mou-2021]. A logistics center represents a central point for material suppliers. Hence, material supplies to different sites can be prepared by preloading, which minimizes the number of trucks, the required packaging and the handling effort at the site [Ran-2005; Mos-2007]. Moreover, logistic centers can contribute to decrease the effort of on-site logistics and to improve the overall quality of logistics, e.g. by offering modern information and tracking services, kitting, damage control, or e-commerce [Ham-2007]. However, consolidation centers are rarely used in practice and still relatively unexplored within the construction industry [Hsu-2018; Mou-2021].

Production and information logistics

Efficient material management is the main task of production logistics. If there are large volumes of materials supplied to the site, it is common to stockpile the materials on site before they are transported to their installation location [Ran-2005]. Therefore, the positions, sizes and organization within the site depot and the intermediate storage areas on the floors have to be planned considering the limited availability of space and the spatial variability caused by continuously changing working areas [Voi-2010]. The necessary equipment, including vertical and horizontal transportation means, is usually provided by superior structures, e.g. the general contractor [Voi-2008]. The logistical tasks on site can be performed by a hired third-party logistics partner (TPLP) or by the employees of the trades themselves [Sob-2005].

Due to the numerous suppliers and subcontractors involved, communication and coordination is crucial, especially in the urban environment characterized by very tight space [Tom-1999; El -2021]. When developing logistical strategies, the on-site material and waste flow has to be studied in detail in advance to identify arising interfaces and needs for information coordination to attain a reliable and robust logistical system that can meet the material demand of construction processes [Lu-2018].

Disposal logistics

Disposal logistics already start on site. An efficient construction planning resulting in a high productivity increases the waste per time unit [Lip-1999]. The logistics service partner is responsible to provide multiple bins to prepare a separate waste management. The partner has to control an appropriate separation of material according to the defined waste fractions and to organize both the central collection and the final disposal according to previously set waste management processes and to legal provisions [Tis-2013]. A lack of explicit rules regarding cleaning can lead to disorder and possibly unsafe working conditions [Ran-2005]. Consequently, a waste management regulation has to aim at a noticeable improvement of the working environment to achieve a higher acceptance by all participants [Lip-1999].

Overall, the organization of a construction site is associated with a high degree of uncertainty and numerous risks which is reinforced by the high time and cost pressure during all phases. As non-coordinated processes result in a disorganized material storage, a high amount of non-productive actions, and an overall disturbed work flow [Voi-2010], a significant improvement of the overall productivity can be achieved if the building processes are planned from a logistical point of view [Aga-1998]. The savings from well-planned logistics quickly compensate potential additional effort and costs [Mou-2021]. To identify potential areas of improvement, typical planning objectives, constraints, and current activities are investigated in the following.

2.1.3 Planning Process

The planning of construction projects is a highly complex organization problem which has to consider multiple objectives and interrelations and must be adapted individually to each construction project [Voi-2010; Ber-2013]. The main objective is an efficient allocation of available resources to provide a temporal feasible and robust project schedule under minimization of risks and uncertainties in construction [Ber-2013]. To be able to manage the complexity of a one-of-a-kind project, an in-depth and superior planning including the influences by logistical processes is required to ensure an optimal material and waste flow, a high utilization of personal and equipment, and to avoid cost overruns and delays [Wen-2013].

Planning has to consider multiple constraints like technological dependencies (sequence of work steps), capacity (amount of employees and equipment), availability of storage area, safety criteria regarding employees, and equipment [Kön-2007]. Moreover, laws, regulations, and further unique conditions of the construction site have to be taken into account [Ber-2013]. Furthermore, planning operations face difficulties through high levels of risk and uncertainty and incomplete information about interrelations between the individual processes. Also, frequent design changes and high time and cost pressure are major challenges during the planning phase [Abo-2011].

Planning decisions have to be made based on a large number of data sets from different sources. Oftentimes, the information is not readily available. Significant effort is needed to collect and clean up the needed data from the different involved parties [Abo-2011; Lei-2016]. The match of demand and supply on site is another common challenge specifically for logistic processes as both, demand and supply, can vary throughout the construction period. A mismatch will cause an ineffective project management, increasing cost and delay [Arb-2004].

In traditional planning, the focus is primarily set on total project time, total costs, and on the final product design rather than on value generation during building production [Nin-2017; Baj-2021]. To plan on-site logistics, several analytical methods are applied, e.g. Critical Path Method, Location-based Management for Construction or Earned Value Analysis [Beh-2015]. Additionally, managers use structural process plans including milestones, gantt-charts, excel sheets and production plans to plan and control construction processes [Wen-2013]. Nevertheless, managers still rely on data collected during earlier projects and expert judgements [Akh-2013]. *Jeong et al.* found that for new projects, historical data is complemented by characteristics of material and available machinery to calculate project plans and overall costs and duration [Jeo-2016]. Afterwards, the involved individuals heuristically adjust the calculated plans based on their experiences. Additionally, the reserachers propose to also include further complexity details, learning curves, and the coordination process to identify bottlenecks at an early stage. However, historical data and heuristics can hardly incorporate all aspects of the new project or react properly to constantly occuring modifications [Fei-2016; Jeo-2016]. Even if 69% of all participants in the study of *Leite et al.* stated that they use visualization during planning [Lei-2016], a systematic analysis and optimization of different process sequences and variations of resources isn’t conducted in a systematic manner but largely following the principle of “trial and error” [Ste-2010; Abd-2020].

The increase of size and complexity combined with problems of multidimensional optimization reaches the limit of analytical tools [Fei-2016]. However, optimizing only partial aspects can be counterproductive [Voi-2010]. For further improvement of construction planning, a holistic approach is required which considers all relevant data within the ERP-system and supports an interdisciplinary communication and transparency [Wen-2013]. Recent approaches for optimizations can be found within the lean construction philosophy and new digital developments which will be further discussed in the following.

2.1.4 Lean Construction

Lean is a production philosophy developed within the automotive industry by *Ohno* [Ohn-1988]. It describes a fundamental management ideal of customer-focused production which follows certain principles, systematically eliminates wastes in the production process and applies several methods to perfectly match supply and demand. *Koskela* first linked the term “lean” to the construction industry in 1992 [Kos-1992].

The main principles of lean were compiled by *Brodetskaia et al.* and *Bajjou and Chafi* [Bro-2013; Baj-2021]: “specify value” means classifying activities based on their value, “map the value stream”, “make value flow without interruptions”, and “pull value” derives the identification of waste and opportunities within the process in order to improve it where possible, and finally “pursue perfection” which refers to the continuous improvement principle of lean.

According to *Bajjou and Chafi*, activities can be divided into three categories: value-adding activities add value from a customers’ perspective, e.g. processing construction material. Non-value adding but required activities directly support VA activities, e.g. by positioning or inspecting material. Non-value adding activities are specified as waste because of their missing contribution to value creation for the customer [Baj-2021]. Following the seven kinds of wastes defined by *Ohno* [Ohn-1988], several non-value adding activities were identified in the construction industry, e.g. oversized use of material or equipment (overproduction), goods awaiting process or consumption (excess inventory), unnecessary transportations of goods or movements due to a non-optimized logistic flow or displacements, or waiting of employees for predecessor activities to be finished or material to be delivered [Baj-2017] .

The waste rate of the construction industry is still at a high level of 57% (compared to 26% in manufacturing industry) [Bla-2008; cited by Tri-2014]. To eliminate the identified wastes, several methods are proposed within different process dimensions. For the construction processes, exemplary methods include root-cause diagrams, the five why method, or the Last Planner System (LPS) to improve the process performance [Bam-2019]. LPS supports managing reliability and variability within project planning and project control. LPS has already been developed in 1992 in response to major discovered deficits in scheduling as only almost half of the tasks have been completed in time due to unplanned changes in schedule and later rework [Bal-2012]. Using LPS, weekly workplans are developed based on definition, soundness, sequence, and size of the tasks, and further aggregated to the overall project schedule [Bal-2012]. However, the system cannot support pull control or further logistical aspects [Bro-2013].

For the organization of the site, 5S has been proven to be an effective method as both material and equipment are assigned to a place. Thereby, visual management is improved, and non-value adding searching activites are reduced [Baj-2017].

For logistical processes, Just-in time (JIT) supply and kitting have been often proposed in the literature. *Tommelein and Weissenberger* describe the JIT approach as delivery of materials to the site to be installed immediately without any storaging. The orders are triggered rather by the construction management (pull) than by fixed scheduled delivery plans (push). However, a strategically sized buffer is necessary in practice [Tom-1999]. Furthermore, the probability of success decreases for a high number of supply systems coordinated by each subcontractor and by truckload [Arb-2004; Sep-2016].

Kitting is a solution that gains interest within the more recent literature, especially for urban projects [Mou-2021]. Construction logistic centers (CLC) are installed to receive the supplies of different subcontractors in a multi-project view. Material packages are separated and kitted considering the exact material requirements by each construction site. Afterwards, a minimum number of packages is delivered to the site consolidating multiple trades [Whi-2018]. Therefore, non-value adding activities, such as material unpacking or separating, can be reduced on site [Mou-2021].

The effectiveness of these methods has been proven in several case or simulation studies, e.g. [Bam-2019; Mou-2021]. Since the cost- and quality-related benefits have been quantitatively investigated, the acceptance of the proposed methods increases within the construction industry [Bam-2019]. However, finding the optimal combination of different strategies considering site specific influencing factors is still challenging [Voi-2008].

2.1.5 Digital Tools

To improve the quality decisions within construction planning processes, managers often refer to supportive digital tools. To maintain a high-performance standard despite the increasing competitiveness and complexity of construction industry, supportive tools represent a great opportunity to increase productivity [Abd-2017]. *Leite et al.* conducted a survey on an expert task force from academia and industry to identify, among others, current benefits and challenges of visualization and information modeling. Information modeling faces major challenges with respect to data format and interoperability issues and missing big data resources. For visualization, the survey participants also stress problems arising from different output formats and mediums and budget limitations. The benefits of using information models and visualization were indicated in planning for productivity management and progress monitoring. Hence, *Leite et al.* see high potential for application in domains like planning, control or spatial and temporal conflict resolution. [Lei-2016]

A rapid pace of enhancements in IT has been observed within the past several years. New approaches have been developed and partly integrated in current planning processes, e.g. Building Information Modeling (BIM), remote sensoring, and simulation [Jeo-2016]. The aim is to create a “digital construction site” where construction and logistical processes can be modeled, visualized, and simulated in advance of construction start [Kön-2015].

BIM is an accurate virtual model of the construction site including information about geometric properties (3D) evolving over time (4D) and required materials and costs (5D) [Gom-2016]. Therefore, BIM represents a consistent and transparent data platform which can enhance collaboration and communication through an effective information exchange [Nin-2017; Wic-2020]. Moreover, the consistent and accurate data stored in a BIM model allows for further analysis, e.g. simulations, in order to evaluate different planning alternatives [Kön-2015]. BIM is still continuously developed by adding dimensions like energy efficiency and life cycle analysis (6D) and logistics, procurement, and contracting (7D) [Gom-2016].

Further digital developments relate to sensoring, tracking, and automation within the production control. Sensors allow for gathering diverse and detailed data which can be used to evaluate, for example, the durability of buildings [Kön-2015]. Tracking and tracing systems, like RFID or bar codes, can be included in real time engineering to investigate the actual material flow and logistical movements [Lee-2013; Sam-2013]. *Akhavian and Behzadan* give a short overview of recent developments [Akh-2013].

To achieve a further integration of digital tools in the planning process of the construction industry, the large amount of data must be available for planners for the entire production process including dynamic interactions in a comparatively short time [Ber-2013]. As a result, the data can be used to develop a high-detail process model which can be analyzed by simulation with regard to behaviors in future without interference with the actual operations [Arb-2004; Kir-2013].

Simulation in building construction is another digital tool which is described in the following.

2.2 Simulation in Building Construction

In the following, simulation is classified as a mathematical solution approach associated with general benefits corresponding to an application within the construction industry. Afterwards, there is a short overview of the development of simulation within the construction industry and current researches of simulations in building construction. Last, identified challenges of current approaches are grouped in four categories together with proposed requirements to overcome these.

2.2.1 Classification and Opportunities

Simulation is defined as follows: "Simulation is the reproduction of a real system and its dynamic processes in a model. The aim is to achieve transferable findings for reality. In a wider sense, simulation means preparing, implementing and evaluating specific experiments using a simulation model." [VDI-3633]

Simulations are classified regarding three dimensions: static vs. dynamic, deterministic vs. stochastic, and continuous vs. discrete. Within static models, also referred to as Monte Carlo Simulation, a system is represented in a particular point in time, whereas in dynamic models the system evolves over time. In deterministic models, the same, known input always generates the same unique output while stochastic models include at least some random input values which result in an estimation of the true output of the model. However, deterministic models can be a defined as a special case of stochastic models. If state variables of the model only change their value at discrete points in time, the model is defined as a discrete model. If states change continuously over time, the model is called continuous. [Ban-2010; Law-2015, S.5]

Simulations are applied if performing experiments within the actual or physically similar system is too costly or not feasible without biases. In these situations, the system can only be analyzed by mathematical models. If a model cannot be solved optimally by an analytical approach, simulations have to be used instead [Law-2015, S.5]. This often appears if systems are uncertain, complex, or include evident repetition, and if models require flexibility, special detail or an integrated solution [Abo-2010]. Within the construction industry, 88% of the participants in the survey conducted by *Leite et al.* described simulation as a value-adding research direction [Lei-2016]. Simulations in construction are characterized as computer-based representation of the construction system which is investigated under different sets of parameters to understand the behavior of the system [Abo-2010; Fei-2016].

In the planning process, a simulation can support the understanding of interdependencies in the system which leads to an efficient knowledge acquisition. Through the consideration of all influencing factors, the construction project can be analyzed in detail without having to be present at site. The layout of the construction site can be designed in a way that avoids bottlenecks. For both logistical and construction processes, resource allocation and usage can be optimized to eliminate waste. The impact of possible disruptions can be studied through experiments with different parameter sets. During the execution phase, simulations can enhance production control. If deviations occur, the impact and, if necessary, potential solutions can be quickly calculated to enable a reasonable reaction. [Abo-2010; Spi-2010; Ber-2013; Beh-2015]

Simulations can support decision-making numerically and graphically which can improve decisions throughout all project stages. Hence, project plans can be enhanced and faster developed which leads to minimized cost and project duration [Cha-2005; Abo-2010]. Within project coordination, simulations can provide a visualization of systems over time whereby stakeholders can better understand the system [Abd-2020]. This leads to an increased credibility and acceptance and a better communication between the involved parties [Cha-2005; Abo-2011].

2.2.2 Development of Simulation Tools in Construction

First, *Halpin* introduced CYCLONE as an intended general-purpose simulation system [Hal-1977]. CYCLONE was able to model cyclic networks but was limited to its inability to model resources [Abo-2010]. Since then, several researches introduced multiple tools attempting to improve the simulation quality within construction industry. The most important steps can be seen in STROBO-SCOPE, introduced as a special purpose modeling and simulation tool adaptable to numerous construction systems [Mar-1994], and Simphony, a simulation language capable to model e.g. tunnelling, earthmoving, and dewatering construction projects [Abo-1998].

Following the new opportunities identified, research was attempting to integrate other tools, like visualization, within simulation. *Xu and AbouRizk* extended Simphony through an integration of AutoCAD models [Xu-1999]. *Kamat and Martinez* introduced a new approach called Vitascope, which is capable of planning construction operations by a DES for construction followed by an integrated 3D visualization [Kam-2003; Abo-2011].

Current developments have focused on the model quality and applicability in the construction industry. *AbouRizk and Hague* introduced COYSE which is applicable to multiple sites as it enables the reuse of certain components and a collaborative development [Abo-2009]. *König et al.* adapted a specific purpose simulation toolbox from the shipbuilding industry which allows for further generalization over multiple construction sites [Kön-2007].

2.2.3 Application in Building Construction

In the past, several research studies have applied simulation tools in order to investigate different influencing factors of building construction and to achieve an improvement of construction and/or logistical processes. In the following, the most significant studies regarding the present research are briefly summarized.

Table 2-1: Overview of researches applying simulation in Building Construction

Author/ Research group	Construction Phase/Project	Software	Objective
Weber [Web-2007]	Shell construction + Outfitting	Enterprise Dynamics	Verify logistics strategies (supply and warehousing strategies)
SIMoFIT e.g. [Kön-2007]	Outfitting	STS	Develop a feasible construction schedule under consideration of constraints regarding material, space, and efficiency
Mefisto [Spi-2010]	1) Hotel building 2) Gate construction	STS	Develop a block library for 1) logistics and 2) construction processes
Bamana et al. [Bam-2019]	Erection of wood shell	Simio	Investigate effect of lean construction on construction duration
Kugler [Kug-2012]	Shell construction	CiSmo	Develop a user-friendly tool with high degree of automation within data acquisition
Simject [Gut-2014]	Windmill	simAssist + Plant Simulation	Simulation-based and logistic-integrated project planning and scheduling
Voigtmann [Voi-2014]	Outfitting	STS	Investigate influencing factors on construction logistics by considering the variability of construction and logistical processes

The research of Weber 2007 aimed at developing a digital tool which supports planning activities of managers regarding logistical strategies. He used the software enterprise dynamics (Fa. INCONTROL GmbH) to model logistic processes including material supplies to the construction site, potential material storage, and supply to the installation locations. Quantities of required materials are obtained from the 3D-CAD-modell of the planned hotel building and subsequently linked to construction processes. Schedules are considered within the simulation to determine timing and destination of material transportations. Construction processes are not further investigated as the main objective of the study is the dimensioning of unloading zones and transportation means in the early planning stage.

The research partnership *SIMoFIT* (Simulation of Outfitting Processes in Shipbuilding and Civil Engineering) transferred the Simulation Toolkit Shipbuilding (STS) to building constructions as they described significant similarities between the interior construction processes of shipbuilding and building construction [Ste-2010]. The focus of simulation studies within this partnership was set on predecessor-successor-relationships of works during outfitting depending on the availability of required resources such as personnel and material [Kön-2007; Ste-2010]. However, the logistic processes have been limited to statistical distributions of material availability without further investigating the transportations at the site.

The research alliance *Mefisto* developed a block library for assembly and logistic processes within the construction industry based on the existing STS [Spi-2010]. Construction processes have been investigated for a hotel building construction project considering a detailed schedule whereas the logistical processes are based on supply systems within gate constructions in early planning stages with only rough schedules. A combination of both libraries in building construction did not take place.

A lean focused approach was developed by *Bamana et al.* [Bam-2019]. Logistical processes were taken into account regarding material supplies, material storage, and lifts to installation locations. Construction processes were only implemented to determine the quantity and timing of required material at the site and at the working areas. The impact of certain lean methods (prefabrication, 5S and JIT) have been studied for a six-story wooden building in Canada using the software Simio. Even though *Bamana et al.* only considered the erection phase of the building construction project, the detailed modeling of transportations, storage issues and of movements of workers of both logistics and trades provide an accurate understanding of important logistical processes.

Kugler aimed at providing a tool with a high degree of automation in data acquisition and a simple user interface which can be applied to any kind of building construction projects [Kug-2012]. However, he concentrated on direct production logistic processes, neglecting all kinds of procurement and disposal logistics [Voi-2014]. To validate his software prototype CiSmo, he applied the agent-based simulation model to two real projects, a passive trakt housing project (four houses including 22 single-family homes) and a senior center with three floors.

From a project planning point of view, the research alliance *simject* developed a “demonstrator for a simulation-based and logistic-integrated project planning and scheduling” especially for small and medium-sized companies [Gut-2014]. The project provided an entire IT-architecture which includes both logistical processes (from material supply until the point of installation) and construction schedules connected to required resources. To combine both processes, the researchers used the software simAssist in combination with Plant Simulation from SimPlan AG to optimize schedules of a building construction. Even though the researchers investigated a case study for a windmill plant in detail, the researchers promise a wide application potential in building construction [Gut-2014]. However, the logistical processes and the construction processes are optimized in two separated simulation models.

The dissertation of *Voigtmann* published in 2014 can be regarded as the most relevant study relating to the present work [Voi-2014]. Her objective was to provide a simulation-based planning tool which 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 modularized, constrained-based simulation approach using the modular STS block to investigate logistical processes during the outfitting phase in building construction, specifically tested for a multi-story office building. Construction processes are modeled variably, only constrained by predecessor-successor relationships and resources requirements. The logistical processes are considered from the point of material supply to the point of material installation. Even though she mentions that disposal tasks have to be considered to get a complete understanding of the logistical processes at a building construction site, she assumed that the material is delivered in the exact needed amount and neglected possible arising blend. Therefore, disposal logistics are not considered.

2.2.4 Challenges and future Requirements

Though simulation has been investigated in academia for decades, there has been no widespread adoption of discrete-event simulation in the construction industry [Abo-2010; Lee-2013]. This is especially true for small and medium-sized companies [Fei-2016]. Nevertheless, there is limited use in early planning and design stages [Akh-

2013; Oso-2020]. Within literature, there have been identified several challenges, which can be grouped into four main categories: challenges related to the stakeholders, to the modelled projects, to the simulation model itself, and to the required input data.

Challenges related to the stakeholders

Stakeholder-related issues can arise from a lack of expertise in using simulation tools [Bar-2015]. Missing training leads to a lack of trust in the effectiveness of simulation tools [Lei-2016]. Low confidence may also be caused by too little involvement of stakeholders in the phase of conceptual modeling. Therefore, the model may not comply with their expectations referring to the desired level of detail and, again, leads to missing knowledge about the modeling logic [Mar-2010; Abd-2017]. Hence, most practitioners perceive simulations as a “black box” which can decrease their perceived value of opportunities through simulation and reduce their willingness to invest [Beh-2015]. This is even more crucial as stakeholders in a survey conducted by *Leite et al.* stated a limited budget as the greatest barrier [Lei-2016]. This fact is enhanced if the use of a simulation is evaluated as an investment for a single project rather than a series of projects [Fei-2016]. As management decisions are primarily cost-based, simulation will only be integrated within the curricula of a company if a cost advantage is seen [Lee-2013] and if management has accepted simulation as a valuable tool to support planning [Ber-2013]. Nevertheless, the lack of integration in the company process is claimed by several researchers as limiting factor of simulation application [Kug-2012; Beh-2015; Gut-2015].

Challenges related to the project

Challenges related to the modeled project are mainly based on the unique and complex nature of construction projects. Due to the uniqueness, each project may require a new simulation model in an extreme case [Voi-2008]. *Wegelius-Lehtonen* compared a new project to prototyping in manufacturing industry [Weg-2001]. Therefore, validation against the real world in its original meaning is difficult to realize [Lee-2013]. A simple reuse of simulation models across multiple projects is not possible due to strong, complex, and site-specific interdependencies between the different processes and resources [Spi-2010]. These interdependencies are often specified manually which is an elaborate and error-prone process [Kon-2012]. Moreover, a high degree of alternation, especially in the finishing phase, enlarges the effort for modeling [Ste-2010; Bar-2015].

Challenges related to the simulation model

The simulation model itself might also contribute to the lack of adaption within the construction industry. As there is no simulation tool especially for the construction industry [Ste-2010; Bar-2015; Abd-2020], modeling is associated with high effort, relatively high cost, and a unique set of skills [Abo-2011]. If there are no graphical representations or navigation schemes included within the model, simulations tend to be abstract and confusing [Haj-2002; Oso-2020].

Moreover, there is a tradeoff between accuracy & reliability and efficiency & programming effort. Accuracy and reliability can be enhanced through a more detailed representation of the processes, tested across several projects [Fei-2016]. However, if there are more process details and data included than required, modeling effort is increased, and efficiency is decreased [Kug-2008; Ail-2008]. Another challenge can be seen in the high effort required to adapt the simulation model either towards changes of the current project or a new construction site [Akh-2013; Fei-2016].

Furthermore, the output of the simulation is often statistical and in text format [Oso-2020]. To improve user-friendliness, the output has to be relevant and efficiently presented in an understandable format [Kug-2008]. Finally, the model has to enable engineers to investigate typical planning problems in an appropriate manner [Fei-2016]. Testing interventions and adjustments have to be easily undertaken [Ber-2013].

Challenges related to the required input data

Data is often not readily available to be immediately imported into the simulation. Hence, a great effort is needed for data collection and data clean-up [Abo-2011; Ber-2013]. To obtain an accurate representation of the construction project, a large amount of data from many different sources is required [Oso-2020]. As there is currently no suitable linkage of data corresponding to schedule planning, logistical processes, and construction progress [Gut-2015], the required data are often collected by several people, each having his/her own “human judgement” regarding relevance. Moreover, data are often collected for a different objective. Therefore, obtained data are heterogeneous and not independent, identically distributed due to lack of consistency during data collection. [Mar-2010; Ste-2010]

2.3 Conclusion

Construction projects are characterized as unique and complex due a great number of participants involved and a high interconnection of construction processes and logistics processes. Traditional planning processes are mainly based on experience, heuristically adapted historical data, and analytical methods. The increasing complexity, uncertainty, and time and cost pressure call for innovative approaches to optimize processes at the construction site and to support decision-making.

One approach is to integrate the lean construction philosophy to systematically identify non-value adding processes. Through a targeted use of lean tools such as 5S, JIT, or kitting, waste can be eliminated. Additionally, new opportunities arise through the development of digital tools. Current digital tools only support a central data management and, hence, a better communication between involved individuals. A great potential is seen in simulating the processes before construction begins.

A simulation can support the decision-making as it allows for testing different strategies in a virtual environment, already at an early planning stage. Discrete-event simulation is the most used approach in the literature for addressing building construction. Research is mainly concentrated on scheduling problems. Logistical processes are often analyzed within the shell construction phase or only for production relevant logistical means. So far, *Voigtmann* has presented the most sophisticated approach analyzing building construction projects within outfitting considering logistical processes [Voi-2014]. However, the simulation model neglected disposal logistics which is an important part of logistical processes.

To the author's knowledge, there is no literature until now which developed a simulation for building construction which also consider disposal tasks. Therefore, the presented simulation approach considers the entire material and waste flow which is coordinated by a TPLP. Within the modeling approach, this work addresses the challenge of user-friendliness to achieve a greater adoption within the construction industry. Furthermore, the work deals with the 5S lean philosophy, and its methods, such as kitting, to optimize the current processes.

3 Conceptual Model

3.1 Process Description

The conceptual model represents a simplified and generalized model of the real system and is independent of the used simulation software [Pos-2016]. This work is based on the construction and logistical processes of a real hotel building project conducted by the industry partner Züblin AG. To achieve a wider application area, the layout and the processes have been generalized towards arbitrary hotel and office buildings sharing the same internal characteristics as the example project. The conceptual model has been developed in close cooperation with the contact persons of the industry partner.

In order to improve readability, only the male form is used in the text, nevertheless all information applies to members of all genders.

3.1.1 Construction Site Layout and logistical Equipment

The represented building design is characterized by multiple upper floors which are designed in a repetitive way using the approximately same layout. Hence, each floor which is designed using 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. Takt areas are characterized by similar resource requirements regarding material quantities and work expenses of construction processes.

In this work, the ground floor represents a lobby, a foyer, or an entrance area. The layout characteristics greatly vary across several projects. The processes are commonly organized largely independent from the rest of the construction site. Therefore, the construction processes of the ground floor are not further considered in the present work.

To follow the 5S lean approach, certain areas are specifically classified and marked within the layout of the construction site (see Figure 3-1). On the ground floor, an unloading zone, a material storage combined with a separate area for reusable, empty pallets, and a recycling center are defined. Trucks arriving at the construction site park in the unloading zone during loading processes. Material storage is regarded as transition area for the supplied materials. After unloading, materials are only temporally stored within this area until they are transported to their installation location. Within the recycling center on the ground floor, containers are placed next to each other. The number of containers depends on considered waste fractions for the construction project. Each container is assigned to a fixed waste fraction.

On each standard floor, one logistics area is defined. The area is divided in a recycling center and an area for empty pallets. One bin of each waste fraction is positioned within the recycling center. The material storages are defined as transfer areas between the third-party logistics partner (TPLP) and the respective trade, located at the center position of each takt area.

The arrangement of all moveable elements within a fixed area is assumed to follow the lean construction philosophy “5S”, too. The positioning of materials, bins and containers is well organized to minimize the occupied area and to avoid long searching times.

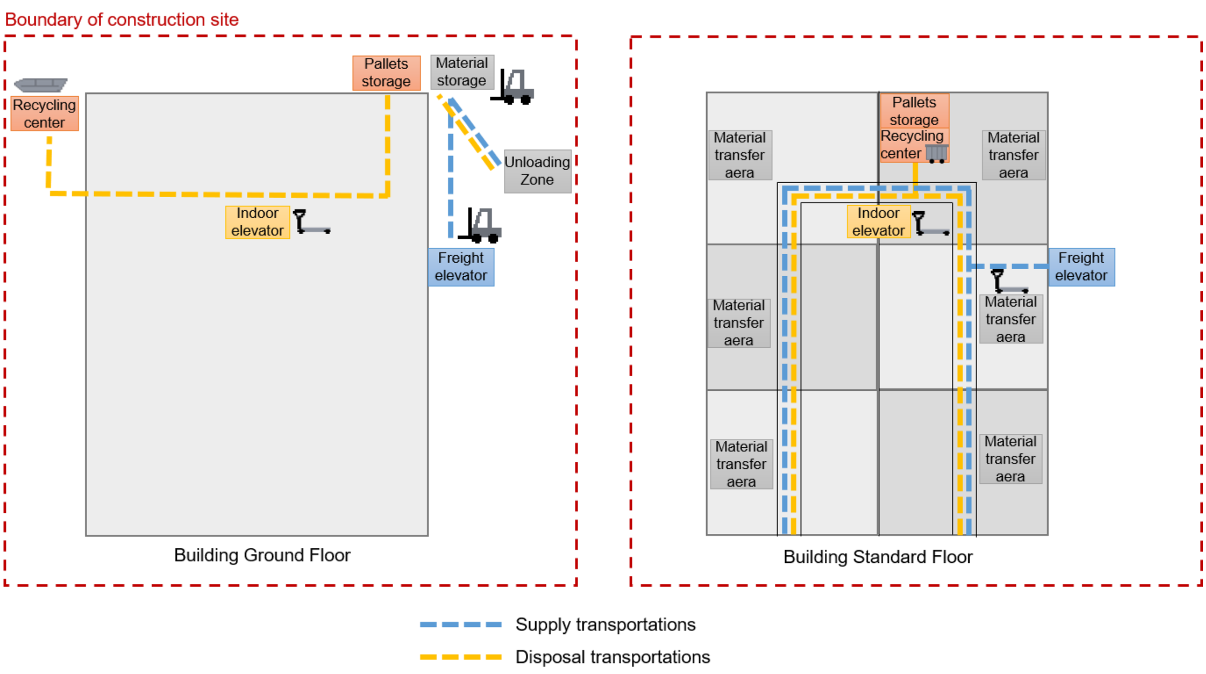


Figure 3-1: Construction site layout

The transportations required through logistical processes are performed by horizontal and vertical transportation means (TM). In the following, the vertical transportation means are referred to as “elevator” in order to describe the transportation behavior. Once a 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. Moreover, each horizontal TM is assigned to specific parking areas, again following the lean principles defined as 5S.

At least one freight elevator is positioned on the façade of the building which mainly transports material and persons. In the inside, there is an indoor elevator placed in the future elevator shaft of the building. As the shaft size is limited, the indoor elevator is too small to be able to transport material on their handling units. Therefore, it can only be used to perform disposal transportations, e.g. bins or empty pallets. The use by persons can be restricted by the site manager.

On the ground floor, there is at least one outdoor TM and one indoor TM. An outdoor TM can be parked next to the freight elevator or next to the material storage. The parking position of an indoor TM is located next to the indoor elevator. Additionally, there is at least one horizontal TM per standard floor which is parked next to any elevator.

3.1.2 Construction Process

The construction processes are repeatedly performed by the trades' employees, potentially by multiple crews per trade. The crews are organized within a so-called "train of trades" of which each wagon represents a set of tasks performed within one week in one takt area. The sequence of the wagons is described within the construction schedule. Therefore, the construction schedule gives a structured overview of which tasks are performed per week and takt area throughout the considered construction phase. The order of the tasks must be followed due to strict predecessor-successor relationships.

To adequately model each construction task, it is necessary to determine the work expenses per task based on the duration of processing one unit respectively. The definition of the unit depends on the type of task performed, e.g. a unit of length, area, or one material unit. The work expense per task (t_{task}) is calculated by the amount of units required within one takt area (x), the work expense for one employee processing one unit (t_{unit}) and the amount of employees available to perform the task per takt area at the construction site (n).

$$t_{task} = \frac{x \cdot t_{unit}}{n} \qquad (3\text{-}1)$$

Equation 1: Work expense per task

The employees of the trades use the elevators to get to their working floor in the morning, and to get back in the evening. Additionally, there are two breaks per working day, a morning and a lunch break. However, the employees spend their breaks on different locations due to cultural habits. Some stay on their working floor whereas others use the elevator to get to the ground floor to spend the break in the personnel containers.

Every Monday the crews move on to the next takt area according to the construction schedule. They start to work if all predecessor tasks are finished and if all materials required are readily available within the working space. Throughout the construction process, remaining empty pallets are centrally collected within the takt area. At the end of each task, the workers consolidate potential surplus material to one package.

3.1.3 Logistical Processes

Logistical processes are performed by a third-party logistics partner (TPLP) hired by the general contractor to increase productivity as the trades can fully concentrate on construction activities. The TPLP is aware of the construction schedule and of the required materials per wagon to be able to support the construction processes. The TPLP is responsible for both supply and disposal tasks. Transportations of materials and waste are carried out by one employee using available transportation means and bins. Figure 3-2 shows the flow of materials, waste, and empty pallets.

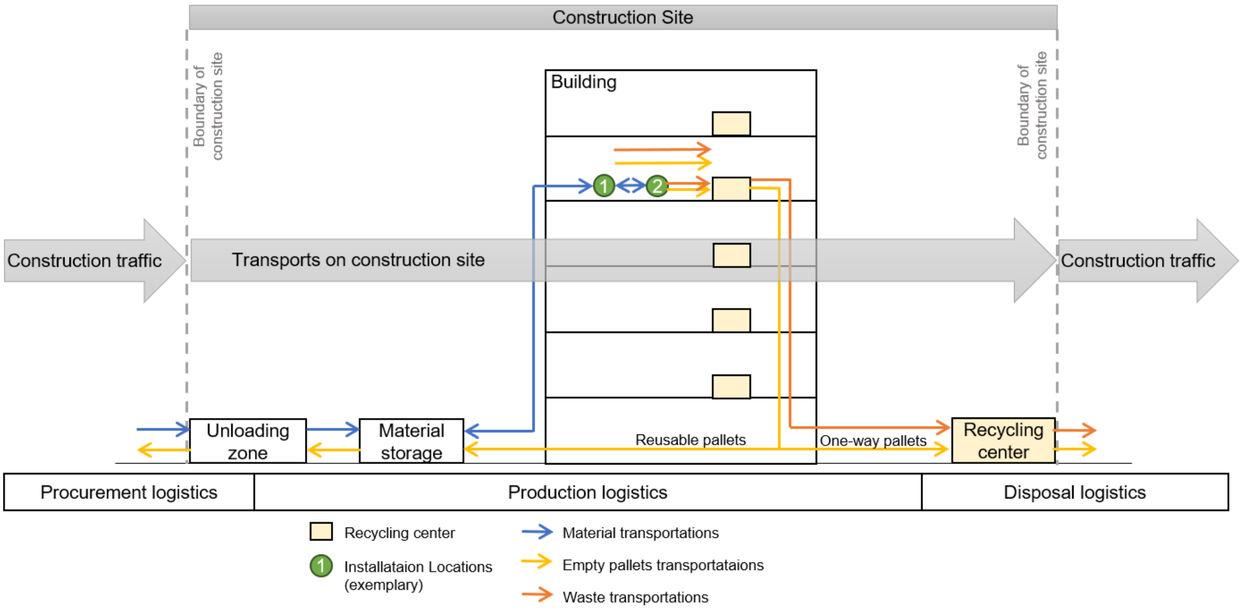


Figure 3-2: Logistic processes (based on Voigtmann [Voi-2014] and Boenert and Bloemke [Boe-2003])

Material supply to the construction site

The required materials are ordered by each trade separately and delivered to the site in the preceding week. The orders have to be placed timely considering the delivery time of the materials.

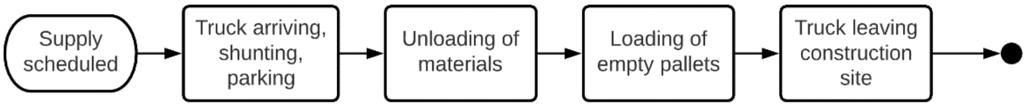


Figure 3-3: Material supply

The materials, loaded on handling units, are delivered to the site by trucks, which potentially shunt after arriving at the construction site, and park in the defined unloading zone. First, the trucks are unloaded by an employee of the TPLP, one handling unit at a time, using an outdoor TM. The duration of unloading one handling unit depends on the kind of handling unit and on the kind of TM. The materials are placed in the material storage which is often located in close proximity to the unloading zone. After having unloaded the material intended for the construction project, the employee potentially loads empty pallets on the truck, having stacked up to five pallets per transport. Thereby, the maximum loading area available on the truck is determined by the area that has been needed by the materials delivered to the site. The remaining area may be occupied by materials ordered by other construction sites. When the loading process is finished, the truck leaves the construction site.

Material delivery to the takt areas

The TPLP delivers material from the material storage to each takt area according to the required materials per wagon scheduled in the next week. The transportations are performed per handling unit separately. If a task is scheduled over two weeks, the required material is completely delivered in the first week. Particularities regarding potential separation of handling units are further discussed in chapter 3.1.4.

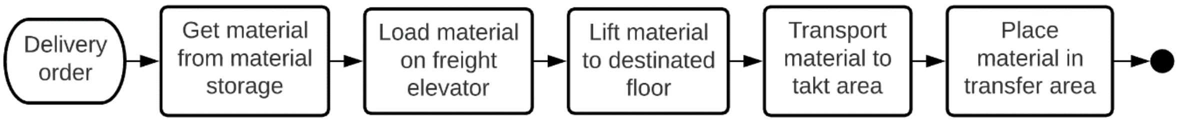


Figure 3-4: Material supply to takt area

The employee gets the material to be supplied from the material storage using an outdoor TM on the ground floor. Then, he brings the material to and loads it onto a freight elevator. He parks the outdoor TM in the assigned parking lot and gets on the elevator. As soon as the elevator arrived at the destination floor, the employee reaches out for a TM on the standard floor respectively. He unloads the elevator, transports the handling unit to the destination takt area, and places the material in the transfer area of the takt area. If another task has to be completed on the same floor, the employee starts the next task. Otherwise, he brings the TM back to its parking position next to a freight elevator and gets back to the ground floor.

Handling of surplus material

Surplus material arises if a trade has not processed all material units loaded on the delivered handing unit. As soon as a trade has finished processing the material, it notifies the TPLP in case there is surplus material left in the takt area. An employee of the TPLP checks where the material is required in the following week and determines the next destination of the surplus material according to the following priority rules:

1) Subsequent takt area on the same floor
2) Any takt area on the same floor
3) Any takt area on a subsequent floor
4) Any takt area

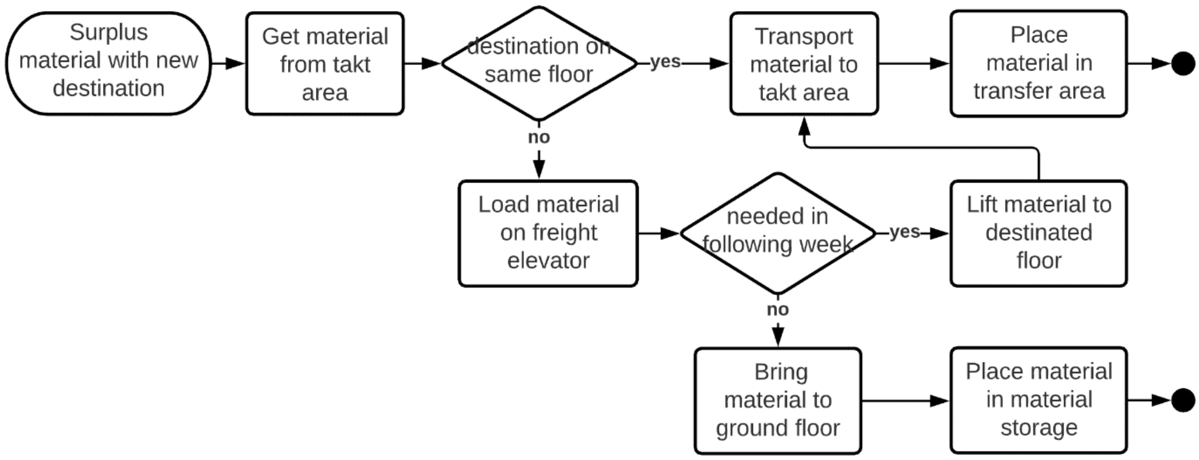


Figure 3-5: Handling of surplus material

If there is no need for the surplus material in the current takt area, the employee gets the material from the takt area using the TM of the floor respectively. Then, he either transports the material to the next takt area, potentially using the freight elevator, or he brings it back to the material storage on the 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 packages 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. Potentially arising empty pallets are appropriately handled.

Handling of waste

As the TPLP knows which material is processed in which takt area, the employees can evaluate where waste is produced per day. Waste is collected daily, starting in the afternoon according to the assumed waste management regulatory. Furthermore, there is a defined maximum filling level defined at which a container or a bin has to be emptied. This is necessary as a disposal mean cannot be perfectly filled, there is always a certain degree of air pockets. Moreover, completely full disposal means are difficult to handle, as material could drop during transportations. Therefore, an appropriate defined maximum filling level is taking account for these issues.

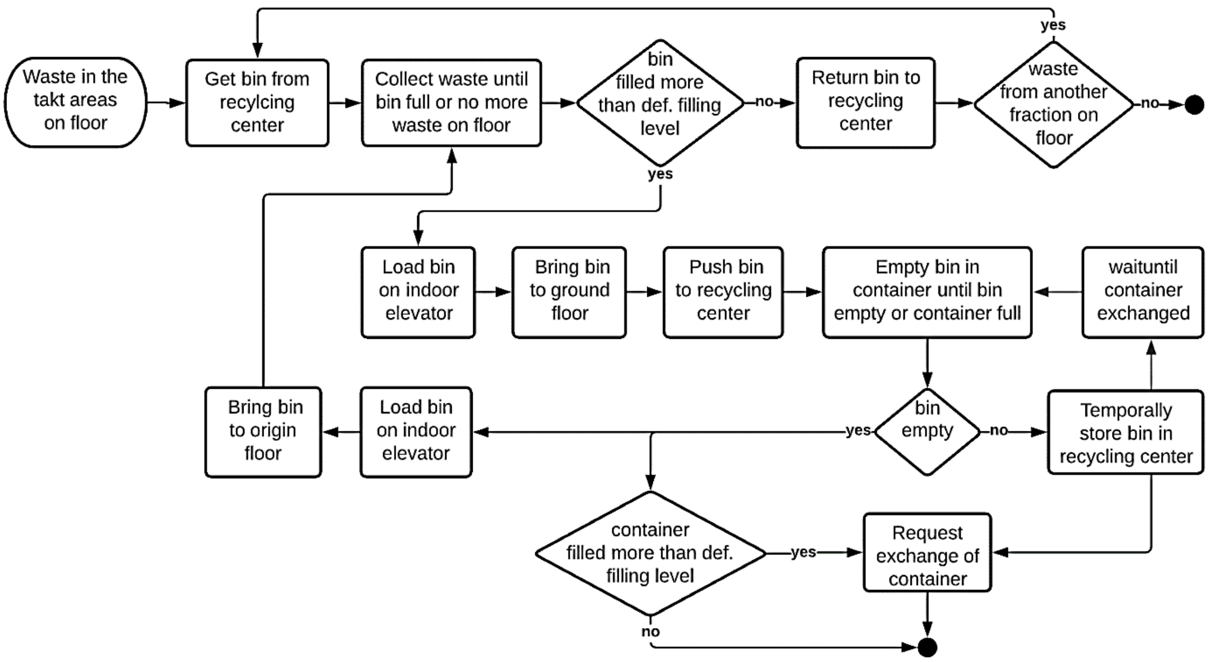


Figure 3-6: Handling of waste

The waste collection per floor is performed by one employee. First, the employee gets the bin of a waste fraction of which there is waste on the floor. Then, he pushes the bin to all takt areas where he needs to collect waste. He searches for waste in every room of the takt area and loads it into the bin. After having finished the collection, he returns the bin to the recycling center and potentially gets the next bin of another waste fraction to continue collecting waste.

If the bin is full, the employee empties the bin into the corresponding container on the ground floor and continues the collection process once he returns. If the filling level of the container is over determined level after emptying the bin, the employee requests an exchange of the container. The container exchange takes place on next working day. If the container is full before the bin is completely emptied, the bin is temporally stored in the recycling center on the ground floor. As soon as the container is exchanged, the bin is emptied and brought back to its origin floor.

Handling of empty pallets

Similar to the handling of waste, empty pallets on each floor are centrally collected by one employee of the TPLP on a daily basis, starting in the afternoon. At first, the pallets are temporally stacked on the floor, as the indoor elevator should not be blocked just because of one pallet brought to the ground floor. However, space is a limited resource within building construction. Therefore, a maximum number of four pallets is allowed to be temporally stored on the floor. Furthermore, transportation means can transport up to five empty pallets simultaneously.

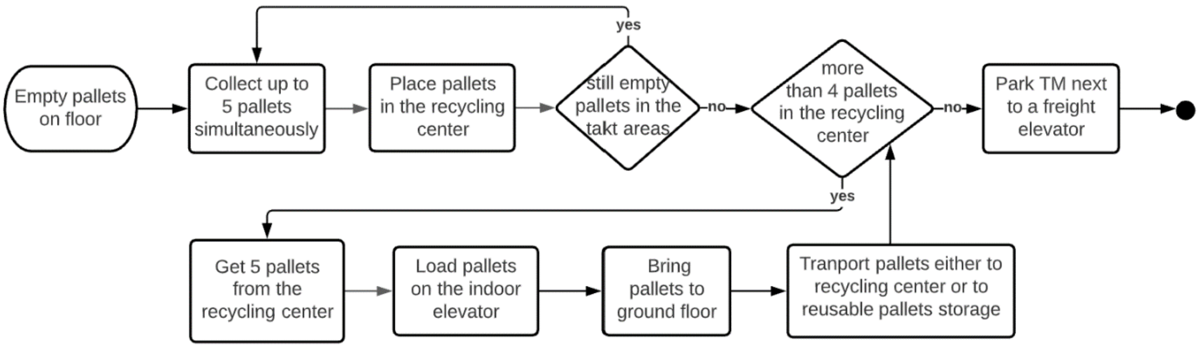


Figure 3-7: Handling of empty pallets

If there are empty pallets within the takt areas on the floor, an employee gets a TM on the respective floor and collects the empty pallets which are centrally stored within the takt areas. He can stack up to five pallets on the TM per drive before he brings the pallets to the recycling center and stores them next to the bins. If there are no more empty pallets in the takt areas, the employee checks the number of empty pallets temporally stored in the recycling center. If there are more than four pallets, the employee of the TPLP gets five pallets and loads them on the indoor elevator. He parks the TM next to the indoor elevator, gets on the elevator and brings the pallets down to the ground floor. There, he gets an indoor TM and unloads the elevator. The handling of empty pallets on the ground floor is distinguished between reusable and disposable pallets. Disposable pallets are transported to the recycling center where the employee disposes the pallets in the container for wood. Reusable pallets are stacked next to the material storage in a separately marked area. Afterwards, the employee returns the TM to its parking lot next to the indoor elevator. If there are still more than four pallets in the recycling center of the floor where the employee was coming from, he returns to the floor in order to bring five more pallets down to the ground floor.

3.1.4 Construction Material Management

Construction tasks 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 only be ordered 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.

Furthermore, only for some materials, it is common practice to separate handling units on site regarding the exact amount needed within the takt areas. For example, the handling effort of plasterboards is very high. Therefore, plates are not counted, and handling units are not separated on the ground floor, but only entire pallets are transported from the material storage to the takt areas. The result is material, which is left after the crew finished their tasks, so-called surplus material. However, for other materials, especially for materials delivered in bags, it is common practice to only transport the number of bags needed to the takt areas. Handling units are separated at the material storage on the ground floor by transferring the required number of bags on another pallet which is transported to the takt area. This leads to partly filled handling units in the material storage on the ground floor. Hence, the employee responsible to supply material to the takt area has to check in advance which handling unit is suitable to be delivered. Table 3-1 gives an overview of which material is delivered to the takt areas depending on the required package size of the takt area and on the packages that are stored in the material storage.

Table 3-1: Supply strategies at site depending on material separation, packages stored in the material storage, and required amount by the takt area

<table>
<tr><th colspan="2" rowspan="2"></th><th colspan="3">Required package for supply to takt area</th></tr>
<tr><th>Entire package</th><th>Partly package (no separation allowed)</th><th>Partly package (separation allowed)</th></tr>
<tr><td rowspan="6">Packages in storage</td><td>Only entire packages</td><td rowspan="4">Supply entire package</td><td>Supply entire package</td><td>Separate entire package</td></tr>
<tr><td>Entire packages + part package (more)</td><td>Supply part package (complete)</td><td>Separate part package</td></tr>
<tr><td>Entire packages + part package (proper)</td><td>Supply part package (complete)</td><td>Supply part package (complete)</td></tr>
<tr><td>Entire packages + part package (too less)</td><td>Supply entire package</td><td>Supply part package filled up with separated entire package</td></tr>
<tr><td>Only part package (more)</td><td rowspan="2">Supply whole part package</td><td rowspan="2">Supply whole part package</td><td>Separate part package</td></tr>
<tr><td>Only part package (less or proper)</td><td>Supply whole part package</td></tr>
</table>

To keep an overview of material currently stored in a best possible way, the present work assumed a regulation by which at most one partly filled package is allowed per material in the storage. This has two major impacts. When surplus material returns to the material storage, where already a partly filled handling unit is stored, the two packages have to be consolidated. On the other hand, employees of the TPLP preferably have to deliver partly packages to the takt areas. If the number of material units contained in the partly package is not sufficient, the partly package is either filled from another package, if separation is allowed, or another entire package has to be supplied to the takt area.

Lastly, if there is only one handling unit of material in the storage which is required by a takt area, it is always supplied to the takt area, regardless if the handling unit contains an insufficient amount. The remaining material units will be delivered to the takt area as soon as new material has been supplied to the construction site.

3.2 Requirements as Planning Tool

In addition to the process description, general requirements have been elaborated which are necessary to allow an efficient support for the planning processes of the industry partner. These are presented in the following.

3.2.1 Input Data

The effort to import needed data to the simulation has to be as low as possible to increase the willingness to use simulation in planning. For this work, there has been no input connection to BIM or similar digital tools available. Therefore, the needed input data has to be organized in a different way, which also fulfills the requirements regarding efficiency, consistency, and accuracy.

Moreover, the integrated input data must be able to represent the building construction project while keeping the required amount to a minimum [Ail-2008]. *Feine et al.* classified input data for simulation models in construction in four different dimensions [Fei-2016]:

- Construction site-specific data
- Construction task-specific data
- Company-specific data
- Construction technology-related data

Construction site-specific data include the size, the layout, and certain characteristics of a building, e.g. the zoning of a standard floor in numerous takt areas, or the distance between the material storage on the ground floor and the freight elevator.

Construction task-specific data contain a detailed description of the construction process. In the present work, the information is provided through the construction schedule combined with the material and work expenses per task respectively.

Company-specific data represent characteristics of the resources that are required at the construction site to perform both logistical and construction processes. This includes, for example, the characteristics of transportation means, which are commonly used within the projects of the company, such as speed and capacity, or characteristics of materials required by the trades, such as waste fraction or blend.

The term “construction technology-related” rather refers to methodologies implemented at the construction site than to machinery or production technologies. Data are necessary regarding different possible supply strategies (e.g. amount of supplied materials per handling unit), material management (e.g. storage strategies), waste management (e.g. defined maximum filling level), and overall coordination strategies regarding who is responsible for which task (e.g. TPLP hired for construction logistics).

The last two dimensions 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 [Fei-2016].

3.2.2 Modular Design

Another important factor is the adaptability of the simulation model towards both several construction sites and design changes within each construction project without extensive programming effort [Voi-2010].

Due to the unique nature of building construction, there is a high need for adaption. Additionally, the budget in construction industry is limited. The costs of a simulation can be decreased if the model can be used across several projects. In a multi-project view, the marginal costs of a simulation model are significantly lower if an adaptation of a simulation model is only associated with relatively low effort.

To enable the users of the simulation to modify all influencing factors, such as layout, construction processes, or logistics, the corresponding elements within the simulation model have to be generalized and modularized. These elements should be able to cover as many use cases as possible to increase the value of the simulation model for the construction industry [Kug-2008].

3.2.3 Simulation User Interface and Visualization

In addition to the modular design, the parameters and input data have to be designed in a user-friendly manner. As there is a lack of expertise in using simulation tools within the construction industry, the surface of the simulation model has to be designed understandably by using graphical navigation schemes and visualization rather than abstract simulation elements.

An intuitive visualization of the processes on construction site can enhance the understanding and the acceptance of the model as the stakeholders no longer perceive the simulation model as a “black box” but can observe the processes throughout the virtual construction. Hence, the stakeholders can easily verify if the model’s behavior suits the expectations.

Moreover, users should be able to change parameter settings and input data input via user-friendly graphical user interfaces. These can simplify and accelerate adaptations and avoid errors by comprehensive explanations. Regarding the time and cost pressure during planning, this is a valuable characteristic for simulation tools.

Furthermore, there is no need for an extensive training for all users which again leads to lower cost for the construction industry. However, there should be a “champion” who is aware of the simulation logic to be able to perform adaptations apart from the modularized settings [Lee-2013].

3.2.4 Simulation Results

The simulation results must be relevant, efficiently generated, and presented in an understandable format.

The relevance of certain measures depends on the objective of the study respectively [Ber-2013]. Total project cost and time, resource allocation/use, and waiting times of the simulated entities are measures that are often used to evaluate construction projects [Lei-2016]. In coordination with the industry partner, the following measures have been added for this work: storage use, waste volume, workers on site, and supply expenses. All measures are evaluated over time to be able to identify potential wastes or bottlenecks. Nevertheless, the analysis should not be limited to the defined measures. Due to the uniqueness of construction projects, new objectives can arise which are particularly important for a construction project. Therefore, the output of the simulation should be provided in a format which enables further analyses.

Moreover, the simulation results should be efficiently generated and saved in a common file format. Additionally, the simulation output should be presented graphically including filter options for certain production factors to optimally support decision-making [Kug-2008].

4 Model Implementation

The simulation is implemented within the standard simulation software Plant Simulation provided by SimPlan AG (Fa. Siemens AG). As *Pitsch* stated, the use of standard simulation software is beneficial within construction industry as the numerous influencing factors of a construction site can variably be modeled using the standard elements [Pit-2011]. The Simulation Toolkit Shipbuilding (STS) of Plant Simulation has already been used by multiple researches. However, *Bargstädt and Feine* question if STS can be regarded as standard software due to the customs made towards modeling shipbuilding [Bar-2015]. Therefore, the present simulation study aimed at the implementation only using the standard elements of Plant Simulation version 15.1.0 .

However, the model is implemented to be used by people who are not familiar with the Plant Simulation software. Therefore, the input and output data are managed through tables saved in the format of MS Excel. In the following, the simulation model is presented including the calculation of required input data, the layout, the overall logic, and the evaluation of the simulation output.

4.1 Simulation Layout

The simulation layout is either automatically created following the lengths and distances specified in the input data or manually adapted to an imported picture of the layout. For the layout of the ground floor, the required positions and distances must be specified as presented in Figure 4-1 in general form.

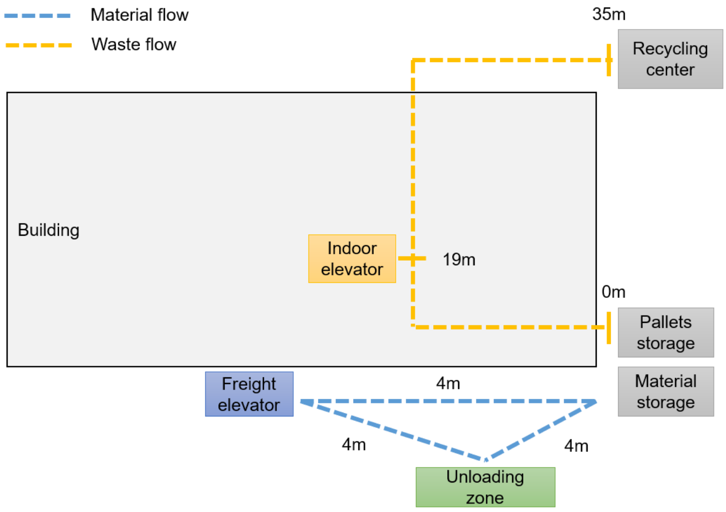


Figure 4-1: Input data - layout ground floor

The layout of the standard floors is specified in relation to the hallway. The central positions of the takt areas, of the elevators and of the recycling center are placed along the hallway respectively (see Figure 4-2). The hallway can also include curves and potentially even be circular.

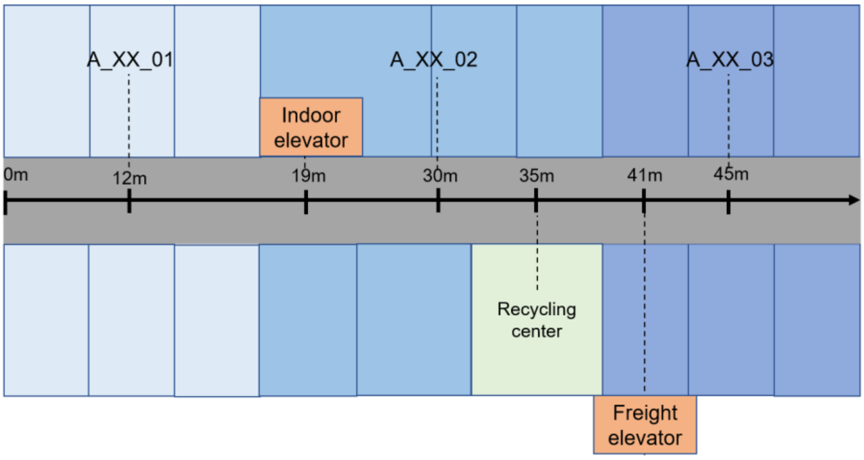


Figure 4-2: Input data - layout standard floor

The implementation follows a modular approach. The standard floors as well as the takt areas are modeled as so-called replicable networks. The takt areas are labeled in the format “A_01_04” whereas “A” refers to the part of the building, “01” to the floor, and “04” to the takt area (in the example: takt area number 4 on first floor in part A). The labeling followed the practices of the industry partner. Therefore, a building can consist of max. 99 standard floors, and each standard floor can be zoned in max. 99 takt areas.

The basic frame of the simulation model represents the ground floor of the construction site including the elevator and the networks for the specified number of standard floors. The bins and containers are created within the recycling centers, the transportation means within their primarily parking position. The kind and the number of both depend on the specifications within the input parameters.

The vehicles and employees in the simulation move on ways which are modeled by two-lane tracks to simulate possible oncoming traffic. The entities can use both lanes equally. On the ground floor, the paths describe the material and the waste flow. On the standard floor, the entities move along the hallway. The respective positions of takt areas, recycling areas and elevators are marked by sensors.

Multiple screenshots of the simulation layouts can be found in Appendix A.

4.2 Input Parameters

First, a weekly material demand is calculated by combining the construction schedule and the material requirements per task. Afterwards, a MS Excel Sheet is used to handle the required input data. Finally, different parameter settings are specified within the simulation interface using a graphical user interface (GUI).

4.2.1 Calculation of Material Demand

The weekly material demand is represented by a so-called order list and a so-called delivery list. The order list describes the materials which are supplied to the site per week and trade whereas the delivery list contains the weekly material deliveries from the material storage on site to the takt areas.

For the calculation of the material demand, construction schedule per task and the material expenses per task are inserted into an MS Excel Sheet. Both input tables are compressed to get a construction schedule per wagon and a list of required materials per wagon. Afterwards, the compressed tables are joined, using a right outer join on the column “Wagon Nr” (⟖$_{\text{Wagon Nr}}$). This means that each entry of the left table (Construction schedule per wagon) is combined with all corresponding entries of the right table(material expenses per wagon). Finally, the required materials per week are aggregated per material to obtain the order list. Figure 4-3 presents a general example (values do not refer to real values). The calculations are made within MS Excel using the Add-In MS Excel Power Query to calculate the delivery list. The subsequent aggregation is calculated using a combination of standard Excel formulas.

Construction schedule per wagon

Scheduled week	Wagon Nr	Takt area
14	01	A_01_04
14	01	A_02_04

⟖ Wagon Nr

Material expenses per wagon

Wagon Nr	Material	Material units	Handling unit	Number of handling units
01	Plaster-board	3	Euro pallet	1
01	Profile	4	Package	2

Delivery list

Delivery week	Takt area	Material	Material units	Number of handling units
13	A_01_04	Plaster -board	3	1
13	A_01_04	Profile	4	2
13	A_02_04	Plaster -board	3	1
13	A_02_04	Profile	4	2

Aggregate →

Order list

Delivery week	Trade	Material	Material units	Handling unit	Number of handling units
13	Dry building	Plaster-board	6	Euro pallet	2
13	Dry building	Profile	8	Package	4

Figure 4-3: Exemplary calculation of the delivery and order list

The number of both material and handling units are rounded up in case only partial units are required. Hence, possible blend is already included in the material expense per task. The delivery week is set one week prior to the scheduled week. For the order list, both the number of material units and the number of handling units are required due to different material characteristics described in chapter 3.1.4.

After the user inserted the construction schedule and the material expenses per task, the calculations are executed automatically at the push of a button to reduce effort and increase user-friendliness.

4.2.2 MS Excel Input-Sheet

Construction task-specific, construction site-specific and company-specific input data are controlled within an MS Excel Input-Sheet which is associated with several benefits. MS Excel is specialized for dealing with large amount of data. Therefore, it enables a clear organization of the required input data. As stakeholders are usually familiar with MS Excel, the handling of input data is easier in a familiar environment. Furthermore, essential labeling of columns can be protected against changes within MS Excel whereby the import is less prone to errors. Moreover, the programming language VBA allows for automated input checks which again enhances the input quality.

Table 4-1 gives an overview of required input data. The order list and the delivery list from the previous calculations are simply copied into the MS Excel Input-Sheet. Company-specific input data can be re-used for multiple construction projects. However, all the materials required by a construction process have to be specified in the material library. Similarly, all handling units needed to transport the specified materials need to be listed in the handling unit library. Materials which are transported without a handling unit are assigned to a dummy handling unit called “piece”. This is necessary, as the simulation software is only able to handle a standard material flow.

The implemented input check can be executed by pressing a button. The input is checked for allowed signs restricted within the libraries in Plant Simulation, for empty cells and for correct interdependencies between different data sets. These interdependencies include, for example, the positioning of takt areas in the layout of the standard floors if they are listed in the construction schedule, the tasks specified in the construction schedule and in the expenses list, or the bins and containers selected in the waste fraction which also have to be specified in the respective library.

Table 4-1: Input data MS Excel Input-Sheet

Input data	Description
Construction task-specific input data	
Construction schedule	Sequence of construction tasks performed per takt area throughout the construction project
Order list	Material supplies to the construction site per week and trade
Delivery list	Material supplies to the takt areas per week and takt area
Expenses	Material and work expenses per construction task
Waste fractions	Required waste fraction combined with desired bin and container sizes per fraction
Construction site-specific input data	
Ground floor layout	Distances between and positions of unloading zone, elevators, material storage, and recycling center
Standard floor layout	Central positions of takt areas, recycling center, and elevators in relation to the hallway
Further building characteristics	Number of standard floors and takt areas, floor height, length, and characteristics of the hallway
Company-specific input data	
Materials	Characteristics, e.g. size, package size, handling unit, waste fraction, blend ratio, and separation behavior
Handling units	Characteristics, e.g. size, storage area, and specification disposable/reusable
Horizontal transportation means	Characteristics, e.g. speed and durations for (un)loading depending on load, and cost per operating hour
Vertical transportation means	Characteristics, e.g. speed depending on load and cost per operating hour
Bins	Characteristics, e.g. capacity, storage area, and duration of emptying a full load
Containers	Capacity and storage area
Trucks supplying material	Loading area and duration of arrival, shunting and parking depending on characteristics of construction site
Trucks exchanging containers	Duration of container exchange depending on characteristics of construction site

4.2.3 Parameter GUI

However, not all input parameters can be set within the MS Excel Sheet due to software specific characteristics of Plant Simulation. Especially, scenarios with respect to construction technology-related data are better organized by a parameter GUI which is directly linked to the library of the simulation model.

Before a simulation run starts, input data is imported from the MS Excel Input-Sheet. Then, the class libraries and the Parameter GUI are updated before the user can set parameter settings. The following parameters can be specified within the parameter GUI.

Table 4-2: Input parameter set by the parameter GUI within the simulation model

Category	Parameters
Horizontal transportation means	- Number and kind of outdoor TM on ground floor - Number and kind of indoor TM on ground floor - Number and kind of TM per standard floor
Vertical transportation means	- Number and kind of freight elevators - Number and kind of indoor elevators - Requirement of a ramp - Maximum capacity of persons - Availability of indoor elevator for transports of people
Personnel	- Number of employees of TPLP - Begin and end of working days, break times - Ratio of trade personnel using elevator to spend breaks on ground floor
Supply	- Expense for trucks to arrive - Supply days for material supplies to the site - First day for deliveries to the takt areas
Disposal	- Expense for trucks to exchange container - Defined maximum filling level of disposal means
General simulation Parameters	- Start and end date of considered construction phase

A screenshot of the layout of the parameter GUI can be found in Appendix A. A simulation run is started through the parameter GUI, the resources initialized according to these specified parameters.

4.3 Simulation Logic

Construction material and waste are controlled by a material and disposal management which can be triggered by certain events. If the event causes an action within the respective management, the management assigns a new task to the task control of the transportation means which is required to execute the task. Then, the transportation means requests an employee from the personnel management of the TPLP.

Moreover, transportation means can request other transportation means, e.g. if a truck arrives, it requests an outdoor TM to be unloaded. Furthermore, the personnel management may request an elevator to get to another floor.

Figure 4-4 describes the relationships between the entities which are responsible to implement the supply and disposal tasks. It further specifies the kind of task that is passed along the direction of the arrow.

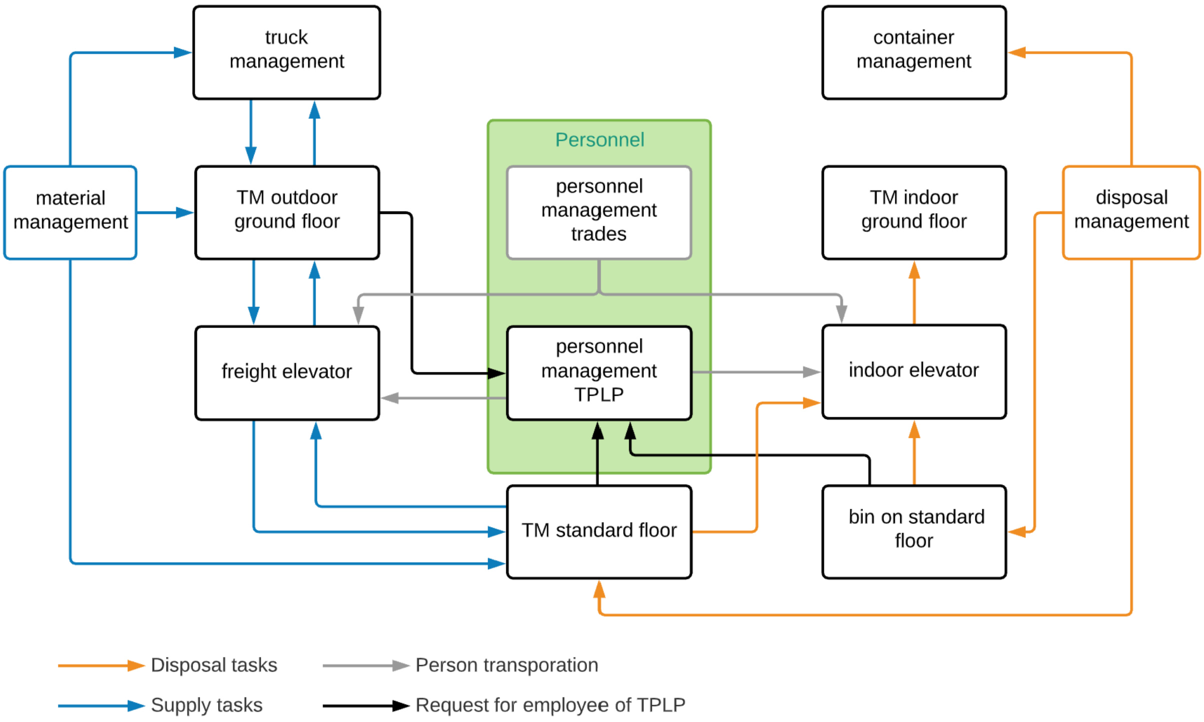


Figure 4-4: Simulation logic regarding task management

The material flow is controlled by destination labels which are attached to each handling unit. The same applies to employees who are moving within the simulation.

The processes within the blocks are described in the following.

4.4 Material Management

Material management includes the management of material supplied to the construction site by trucks per trade, deliveries from the material storage to the takt areas, and the rearrangement of surplus material combined with a correction of future orders and deliveries. The different parts of the material management are triggered by different events.

The material supply is triggered at the beginning of each working day. Thereby, the material management checks if the current working day is specified as valid supply day and if there are orders in the order list with due until the current calendar week. Material orders with due until the previous calendar week are allowed independently of the daily supply restrictions. To start the material supply, a truck is requested as soon as the working day starts.

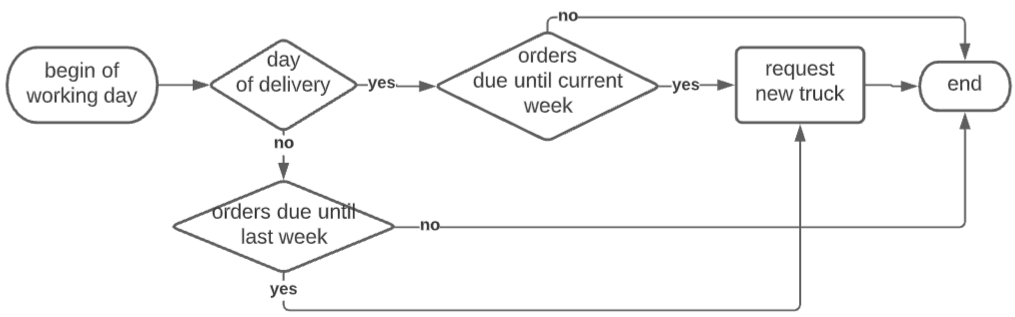


Figure 4-5: Material management - material supply to the construction site

The supply of the takt areas is started according to the specified day within the parameter settings. All entries for the current calendar week from the delivery list are copied into a second, internal table which contains due delivery tasks. The material management compares the stock of the material storage with due delivery tasks each time material is removed from or inserted in the material storage or new delivery tasks are specified. If a delivery can be executed, the material management inserts the task “Load freight elevator” in the central task management of the outdoor TM on the ground floor and places a request for the TM. The same applies if material is inserted in the interims material storage next to the freight elevator (see chapter 3.1.4). However, the task placed in the task list is called “Load freight elevator from interims storage”.

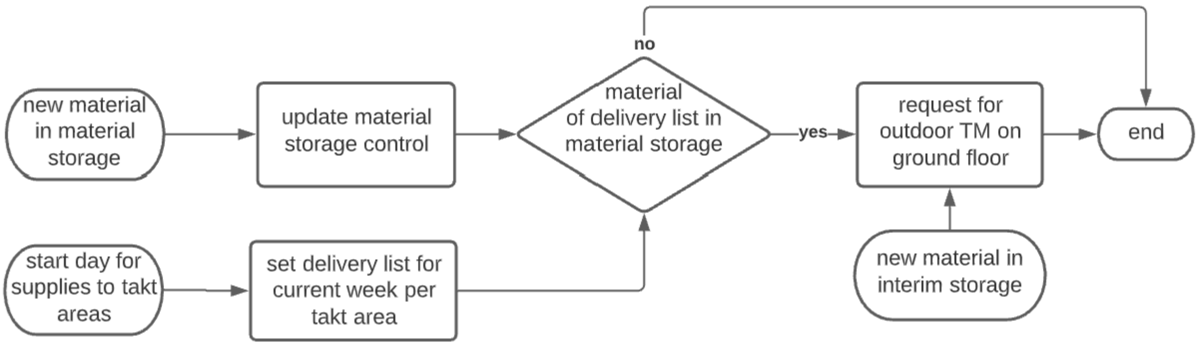


Figure 4-6: Material management - material supply to the takt areas

Before construction processes of a new week start, the material management adapts the order and the delivery list of the new week in relation to expected surplus material. This simulates the behavior of those responsible for ordering material. For each takt area which contains material in its transfer area, the material management estimates the material which will be left at the end of the week. Thereby, the material required for the scheduled tasks of the current week are compared to the stock in the transfer area. If surplus material is expected, the material management checks the next destination of the material according to the delivery list for the current week (which represents the material requirements of takt areas of next week). The appropriate delivery task is determined following the priority rules defined on page 25. However, only deliveries of the subsequent week are considered to avoid multiple order corrections.

If the material isn't needed in the current takt area in the subsequent week, the destination label of each handling unit loaded with the corresponding material is set according to the determined destination. In case the next destination is another takt area and not the material storage on the ground floor, the delivery list and the order list have to be adapted as the surplus material decreases the need for new material. Therefore, the ordered material units are reduced for both the determined delivery task in the delivery list and the material order in the order list.

Additionally, the number of handling units of the determined delivery task is adapted. Thereby, the required material units are divided by the number of material units per (entire) handling unit. Partly handling units are rounded up. If the number of handling units has been decreased for the determined delivery task, the number of ordered handling units of the material is decreased in the same amount within the order list.

This process, also presented in Figure 4-7, is repeated for each material stored in each takt area.

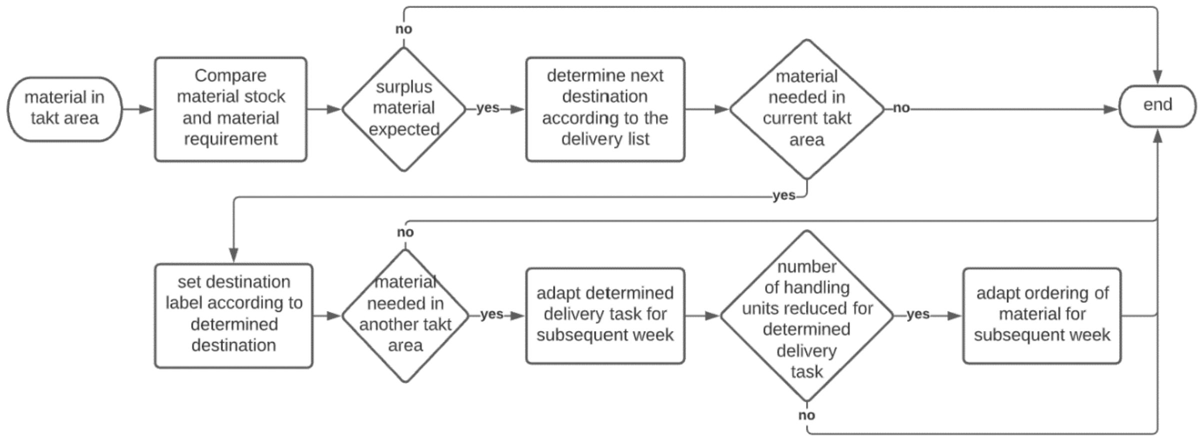


Figure 4-7: *Material management - correction of order and delivery list in relation to expected surplus material*

As there is no physical label on the handling units in the material storage on the ground floor, the responsible employee cannot determine to which takt area the material is expected to be delivered. Therefore, materials in the material storage cannot be considered during calculations of expected surplus material per takt area.

The rearrangement of surplus material is triggered by the construction processes. As soon as a trade finished their scheduled tasks without processing all the material supplied to the takt area, the material management checks the destination labels attached at the remaining handling units. If the label complies with the current takt area, the material may have not been considered in the prior surplus calculation due to a late delivery. Therefore, the delivery list is checked again to determine the next destination of the material, again following the priority rules on page 25. If the material isn't needed in the current takt area in the following week, the material management adapts the destination label of the material. Afterwards, it places the task "Rearrange surplus material" within the task list of the TM on the corresponding floor and requests the TM.

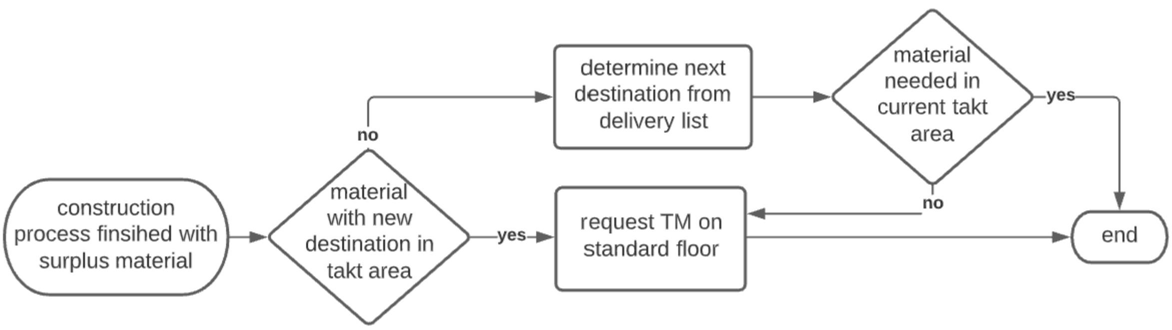


Figure 4-8: *Material management – rearrangement of surplus material*

4.5 Disposal Management

Each afternoon, the disposal management checks for each floor if there are either waste or empty pallets in any takt area on the floor. If empty pallets have been found, the disposal management places the task “Collect empty pallets” in the task list of the TM on the corresponding floor and requests a TM. If any waste was found, the disposal management determines the fraction and places the task “Collect waste” in the task list of the bins on the respective floor to start the task management of the bins.

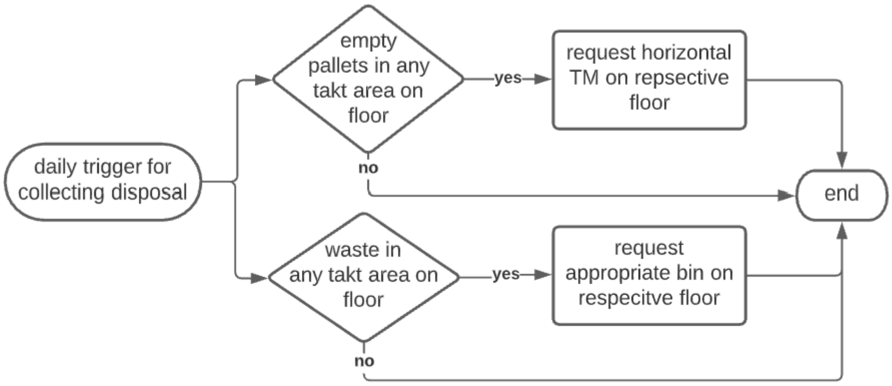


Figure 4-9: Disposal management – daily collection of waste and empty pallets

At the end of a construction phase, all bins are emptied into the corresponding container and remaining empty pallets are brought to the ground floor.

At the end of each week, the disposal manager searches for material in the material storage on the ground floor, which isn’t going to be needed for the remaining construction processes. In practice, the responsible trade loads remaining material on their own vehicles once they finished all tasks on this construction site to use the material for the next construction site. To simulate this behavior, the disposal management removes the material from the site.

4.6 Personnel Management

In the present work, there are two main kinds of workers at the construction site: the employees of the TPLP, responsible for performing the tasks, and the employees of the trades who perform the construction tasks. However, the movements of the workers are only physically considered when it is important for the utilization of logistical means which is further described in the following for each kind of workers.

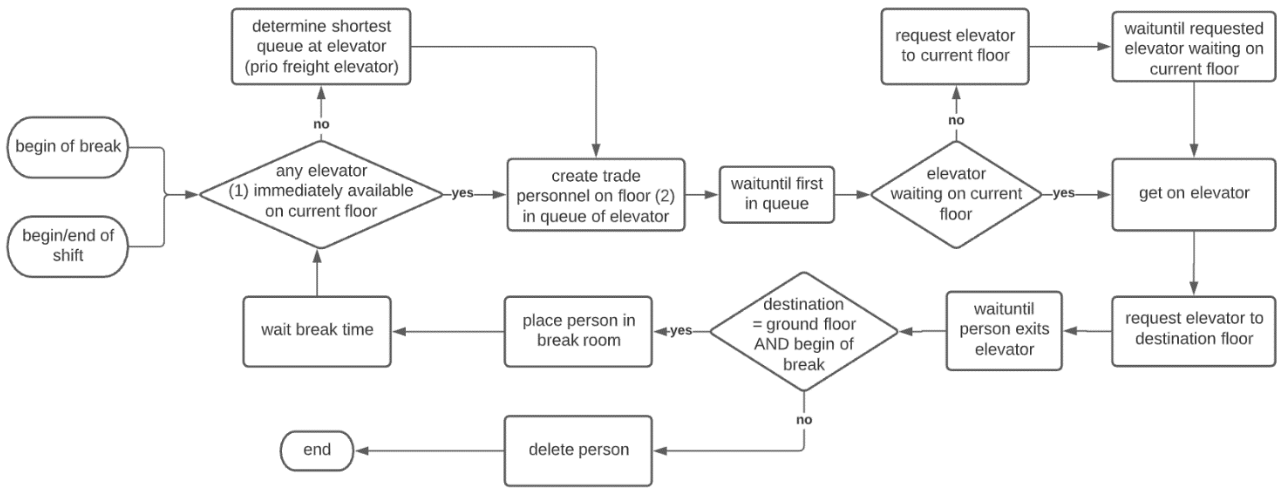
4.6.1 Trades

In this work, the movements of the employees of the trades are only relevant if the employees request the elevator at the begin and at the end of each break and working day to get to their working floor and back to the ground floor again. The representative number of persons created per floor (n_{floor}) to simulate the employees of the trades is calculated as follows:

$$n_{floor} = \begin{cases} \left\lceil \sum_{i \in I} n_i \; / \; c \right\rceil & , if\ created\ at\ beginning/end\ of\ a\ working\ day \\ \left\lceil r \; \cdot \sum_{i \in I} n_i \; / \; c \right\rceil & , if\ created\ at\ the\ beginning\ of\ a\ break \end{cases} \qquad (4\text{-}1)$$

Equation 2: Representative number of persons created per floor

The personnel management sums all employees working in a takt area (n_i) per floor. Then, it divides the sum by the capacity of persons transported simultaneously within an elevator (c), which is specified within the parameter GUI. This results in the number of representative persons which are created to physically simulate the employees of the trade at the beginning and at end of each working day. At the beginning of each break, this number is multiplied by the specified ration of trade personnel which spends their break on the ground floor (r). Finally, the resulting number is rounded up. The representative number of workers is created in the queue of an elevator which is preferably immediately available or in the shortest queue of an elevator, considering the potential restriction of personnel to use the indoor elevator.



(1) if indoor elevators allowed to be used by trade personnel: all elevators otherwise: all freight elevators
(2) representative number of trade personnel following formula (4-1)

Figure 4-10: Simulation of elevator utilization through trade personnel

Additionally, it is assumed that the employees of the trades are working on their scheduled floor for the entire week. This is a worst-case assumption as the processing of the material may be finished early. Nevertheless, it is assumed that the employees perform further finishing tasks without a need for material or preparation tasks for the following week.

4.6.2 Third-Party Logistics Partner

The employees of the third-party logistics provider (TPLP) are responsible to perform the logistical processes on site using the available transportation means. Thereby, it is assumed that every worker can perform every task and only one employee is needed to perform a task. In the basic state, the employees are waiting on the ground floor until they have to perform a task. The movements of the workers are only considered during the fulfillment of a task or if an employee has to use an elevator to get to the requesting TM. The task management follows the first-in-first-out (FIFO) principle. If multiple employees are available, the task is assigned to the employee whose current position is nearest to TM requesting the employee. If an employee is on the same floor as the TM, the employee gets on the TM, immediately starting the task. As soon as a task is assigned to an employee, his state changes according to the task he is requested for. The states and the corresponding scope of task are described in Table 4-3: States of the third-party logistics .

Table 4-3: States of the third-party logistics partner

State	Description
Waiting	Employee waits for a task.
Unload truck	Employee completely unloads a truck.
Load empty pallets	Employee loads empty pallets on a truck.
Supply takt area	Employee supplies one handling unit to a takt area.
Rearrange surplus material	Employee rearranges on handling unit of a surplus material either to another takt area or to the ground floor.
Collect empty pallets	Employee collects all empty pallets on one floor.
Dispose empty pallets	Employee brings 5 empty pallets from a floor to the ground floor.
Collect waste	Employee collects waste of one floor.
Empty bin in container	Employee empties one bin in the corresponding container on the ground floor.
Return to ground floor	Employee returns to the ground floor after having finished a task on an upper floor.

If a task is finished on an upper floor and no follow-up task is assigned to the employee, he waits for ten minutes for another task on the current floor. If the employee is still waiting after ten minutes, he returns to the ground floor. This assumption is made as the employees wouldn't return to the ground floor in reality if they know that they shortly have to perform a task near the current floor.

Moreover, if a searching task takes longer than the scheduled working time (e.g. collecting waste or collecting empty pallets), the task is stopped for the current working day and continued the next working day. All other tasks (e.g. supply takt area or dispose empty pallets) are readily performed until there's no material left on any TM.

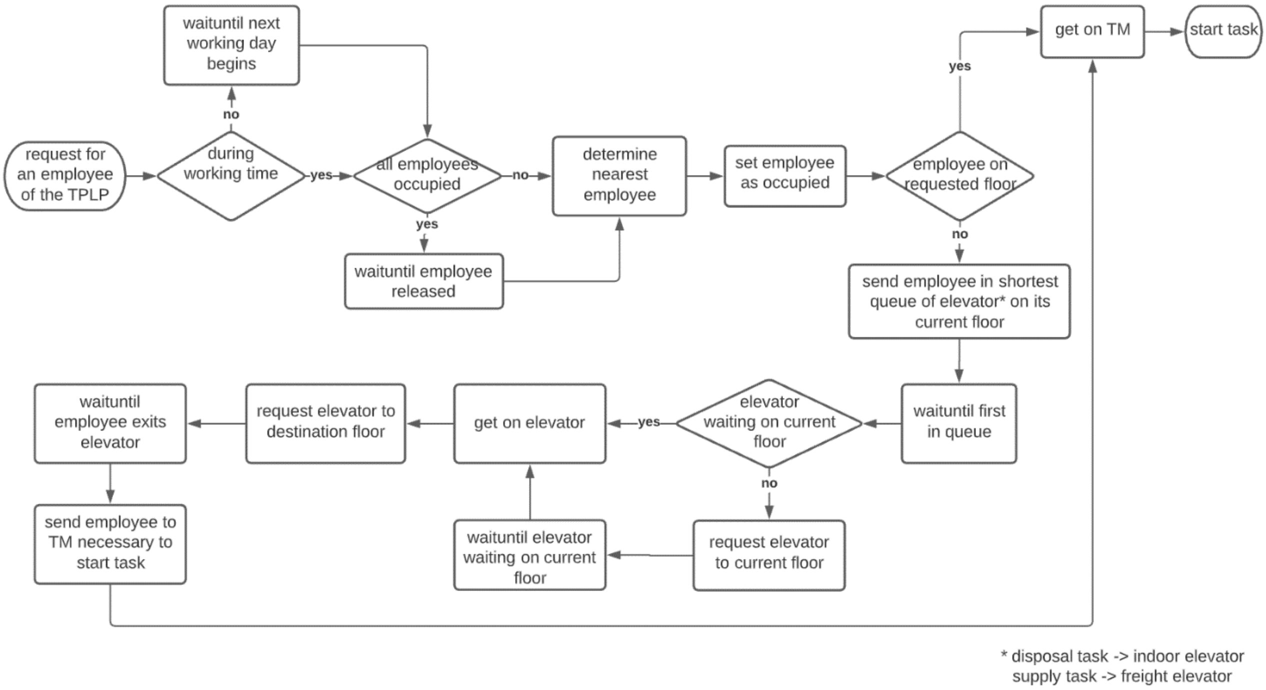


Figure 4-11: Task management for personnel of logistic service provider

4.7 Task Management

In the following, the central task management of all considered transportation and disposal means are described in detail.

4.7.1 Supply Truck

Material supply is requested by the material management on the days which are specified as supply days within the parameter GUI. Following a request, a truck is created in a station apart from the construction site. There, it is loaded according to the order list which contains the orders for materials required in the subsequent week.

One truck can only load materials from one trade in the basic scenario of the simulation. During the loading process, one handling unit of the top material in the ordering list is created on the loading area of the truck. Afterwards, the maximum number of material units per handling unit is created on the handling unit on the truck. Depending on the separation allowance of the material (see chapter 3.1.4), the loading process is performed according to the number of handling units or according to the number of material units within the order list. If a material is not separated in the material storage, there must be enough handling units available within the material storage to be able to perform all delivery tasks. After having loaded the handling unit of the material, either the number of material units is reduced by the number of material units on one handling units, or the number of handling units is reduced by one. If the last unit of the material order has been loaded, the row is deleted from the order list and the loading process continues with the next entry.

It is assumed that materials are not stacked on the loading area of the truck. Moreover, geometric feasibility is not guaranteed. The size of the loading area on the truck is assumed to be chosen as big as necessary. If a trade needs more material than the biggest available truck can load, the loading process is stopped, and a second truck is requested. If there are no more orders for the current trade in the order list, the truck starts to drive to the construction site as soon as the unloading zone is unoccupied.

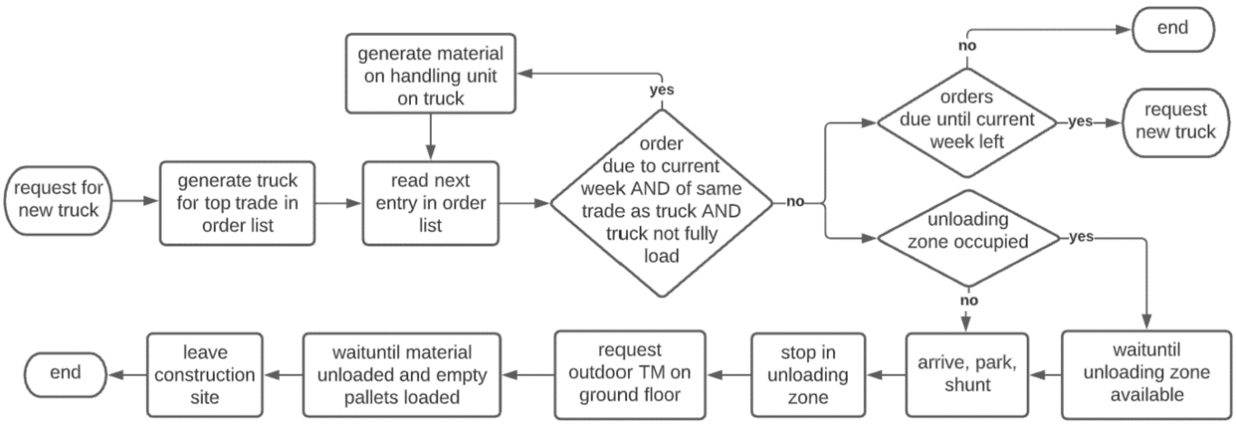


Figure 4-12: Truck management

However, arrivals of material supplies are only scheduled until one hour before the end of a working day. Afterwards, there would not be enough time for unloading. The effort for arriving, shunting, and parking depends on the layout of the construction site and is set within the parameter GUI. Once the truck stopped in the unloading zone, it places the task “Unload truck” in the task list of the outdoor TM and request a TM. When the loading process is finished, the truck leaves the construction site.

In this work, there is no consideration of limitations regarding material availability. Therefore, delayed material supplies can only be caused by possible resource limitations on site, e.g. if the outdoor TM on the ground floor cannot handle all the material supplies in the scheduled time frame.

4.7.2 Horizontal Transportation Means

All logistical tasks are primarily assigned to the horizontal transportation means. As there are possibly multiple transportation means per category, the tasks are managed centrally by a task list for each kind of TM on each floor. Every time, a new request is entered in a task list or a TM has finished a task, the task manager starts a new evaluation if a TM resource is available to perform a task.

The task fulfillment itself, as described in Chapter 3, is controlled by methods linked to sensors or entry/exit controls of the ways. Each TM has a state variable which describes the task, the TM is currently executing. Therefore, the methods can control the behavior of the TM, which triggered the method, by reading its state variable.

If a TM drives against another TM on the same lane, it is allowed to overtake. However, before overtaking, the TM checks if its destination is blocked. If the sensor position on the opposite lane is free, the TM moves there to reach its destination. If both positions are blocked, it waits until the object in front moves away. This behavior simulates a queuing behavior on the way if too many entities are at one place.

At the beginning of the simulation, the TMs are created according to the specifications set in the parameter GUI. The outdoor transportation means are created in their parking position next to the material storage, the indoor transportation means on the ground floor next to the indoor elevator, and the transportation means on the standard floor next to the freight elevator.

In the following, the task management and possible states of all transportation means are further described.

Outdoor transportation means on the ground floor

The outdoor TM on the ground floor is used for all tasks related to loading trucks, loading freight elevators on the façade of the building, and for material handlings within the material storage. Table 4-4 describes the potential states of an outdoor TM.

Table 4-4: Potential states of an outdoor transportation mean on the ground floor

State	Description
Waiting	TM waits until it is assigned a new task.
Unload truck	TM completely unloads handling units from truck (one after another).
Load empty pallets on truck	TM loads empty pallets on truck until a fulfillment criterion is met.
Load freight elevator [from interim storage]	TM searches in [interims] material storage for an ordered material and loads it into a freight elevator to start material supply to the takt area.
Unload freight elevator	TM unloads material from a freight elevator and stores it in material storage.

The task manager of the outdoor TM on the ground is started when there is a new request from another entity or when an outdoor TM finished its task. The tasks are executed according to the FIFO principle, except for unloading a freight elevator. At the interface between TM and elevator, there is a potential risk for a so-called deadlock. To avoid such a phenomenon (further described in chapter 4.7.4), the task "unload freight elevator" is generally prioritized.

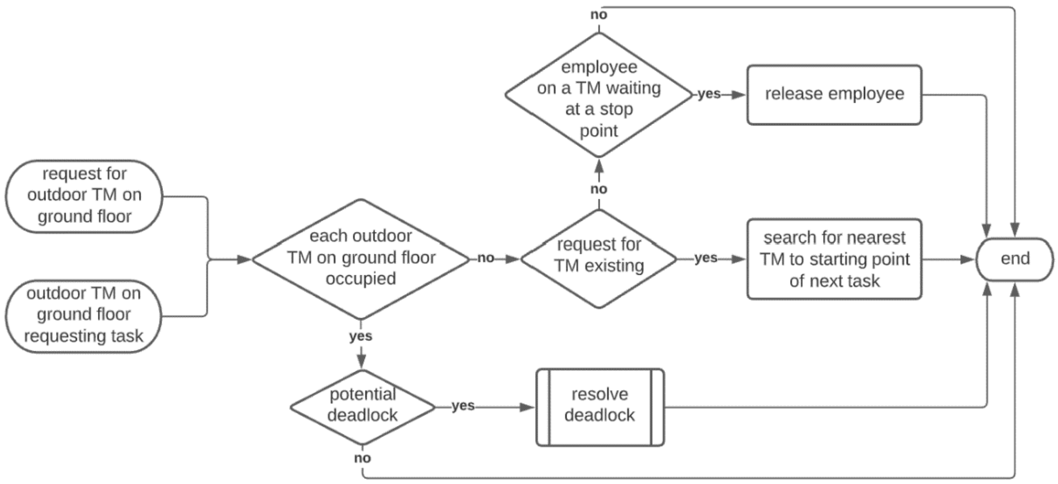


Figure 4-13: Task management of an outdoor transportation means on the ground floor

If all tasks have been finished, the task management checks for employees which are still on a TM and eventually releases them. A new task can be executed if a TM is in the state “waiting”. The task manager assigns the task to the TM which is in closest proximity to the starting point of the next task in the task list by changing its state variable. To start the task, the TM requests an employee of the TPLP (see Figure 4-14). As soon as the employee arrives at the TM, he gets on the TM (on a reserved place only for employees) and thus starts the execution of the task.

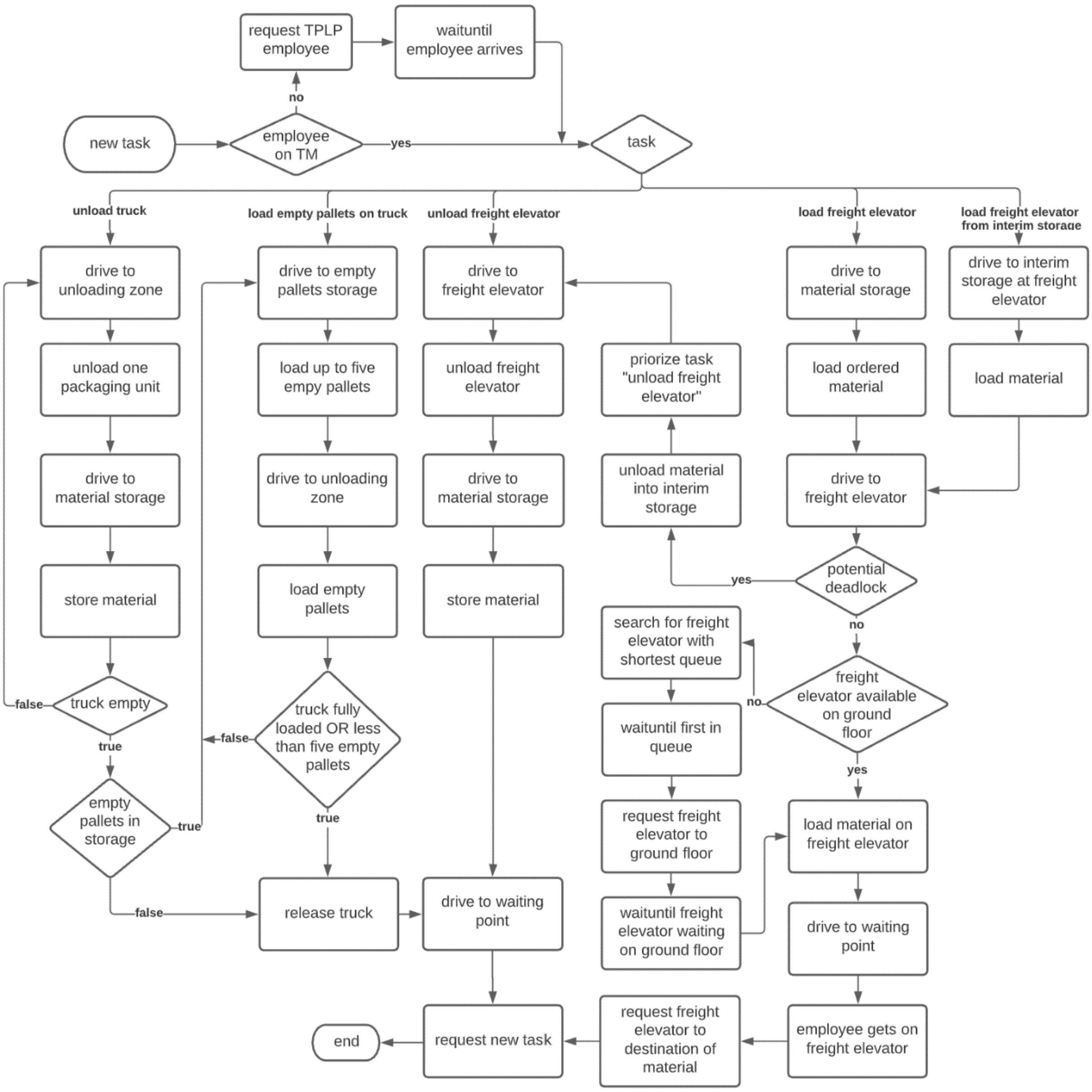


Figure 4-14: Task execution of an outdoor transportation mean on the ground floor

Thereby, the element “load freight elevator” follows the characteristics mentioned in chapter 3.1.4. The interim storage as well as the deadlock detection is further described in chapter 4.7.4.

Indoor transportation means on the ground floor

For the indoor TM, there is no central task management because no task is started by this kind of TM. The TM is only used when an employee arrives on the ground floor through the indoor elevator to dispose empty pallets. Therefore, each indoor TM is waiting at its parking lot next to the indoor elevator until an employee is reaching out for it.

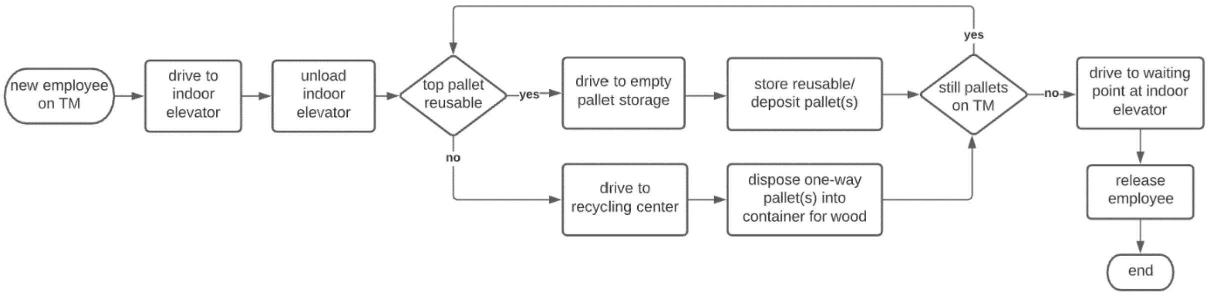


Figure 4-15: Task execution of an indoor transportation mean on ground floor

If an employee gets on an indoor TM, it unloads the indoor elevator, disposes the pallets, depending on the reusability of the pallet, and returns the indoor TM to the parking position next to the indoor elevator. If another employee already waits for the indoor TM, he can immediately start the disposal as soon as the other employee left the TM.

Transportation means per standard floor

The task management of TMs on a standard floor is managed centrally per floor. The design is as almost the same as for an outdoor TM on the ground floor. The only difference derives from the position of the different TMs where they request a new task. An outdoor TM on the ground floor is always in a parking position whereas a TM on a standard floor can be anywhere at the hallway. Therefore, the employee first has to return the TM to its parking position next to the freight elevator before he is released by the task management.

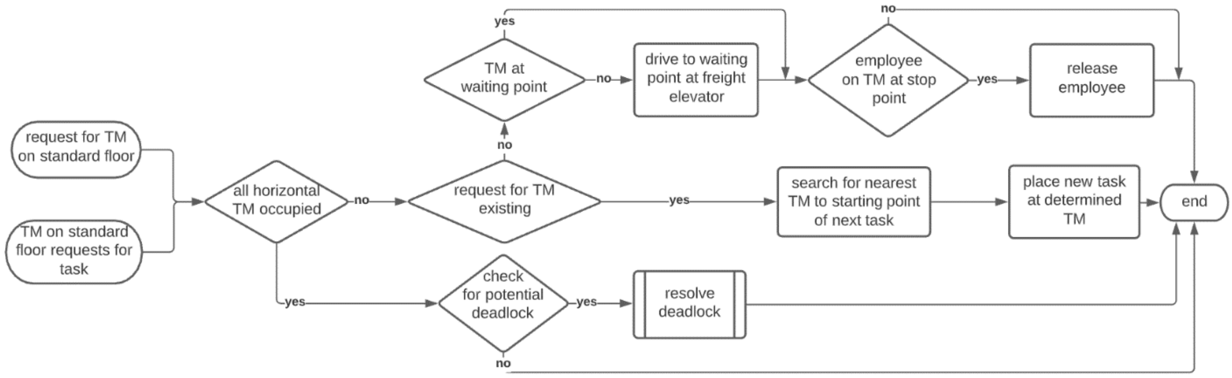


Figure 4-16: Task management of transportation means per standard floor

A TM on a standard floor is used for both supply tasks and disposal tasks (see Table 4-5). Moreover, it is interacting with both elevators whereby its parking positions can be at both elevators. However, the standard parking position is next to the freight elevator.

Table 4-5: Potential states of transportation means per standard floor

State	Description
Waiting	TM waits until it is assigned a new task.
Unload freight elevator	TM unloads material from a freight elevator and changes status to “supply takt area”
Supply takt area	TM transports material to transfer area of supplied takt area
Load elevator from interims storage	TM loads material from interims material storage into a freight elevator
Supply surplus material	TM searches for surplus material in the takt areas on the floor and transports it to next destination
Collect empty pallets	TM searches for empty pallets in the takt areas on the floor and collects it in recycling center on the floor. If more than 5 pallets in recycling center of the floor after finishing task: change status to “empty pallets to ground floor”
Empty pallets to ground floor [from interim storage]	TM gets up to 5 empty pallets per drive from recycling center/interim storage and loads them into indoor elevator.

The task execution of a TM on a standard floor is managed by a central method connected to the sensors on the hallway. The method controls movements and actions of a TM according to its current task, its load, and according to the object the triggered sensor is connected to. Similar as for the outdoor TM, the task “unload freight elevator” is prioritized to avoid deadlocks.

In Figure 4-17, a step-by-step task execution is presented. However, not all tasks are mentioned here due to spatial reasons. The execution of the task “load elevator from interims storage” follows the same steps as for the tasks “collect surplus material” from the step “drive to freight elevator”, including one step “load material from interims storage”. The task “empty pallets to ground floor from interim storage” is aligned with the disposal of empty pallets from the recycling center. The only difference is the place where the TM gets the empty pallets.

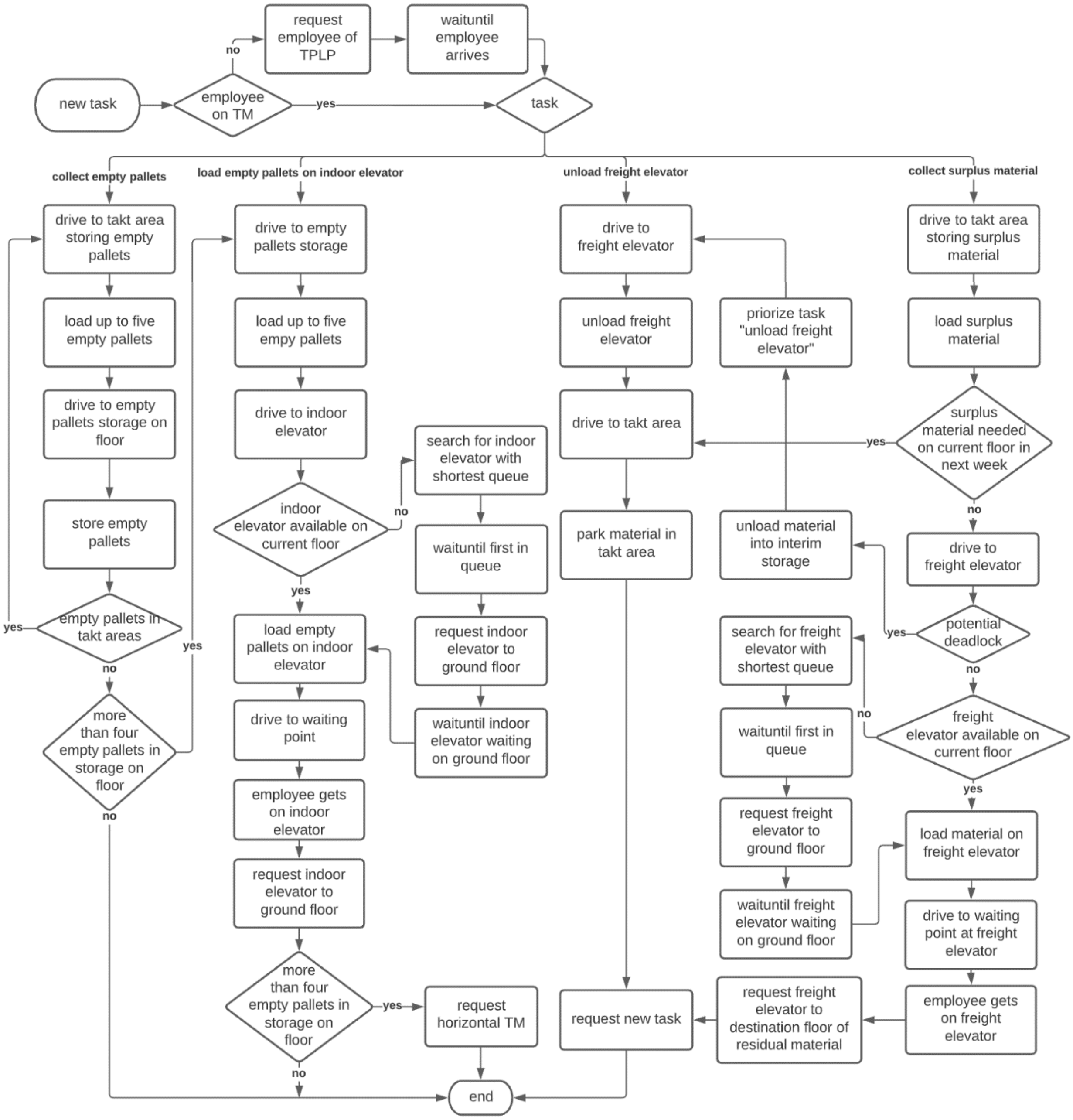


Figure 4-17: Task execution of transportation means per standard floor

4.7.3 Elevators

Recent literature only considered tower cranes, e.g. [Ast-2013], which have a significantly different behavior than a construction lift/elevator. Therefore, a new approach had to be developed to simulate the lifting behavior in this work, following the characteristics described in chapter 3.1.3.

Each elevator is positioned within an elevator shaft (implemented using the standard element “way”). Furthermore, each elevator has its own queue and a loading station for loading and unloading elements. All elevators are controlled by the same method which is managing each elevator based on its own task list and state. The requests for each elevator are fulfilled according to the FIFO principle. The elevator initially has the status “waiting”.

Table 4-6: Potential states of an elevator

Status	Description
Waiting	Elevator waits until it is requested to perform a transportation.
Wait for load	Elevator waits until loading process is finished and its status is changed to “fulfill task” (by element getting on elevator).
Fulfill task	Elevator is driving to requested floor (empty or loaded).
Wait for unloading	Elevator waits until no more material on elevator.
Search for new task	After unloading is finished, the elevator searches for a new task in its requirements list. If there is no task, it changes its status to “waiting”.

The destination of transportation in the state “fulfill task” is set in two different ways. First, an elevator can be requested to another floor without being loaded. Then, the elevator gets its destination from its task list. Second, an elevator is loaded on a certain floor to transport the entity to another floor. All the transported entities have a destination label which is evaluated by the elevator to determine the floor they have to be transported to.

An indoor elevator is mainly used for disposal tasks. It transports full bins to the ground floor and empty bins back to its origin floor, empty pallets from a standard floor to the ground floor and eventually workers, if the corresponding parameter of the parameter GUI is set true. Both empty pallets and bins are always transported together with the employee responsible for executing the task. Therefore, a bin can be unloaded from the elevator without waiting for other resources.

A freight elevator mainly performs material transportations and transports of employees. Materials can be loaded on all floors and are transported together with the responsible person. Hence, the material flow can be upwards and downwards. This causes a potential risk for a deadlock which is described in the following chapter.

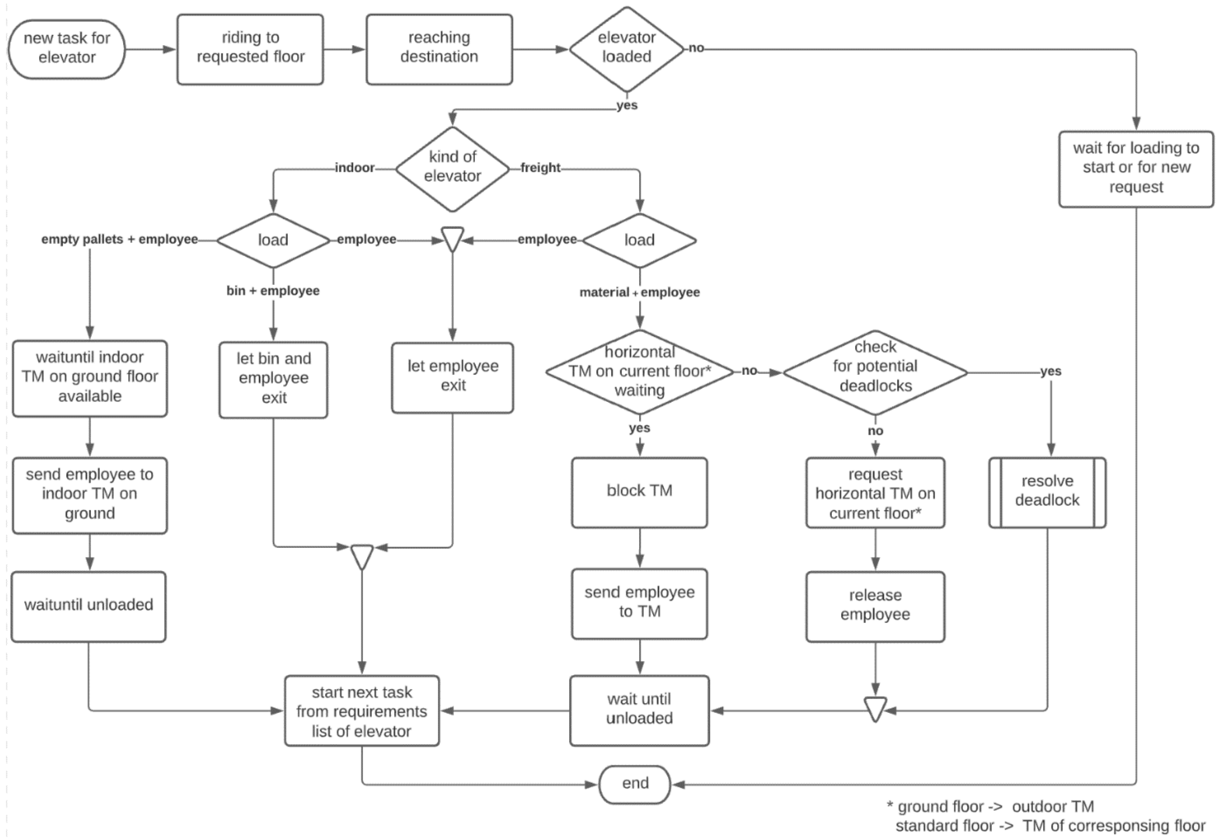


Figure 4-18: *Task execution of elevators*

4.7.4 Interface between Elevators and horizontal Transportation Means

At the interface between elevators and horizontal transportation means, there is a danger for so-called deadlocks. A deadlock describes a state in software where two or more entities wait for each other so that no further action is possible.

In this simulation study, this phenomenon occurs if an elevator waits to be unloaded while all TMs on the corresponding floor are waiting in the queue of the elevator until the elevator is ready to be loaded. As the TMs on each floor are responsible for both loading and unloading the material on and off each freight elevator, the elevator and the TM will be waiting for ever.

However, this risk only exists for the freight elevator. Regarding indoor elevators, the corresponding TM only loads empty pallets on the elevator on the standard floors and unloads empty pallets on the ground floor. Therefore, there is no situation possible where loading and unloading tasks are occurring at the same time on the same floor.

The detection for potential deadlocks can be requested by the task management of a TM, by the TM itself if it enters an elevator queue, or by the elevator if the employee cannot find an available TM on the corresponding floor to unload the elevator. In addition to the above-mentioned, obvious deadlock risk, there are further scenarios where deadlocks can occur due to the implemented task management.

If a freight elevator arrives loaded on a standard floor, and the TM is currently loading an indoor elevator or has already requested an indoor elevator, the employee (A) on the freight elevator would exit, assuming the employee (B) currently driving the TM will unload the elevator. Then, employee (A) could start a new supply task which starts on the ground floor. Therefore, he would queue up in the queue of the freight elevator with the state “supply takt area”. In the meantime, employee (B) leaves the floor together with the empty pallets whereas the TM requests another person to unload the freight elevator. However, employee A is set as occupied and another employee (C) who is taking the task, starting from another floor, could want to use the freight elevator to come to the floor if the queue is shorter. Therefore, no employee is getting the TM to unload the freight elevator which is another deadlock.

On the ground floor, there is no interference of freight and indoor elevator because there are two different TMs. Figure 4-19 presents the mechanism to detect a potential deadlock.

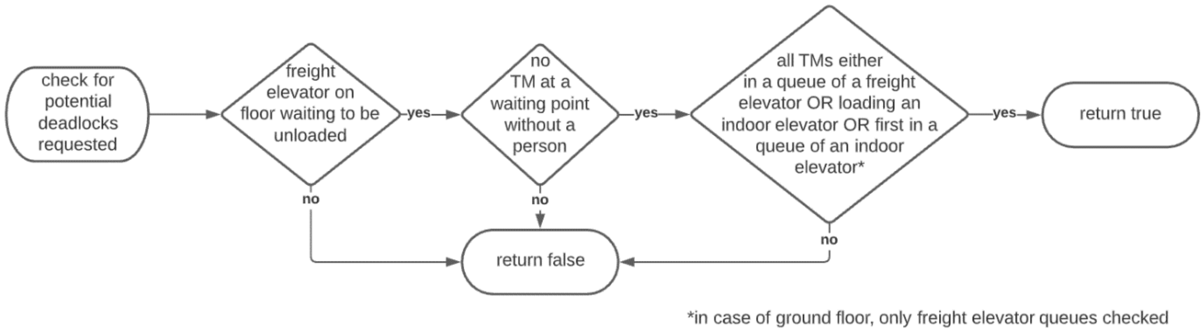


Figure 4-19: *Detection of potential deadlocks in the interface between freight elevator and horizontal transportation means*

In case a potential deadlock has been detected, there are several strategies to solve the phenomenon, depending on the positions of the TMs. If in the meantime, a TM is available again, the employee on the freight elevator is reaching out for this TM. If a TM is waiting in the queue of a freight elevator, the TM places the loaded material in a so-called intermediate material storage next to the freight elevator (just for simulation purposes) and unloads the elevator. Afterwards, it is loading the material and queues up again. The same applies for a TM waiting for an indoor elevator. The TM would place the empty pallets loaded next to the indoor elevator in an intermediate storage, unload the elevator, and continue the origin task. Finally, if the TM already started the loading process of the indoor elevator, the employee on the freight elevator waits until the TM is available again.

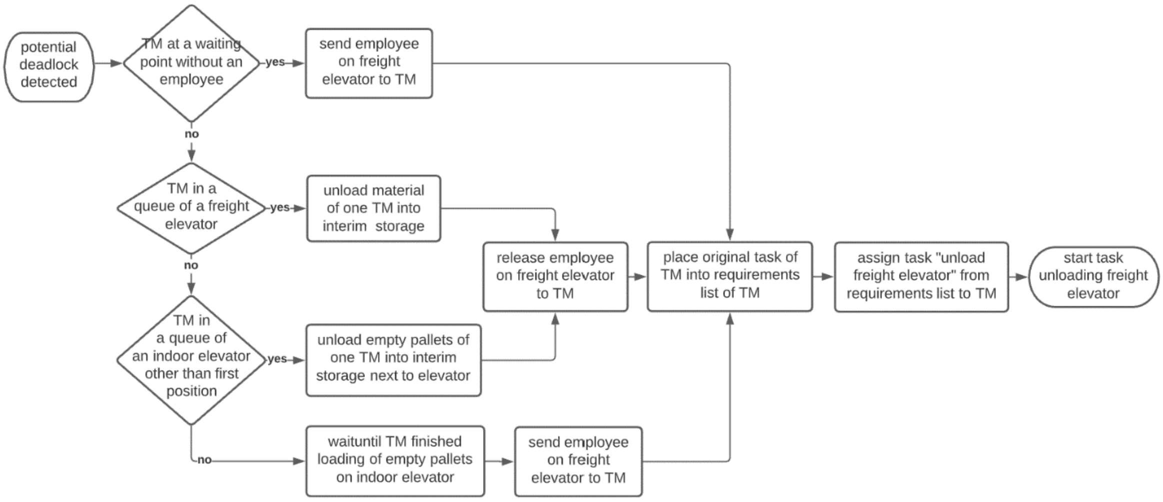


Figure 4-20: Releasing potential deadlocks in the interface between freight elevator and horizontal transportation means

4.7.5 Bins

The task management of the bins per standard floor is centrally controlled over all waste fractions by one task list. For each standard floor, one bin per waste fraction is initialized in each recycling center and assigned to the state “waiting”.

Table 4-7: Potential states of a bin

State	Description
Waiting	Bin waits until it is assigned a new task.
Collect waste	Bin collects waste of the appropriate fraction in the takt areas on the floor. If max. def. filling level reached: change state to “empty bin”
Empty bin	Bin to be emptied. Load on indoor elevator, empty in corresponding container, bring back to the origin floor

A request for a bin can only derive from the disposal management or from the bin itself as it requests a new task after having collected waste in one takt area. Thereby, the task management checks all takt areas on the floor if there is still waste of the fraction to be collected. In case that no more waste was found, the employee returns the bin to the recycling center. Afterwards, the task management checks the takt areas for waste of another subsequent waste fraction (based on the input data for waste fractions). If waste of subsequent fraction has been found, the employee gets the bin of the corresponding waste fraction. Otherwise, the employee is released.

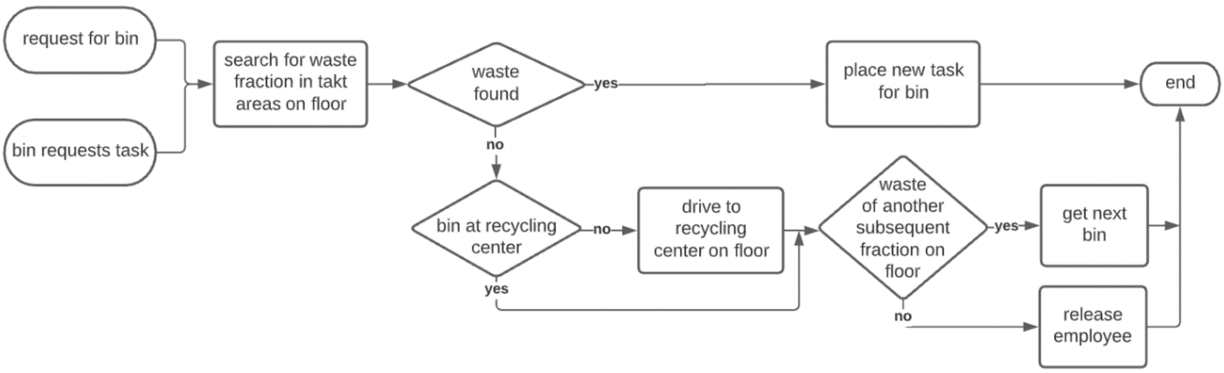


Figure 4-21: Task management bin – standard floor

Furthermore, bins may be placed next to the recycling center on the ground floor if they couldn't be fully emptied into the container. Therefore, another task management is necessary to continue the emptying process once the appropriate container is exchanged.

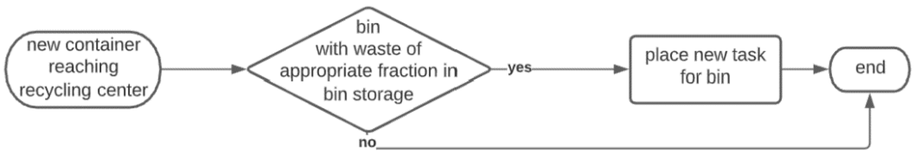


Figure 4-22: Task management bin - ground floor

After the task "empty bin" was set for the bin next to recycling center, the bin requests an employee of the TPLP to execute the task.

4.7.6 Container

At the beginning of the simulation, one container per waste fraction is initialized in the recycling center on the ground floor. These can be requested to be exchanged by an employee using an indoor TM on the ground floor or by an employee who emptied a bin into the container.

The task management for container exchange is checking for a request after each working day. As the exchange takes place on the following working day, the task management waits until the next day begins. Then, it generates the truck and the requested container type apart from the construction site. Afterwards, the truck drives to the construction site, exchanges the container, and leaves the construction site again. If there is a request to exchange another container, the container management generates another truck and starts the exchange process all over again.

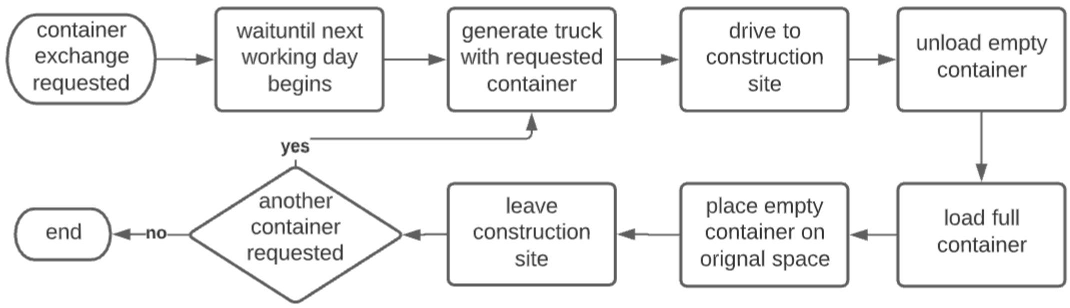


Figure 4-23: *Task management container exchange*

4.8 Construction Processes

Each takt area consists of a transfer area for materials (packages containing new supplied or surplus material), a parallel station representing the work within the takt area and a transfer area for waste and empty pallets. Each Monday, the tasks scheduled for the current week within the construction schedule are transferred to the task list of the takt areas respectively. The assigned tasks are processed sequentially, the materials per task simultaneously. Multiple materials per task are numbered consecutively.

The work in each takt area is represented by a parallel station containing ten stations, each referring to the material with corresponding number in the extends list. Therefore, the station can process maximum ten different materials per task simultaneously. During the cooperation with the industry partner, five materials have been identified as the maximum per task. Hence, ten materials are a reasonable limit to balance the tradeoff between flexibility and model size. Each station processes the assigned material independent of the other stations considering the time expenditure. The processing of materials starts as soon as the working day begins. If material is missing, the tasks start as soon as the material is available in the takt area. To ensure that a delay in delivery also causes a delay in work, the materials are processed simultaneously. Thereby, each delay regardless of which material, results in a delay of the construction process.

To simulate an equally distributed production of waste, the processing of the materials of a task is assumed to be linearly distributed. Therefore, the work expense per task ($\mathrm{t_{task}}$) is divided by the number of units (x) to be processed per material. The materials of a package are processed unit by unit according to the calculated work expense per unit ($\mathrm{t_{unitCalc}}$).

$$t_{unitCalc} = \frac{t_{task}}{x} \qquad (4\text{-}2)$$

Equation 3: Calculated processing time per material unit

At the beginning of the processing, a handling unit of the material, preferably a partly filled handling unit, is moved from the transfer area to the related station. The number of units processed ($x_{processCalc}$) depends on the calculated processing time per material unit, the number of material units within the handling unit ($x_{package}$), the number of units to be processed within the current task ($x_{process}$), and the remaining work time of day ($t_{remaining}$):

$$x_{processCalc} = \begin{cases} Min\left\{ x_{process}, x_{package} \right\} & , if \left(x_{process} * t_{unitCalc} \right) \leq t_{remaining} \\ \dfrac{t_{remaining}}{t_{unitCalc}} & , else \end{cases} \qquad (4\text{-}3)$$

Equation 4: Processed material units

Therefore, only partly finished units are allowed in order to accurately simulate the duration of the construction process. However, waste is only produced if the full unit of the material is processed. As there are only entire units of material in the material expense per task, each required material unit will be processed completely at the end of each task.

4.9 Statistics Output

The simulation model collects two different kinds of statistics: weekly measures and continuous time and task recording.

Weekly statistics are evaluated and stored at the end of each week, considering the following dimensions: amount of personnel, material supplied, waste volume, and storage areas. For all logistical resources, including all transportation means, disposal means, and employees of the TPLP, the simulation records the start and end time of their defined states during the working time. At the end of a simulation run, all logs are summarized into one table per category.

Furthermore, all statistics are exported into usual text - files which are further edited, analyzed, and graphically presented within an MS Excel evaluation sheet. Table 4-8 gives an overview of the simulation results.

Table 4-8: Simulation results

Dimension	Measure
Personnel	- number of employees working on the construction site
Supply	- number of trucks - number of handling units
Disposal	- filling degree of all bins and containers - number of container exchanges - volume of waste disposed from site
Storage	- maximum occupied area in material storage - maximum occupied area per takt area
Horizontal transportation means	- utilization - logistics hours - logistics cost
Elevators	- utilization - logistics hours - logistics cost
Employees of the TPLP	- utilization - logistics hours - logistics cost
Total	- logistics hours - logistics cost

4.10 Validation and Robustness

The simulation model was validated by comparing the outputs to another Master Thesis which developed a linear calculation tool based on the same case study [Den-2020].

The simulation model has been tested by a strategic test case structure which aimed at provoking special scenarios to test the robustness of the system. The tested subsystems include material supply, delivery to the takt areas, processing within the takt areas, handling of empty pallets, collecting and disposal of waste, surplus material, deadlocks, and an entire takt area compared. For each subsystem, extreme cases have been defined, to be able to test the system’s behavior, for example if the working time exceeds the scheduled working time.

To test the overall system behavior, the overall construction process has been calculated by hand for two materials in order to validate the data obtained from the simulation. Thereby, one material is allowed to be separated in the material storage, and one material is processed with surplus material per takt area. Additionally, the entire construction process has been calculated for one takt area to validate all considered tasks of all trades.

5 Parameter Study

The parameter study was conducted based on the data a real project implemented of the industry partner. However, the project has already been finished. Therefore, the construction project was only used for verification purposes instead of using the simulation model as supporting planning tool. In the following, the case study is described in detail. Furthermore, the experimental design and results of different experiments are presented.

5.1 Case Study

The case study was conducted for a hotel building with six standard floors, each 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 shell construction was finished and ends before the final cleaning takes place. The considered trades are called area dependent trades as their material and work expense are calculated based on gross floor area. The trades responsible for technical building equipment rather use special transportation means, e.g. a special crane or screed mixer and pumps. Therefore, these trades aren’t included in the present work. Small materials like screws have not been considered particularly. Material requirements and work expense are the same for each takt area.

Table 5-1: Trades, tasks and material requirements of the case study

Trade	Tasks	Required materials
Electric	Installations of cables, lamps and sockets, fine installations	Cables, lamps, sockets
Dry building	Calibration, building, and filling of dry walls and facings, suspending of ceilings, plastering special parts with dry plaster	Different kinds of plasterboards and mineral wool insulation, CW- and CD-profiles, nonius hanger, gypsum filler, dry plaster
Raised floor	Raising floor (instead of screed)	Raised floor
Painting	Filling of ceilings, plastering and partly wallpapering of walls, painting walls and ceilings	Filler, Plaster, wallpapers, color
Doors	Installation of doors in all rooms and in the hallway	Door frames and panels for rooms, aluminum door for floor

Floor Covering	Laying of floor cover including patching	Floor cover, filler
Ventilation	Installation and connecting of fancoils	Fancoil
Carpenter	Installation of windowsills	Windowsill

Construction site-specific data has been obtained by site layouts. For construction task-specific data, the construction schedule was readily available in a pdf-Format and had just to be transferred in MS Excel Input-Sheet. The work expenses per task had to be combined regarding rooms and the hallway and matched with the construction schedule. Material expenses were calculated in detail for dry building based on required material per the gross area and the material units per handling unit. During the calculations, the worst-case scenario was used for the size of packages, e.g. CW-profile bundles. For the other trades, assumptions have been provided by the contact persons of the industry partner based on the level of handling units. To match the simulated material flow, dummy material units have been placed on the handling units which allows for an accurate representation of the material and waste flow even though the real data base wasn't available in detail.

Company-specific data in regard with supply activities, such as transportation means, have been adapted from the Master thesis of *Dengler* [Den-2020]. In her thesis, she measured different durations of transportation processes. However, the durations have been stated for a completed process, e.g. unloading a handling unit of a truck. To be able to variably design the construction layout, these durations have been split into multiple sub-processes, e.g. driving to the truck, unload a handling unit, drive back to the material storage and place material in the material storage. The remaining company-specific data has been obtained by research of the author in close cooperation with the industry partner. The current state of the libraries for company-specific data can be found in Appendix A. Due to confidentiality reasons, the real values are not included. However, the contained parameter values and parameter settings are explained per input library.

5.2 Experimental Design

For the experimental design, the real scenario of how the case study has been conducted was chosen as basic scenario. Different scenarios have been investigated by changing one parameter compared to the basic scenario. Therefore, the impacts can be clearly allocated to the parameter under investigation. For the basic scenario, the following parameter settings have been set:

Table 5-2: Parameter settings basic scenario

Category	Parameters
Outdoor TM on the ground floor	One telehandler
Indoor TM on the ground floor	One electrical lifting truck
TM per standard floor	One electrical lifting truck
Freight elevators	One construction lift with a speed of 12 m/min
Indoor elevators	One construction lift with a speed of 12 m/min
Requirement of a ramp	No
Maximum capacity of persons per elevator	five
Availability of indoor elevator for transports of people	false
Employees of TPLP	three
Begin and end of working days	07:00 – 16:00
Break times	09:00 – 09:15; 12:00 – 12:45
Ratio of trade personnel using elevator to spend breaks on the ground floor	90 %
Expense for trucks to arrive	High expense
Supply days for material supplies to the site	Wednesday, Thursday, Friday
First day for deliveries to the takt areas	Thursday
Expense for trucks to exchange container	High expense
Defined maximum filling level of disposal means	90%
Start and end date of considered construction phase	26.03.2020 – 05.12.2020

The varied parameters include:

- Kind of horizontal TM
- Kind of freight elevator
- Number of available employees of the TPLP
- Kitting as alternative supply strategy

The variation of the indoor TM on the ground floor is not presented here as the variation had no further impact on the considered output measures. The parameter is therefore set as non-critical parameter [Voi-2014]. The same applies for the indoor elevator.

The results of the experiments are compared based on total logistical costs and total logistical hours. The measure “total logistical hours” is obtained by summing up over the operating time recorded within the tracking table of each logistical resource, including horizontal transportation means, elevators, and logistics personnel. By multiplying the logistical hours of a resource by the corresponding costs per hour, and again summing up over all resources, the measure “total logistical costs” is calculated. Both measures are included in the MS Excel Output sheet. For each experiment, further measures are included to evaluate the scenarios in more detail.

To prepare a simulation run, the data of the MS Excel Input-Sheet have been imported into the simulation model by pushing the start button within the basic frame of the simulation model (see Figure A-1 in Appendix A) which takes 20 seconds. Afterwards, the parameter settings of the simulated scenario have to specified by using the parameter GUI. The simulation is started by confirming the parameter settings. Each simulation run takes about 12 seconds in the non-visualizing mode, including export of statistics at the end of the simulation run. Afterwards, the text-files have to be evaluated by the MS Excel evaluation sheet (about 8 seconds) and a copy of the evaluation sheet has to be saved. Simulated scenarios and corresponding results are presented in the following.

5.3 Horizontal Transportation Means

The variation of horizontal transportation means has been evaluated for 8 different parameter settings representing all possible combinations of outdoor TM and TM per standard floor, which are presented in Table 5-3.

Table 5-3: Parameter settings – variation of horizontal transportation means

Simulated scenario	Outdoor TM on the ground floor	TM per standard floor
Basic scenario	Telehandler	Electrical lifting truck
HTM-1	Electrical lifting truck	Electrical lifting truck
HTM-2	Lifting truck	Electrical lifting truck
HTM-3	Forklift	Electrical lifting truck
HTM-4	Telehandler	Lifting truck
HTM-5	Electrical lifting truck	Lifting truck
HTM-6	Lifting truck	Lifting truck
HTM-7	Forklift	Lifting truck

Comparing the scenarios, it is noticeable that the impact of the variation of the outdoor transportation means is significantly higher than the variation of the TM per standard floor as the basic scenario and scenarios HTM-1 to HTM-3 only slightly differ from the scenarios HTM-4 to HTM-7. The only difference according to a TM per standards floor can be seen in the logistical hours in the scenarios HTM-2 and HTM-6 with a lifting truck on the ground floor. The overall best values are generated with an electrical lifting truck as outdoor TM on the ground floor.

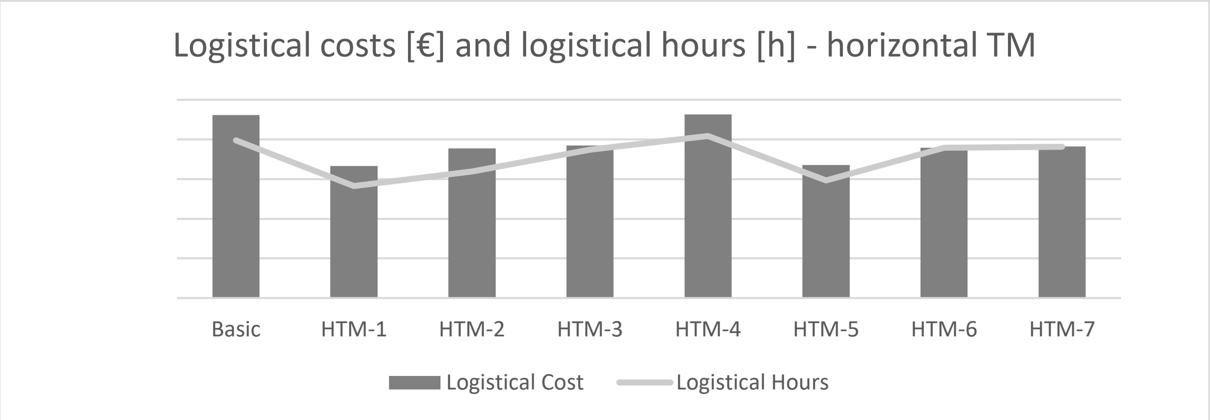


Figure 5-1: Parameter study horizontal transportation means - logistical costs and hours

However, total logistical costs and hours are not the only criterion on which a decision should be based. The utilization rate throughout the construction process is also an important indicator to evaluate the performance of each scenario. As no significant difference was observed by varying the TM per standard floor, the utilization in Figure 5-2 only presents the utilization per week for the outdoor TM on the ground floor. To improve clarity, the basic scenario is compared to the scenarios HTM-1 to HTM-3.

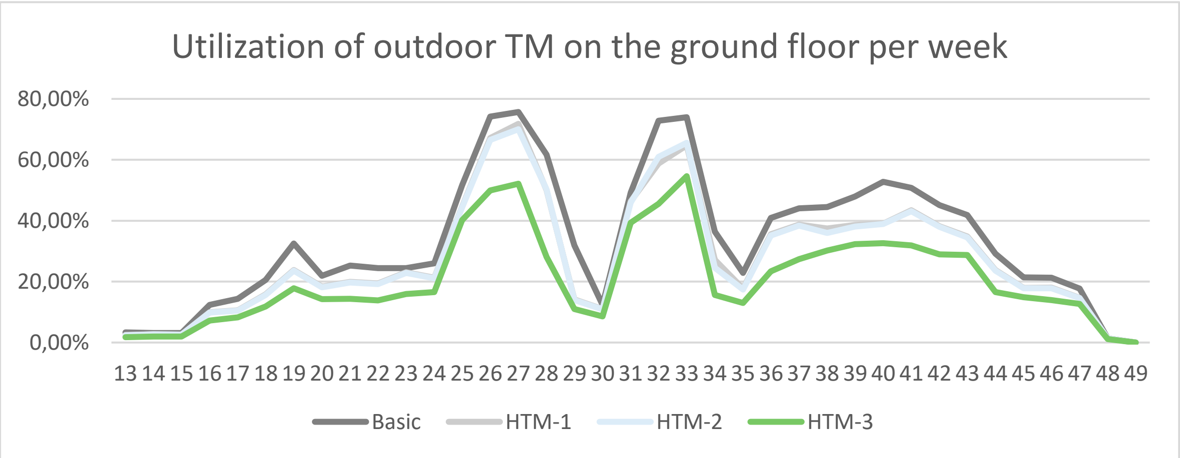


Figure 5-2: Parameter study horizonal transportation means - utilization of outdoor TM on the ground floor

For the evaluation of the utilization calculated by the simulation model, it is important to consider that no external disturbances are included in the simulation model. Therefore, the utilization mustn't be optimized to 100% to ensure feasibility in a real environment with numerous disturbances. The distribution of all transportation means are correlated to the number of handling units supplied to the construction site (see Figure B-2 in Appendix B). In the peak values, the utilization rate of the forklift is significantly lower compared to the other TMs whereas the utilization of the telehandler in the basic scenario has the highest utilization. The main goal of logistics is to maximize utilization by minimizing costs. By taking into account all measures (logistics costs and hours, and utilization rate), scenario HTM-1 or HTM-5 can be considered as the best combination with regard to horizontal transportation means.

5.4 Elevators

For the variation of the freight elevator, all kinds of elevator included in the library of the simulation model were included in the parameter study.

Table 5-4: Parameter settings – variation of elevators

Simulated scenario	Freight elevator
Basic scenario	Elevator (12 m/min)
El-1	Elevator (24 m/min)
El-2	Elevator (50 m/min)
El-3	Elevator (100 m/min)
El-4	Scissors lift

With increasing speed, both logistical costs and hours are decreasing. The speed of scissors lift is also assumed with a speed of 12 m/min. However, the time regarding getting on and off the lift differs from the elevator in the basic scenario. Nevertheless, this time difference has almost no impact on the total logistical costs and hours. Another interesting fact is that even if the speed is increased almost exponentially by the factor two, the savings of logistical costs and hours can be regarded as linear. Furthermore, it can be stated that the elevators overcome additional costs of high-speed elevators through even more efficient transportations.

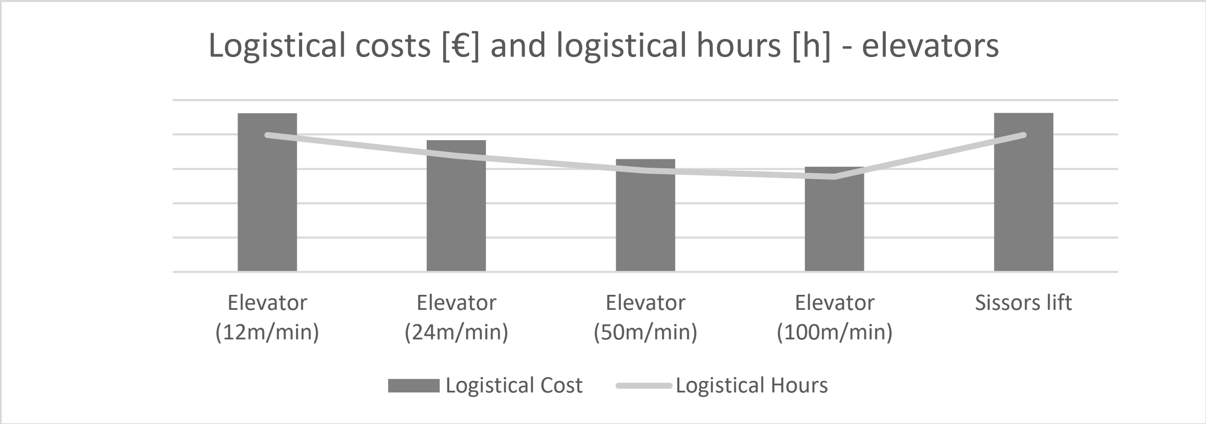


Figure 5-3: *Parameter study elevators – logistical costs and hours*

To evaluate the performance of the different freight elevators, the utilization has to be considered, again, keeping in mind that the simulation scenario doesn't account for external disturbances. Therefore, the utilization of the elevator in the basic scenario and the scissors lift is critical in the calendar weeks 26 to 28. The peaks in the weeks 26 to 28 and 32 to 34 can be explained by the number of supplied handling units which have to be transported to the takt areas (see Figure B-2 in Appendix B). The higher utilization from week 36 to 43 follows the course of the number of trade employees on-site per week (see Figure B-1 in Appendix B). Therefore, both a particularly high number of supplied handling units and a high number of employees of the trades, using the elevator six times a day, have a great impact on the utilization of the freight elevator. The utilization rate of both the elevator with a speed of 12 m/min and the scissors lift is critically high in week 28. Therefore, it could be argued that there is a need for a faster elevator to ensure that material can be provided in time. The utilization of the different kind of elevators decreases along with the increase of speed. The elevator with a speed of 100 m/min in scenario El-3 has the lowest utilization rate.

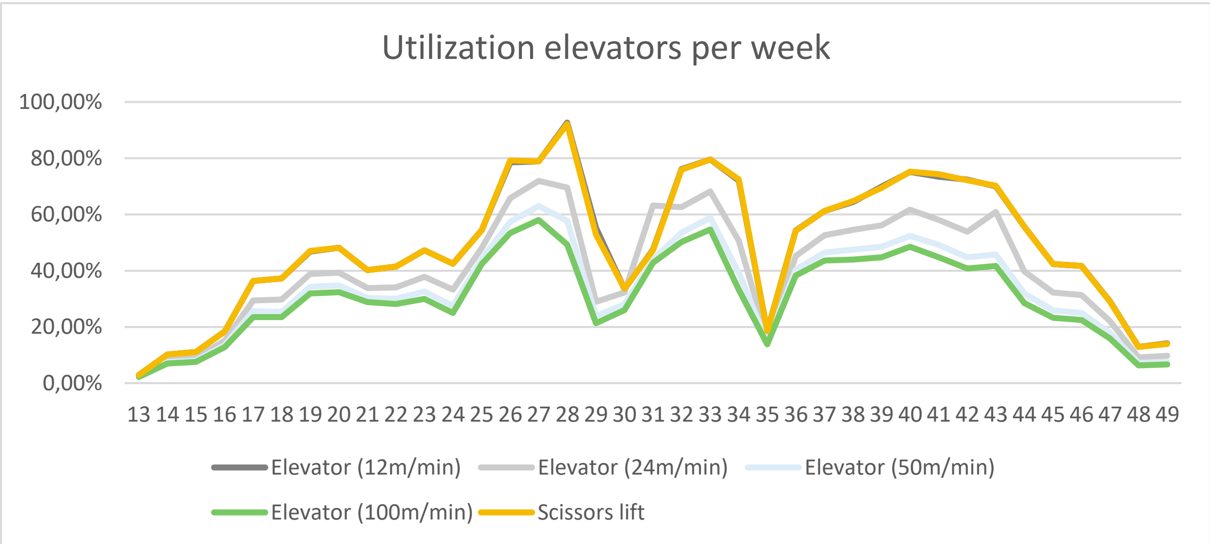


Figure 5-4: *Parameter study elevators - utilization freight elevator*

Another interesting measure is the mean waiting time per transportation. Similar to the utilization rate of the elevators, the mean waiting time per transportation also differs throughout the construction time. There, it's interesting to see that especially in the peaks, the impact of speed variation is even greater. Another interesting observation is that the mean waiting time is higher if the utilization is increased by employees using the elevator than if more handling units have to be transported.

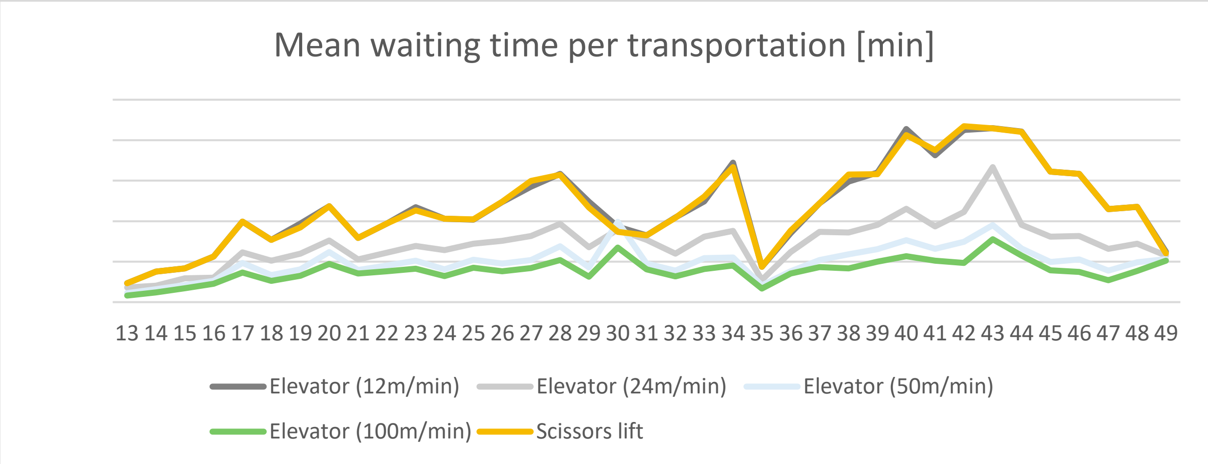


Figure 5-5: Parameter study elevators - mean waiting time per transportation

In relation to utilization, the elevators with a speed of 24 and 50 m/min can be seen as the most effective choice. However, the best values in relation to total logistical costs and hours have been obtained for the fastest elevator. Therefore, there is again a tradeoff between utilization and costs if a manager wants to specify the best logistical strategy.

5.5 Employees of the TPLP

For the variation of the parameter "employees of the TPLP", a minimum number of three employees of the TPLP has been specified according to the basic scenario. The number of available employees has been increased up to eight as the impact stabilized afterwards.

Table 5-5: Parameter settings – variation of employees of the TPLP

Simulated scenario	Number of employees
Basic scenario	3
Empl-4	4
Empl-5	5
Empl-6	6
Empl-7	7
Empl-8	8

The impact on the logistical costs and hours of both the horizontal TM and the elevators is relatively low. However, both total logistical costs and hours increase for the logistics employees. This means that a parallelization of the tasks doesn't increase the effectiveness.

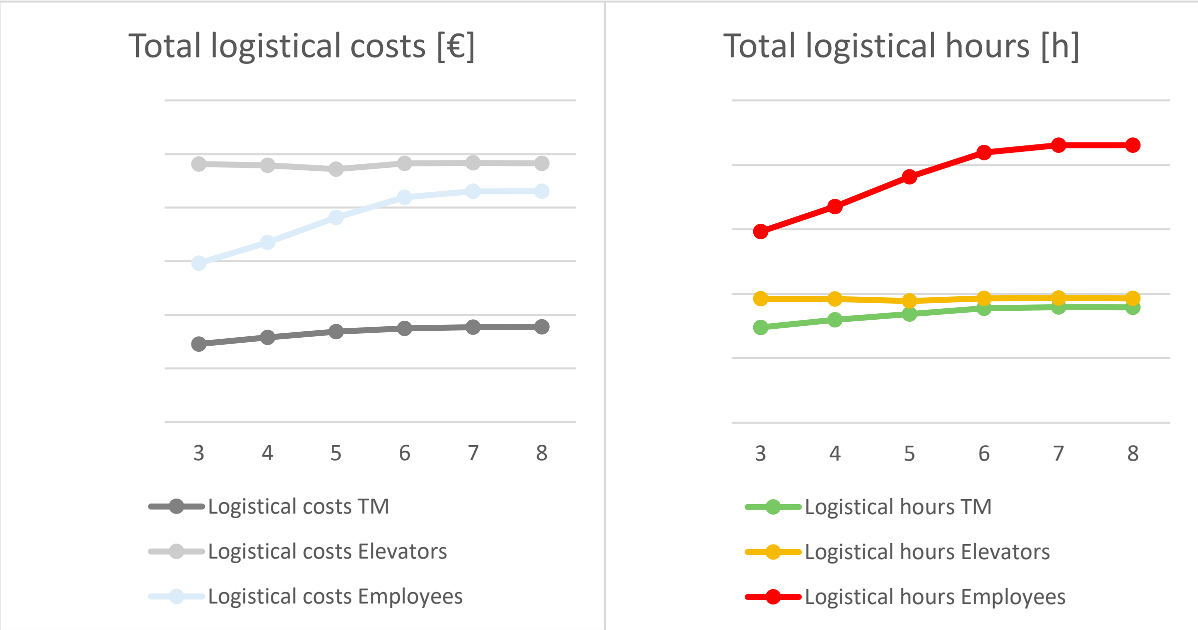


Figure 5-6: Parameter study employees – total logistical costs and hours

The reason can be observed in Figure 5-7. The disposal tasks are evenly distributed over all workers as they all start at the same point in time in the afternoon. However, the workload per person isn't decreasing significantly even if more employees perform the disposal tasks. Referring to supply tasks, the first employee has the greatest workload as he always unloads the trucks at the beginning of respective working days.

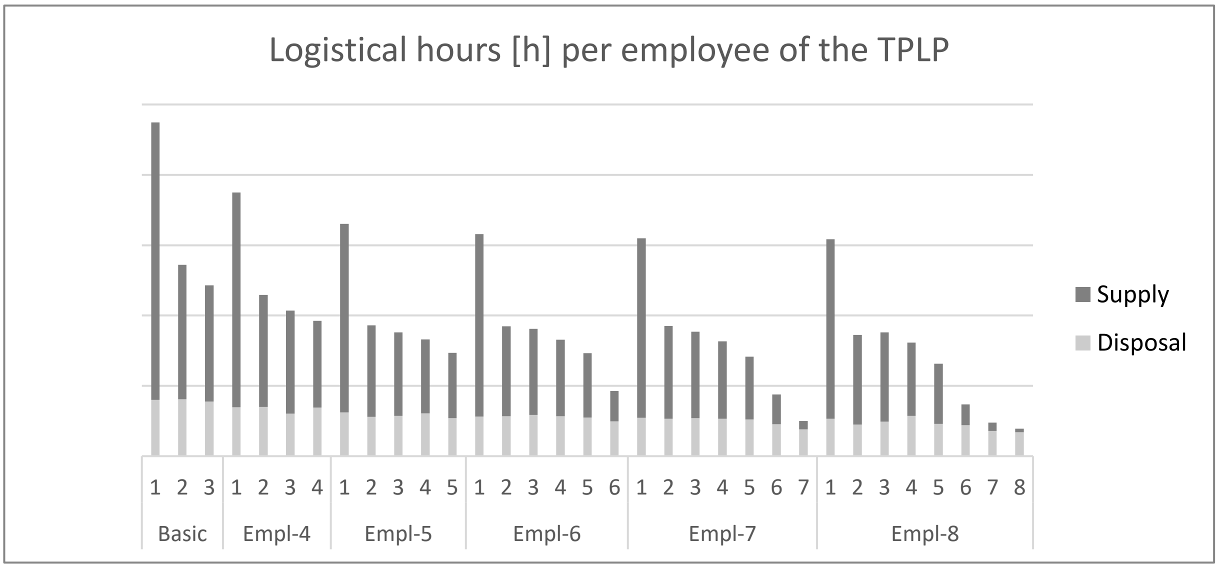


Figure 5-7: Parameter study employees - distribution of workload

Therefore, employing three employees can be seen as the most effective logistical choice with regard to logistical costs and logistical hours.

5.6 Kitting as an alternative Supply Strategy

To vary the supply strategy, a kitting scenario is proposed. Thereby, materials are not directly supplied to the construction site but to an external consolidation center. There, the handling units of the materials are separated and kitted according to the delivery list of each takt area for the subsequent week. On the defined days of delivery, the materials are sent to the construction site without a limitation of trade materials per truck. At the construction site, the handling units are transported to the corresponding takt area without further separation effort in the material storage. Furthermore, there is no more handling of surplus material. The kitting solution has been implemented by adapting the order list according to the delivery list without any trade specifications.

Table 5-6: Parameter settings – kitting solution as an alternative supply strategy

Simulated scenario	Order list
Basic scenario	According to calculations specified in chapter 4.2.1
Kitting	Corresponding to delivery list without a trade specification

As expected, the number of trucks which supply material to the construction site could be reduced by 34%. However, the number of handling units which are delivered increased by 10% (see Figure 5-8). This is caused by two main aspects. First, the material requirements are not consolidated over all takt areas. For example, if a takt area requires 1/10 of the material loaded on a standard handling unit, only one pallet is supplied in the basic scenario for materials that area allowed to be separated on site. This results in nine separation activities in the material storage to deliver the material to ten takt areas. In the kitting scenario, there are ten handling units supplied to the construction site.

Second, the order list isn't reduced by surplus material in the takt areas. In the basic scenario, the responsible employee reduces the initially calculated material requirements per week by the expected amount of surplus material per week per takt area. This applies for material which isn't allowed to be separated in the material storage. In the kitting scenario, there is no surplus material whereas all initially calculated material requirements are supplied to the construction site. However, this increases reliability and forecast stability.

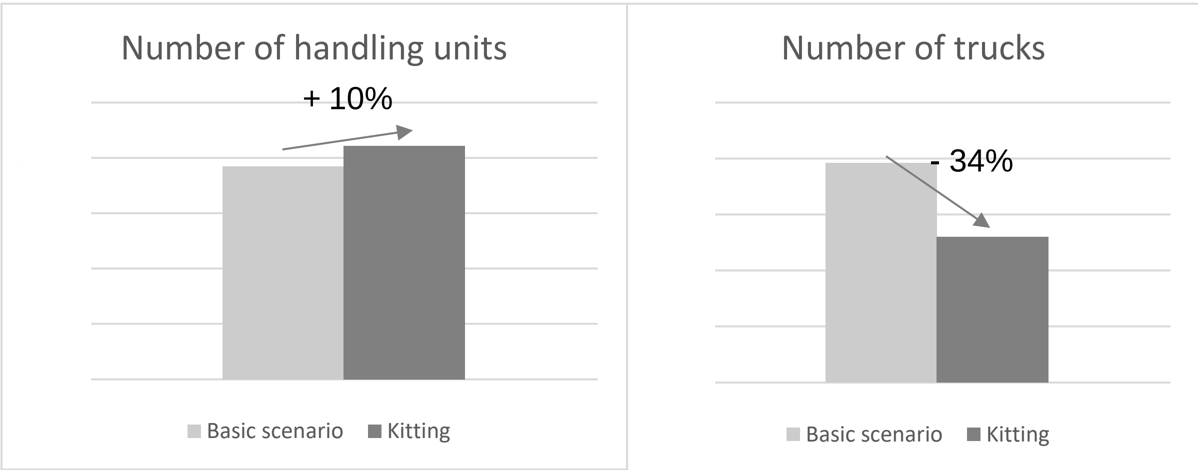


Figure 5-8: Parameter study kitting - number of supplying trucks and supplied handling units

As a fact of interest, especially in peak times, there is more storage area needed to transitionally store the supplied handling units. This has a negative impact on the organization of the construction site as space is a scarce resource, especially in the urban environment.

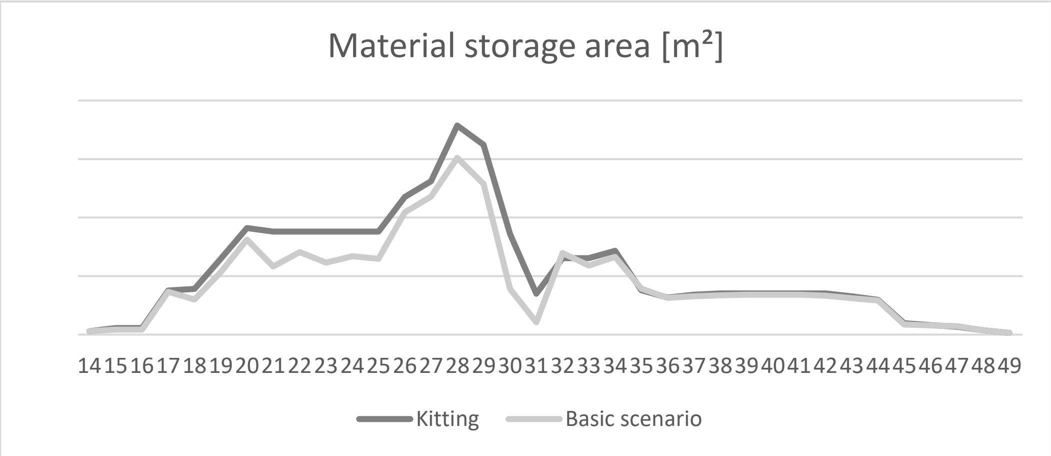


Figure 5-9: Parameter study kitting - material storage area

To further evaluate the impact of a kitting solution, the logistical costs and hours have to be compared. The main point of investigation 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. As presented in Figure 5-10, the reduced effort cannot overcompensate the additional expense caused by the additional supplied handling units. The logistical costs have been increased by 4%, and the logistical hours by 5%.

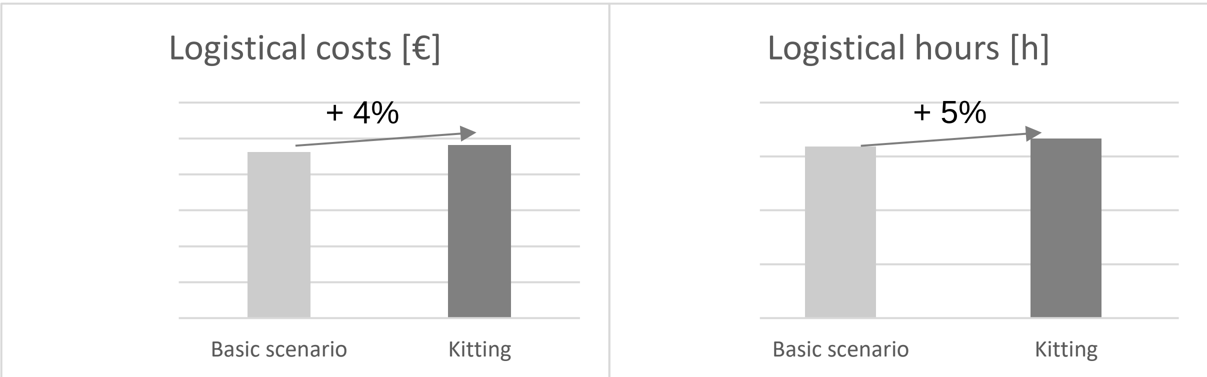


Figure 5-10: Parameter study kitting - logistical costs and hours

Therefore, the implementation of a kitting scenario as presented in this chapter is not favorable considering all measures.

6 Discussion

In the present study, the main goal of developing of a user-friendly simulation model has been achieved. The modular approach allows an adaptation to multiple construction projects. However, the use of separated elevators for supply and disposal tasks may not be the most common approach within building construction.

Also, the use of a standard software was successful as the entire simulation model was implemented using standard elements of the Plant Simulation software. This allows to investigate several interference effects that cannot be considered within analytical solution approaches. In sum, the complexity of the construction site was included from a logistical point considering the entire material and waste management through a third-party logistics partner. Nevertheless, the implemented simulation doesn't involve any disturbances from the environment, such as delays in construction processes, supply difficulties, or the "human factor" which are critical to evaluate construction processes [Lee-2013].

Therefore, the obtained results in the parameter study regarding the variation of logistical resources have to be evaluated under this aspect. Utilization cannot be optimized up to 100% to ensure feasibility in the real environment. To further enhance the simulation model, these points have to be included after having acquired the required data on corresponding probability distributions.

Within the parameter study, it has been observed that the outdoor TM is the bottleneck among the horizontal transportation means. For the case study, the electrical lifting truck has been identified as best logistical strategy. For elevators, the fastest elevator type delivered the best results in regard to logistical costs, logistical hours, and mean time of waiting per transportation. However, there is a tradeoff between the beforementioned measures and the utilization of the elevator. This also applies for the horizontal TM. For the variation of the employees, the basic scenario has been identified as the best among the considered scenarios. Nevertheless, to find global optimum regarding a combination of logistical resources, a superior optimization algorithm has to be developed.

During the research, the same problems with respect to data acquisition have been detected as multiple prior studies stated, e.g. [Abo-2011]. Therefore, the material requirements have only been calculated in detail for dry building. Nevertheless, the material flow of the other trades has been modeled accurately as the number of handling units are crucial to investigate multiple aspects on the construction site. Although, the material details should be included in further investigations to get a deeper understanding of the characteristics of the materials.

Moreover, certain lean construction tools already have been implemented in the simulation model. The organization of the material storage and the fixed parking position of the horizontal TM follow the 5S method which allows to eliminate waste related to searching activities. Furthermore, the material handling was organized from a logistical point of view. Therefore, the materials didn’t necessarily follow the “train of trades” if the surplus material was needed in the takt area or on the corresponding floor in the subsequent week. As a result, a crew is moving on to the next takt area/to the next floor whereas the material stays in the takt area/on the floor to eliminate multiple material handling and to waste logistical resources.

For the materials, the “real” supply strategy has been investigated by only allowing to supply entire handling units. Thereby, an alternating behavior with respect to material handling in the material storage has been observed during the research of this work. This resulted in multiple handling activities of the materials through separation activities and surplus material handling which is classified as waste according to the lean construction philosophy. To eliminate this kind of wastes, a kitting solution has been proposed. However, the kitting solution as implemented in this work could not enhance the construction performance due to the significantly increased number of handling units supplied to the construction site. Further points for improvements could be a JIT delivery strategy. Therefore, the required storage area on the ground floor could be significantly eliminated by directly supplying the materials to the takt areas without temporally storage on the ground floor. Moreover, the handling units of the takt areas could be combined in standard containers, as proposed by *El Moussani et al*. [Mou-2021]. This would decrease the number of supplied handling units while still benefitting from the elimination of separation in the material storage and handling of surplus material.

7 Conclusion

The aim of this work was fulfilled by developing a simulation model which visualizes the entire material and waste flow on a building construction site during the outfitting phase. This reduces the black box effect perceived by the stakeholders as they can clearly follow how the calculated data has been obtained. Furthermore, the design was made in a modular approach whereas the simulation is not limited to the underlying use case study but can be adapted to multiple construction sites having the same material flow and layout characteristics without major programming effort. Additionally, the simulation already contains company-specific and construction technology-related data, which can be used during the modeling of future projects. This reduces the amount of effort needed to conduct a simulation study.

Different parameters have been investigated based on a real case study conducted by the industry partner of this work. Some basic lean construction principles have been implemented and a kitting solution has been proposed as alternative supply strategy. However, the investigated solution didn't increase the productivity at the construction site whereas further developments have been proposed to address the increased number of handling units supplied to the construction site.

Regarding further research areas, the data acquisition is a major point. There, it should be investigated on how data could be organized centrally for logistical processes and material requirements per week in order to reduce the effort of data import. The current values included in the library should be verified by adapting the simulation to another construction project. Furthermore, the simulation could be connected to the developed IT resources of the company to increase efficiency and even enable the use in the construction implementation phase additionally to the early planning stage.

For the model itself, the modular approach could be enlarged, a pull strategy could be implemented in order to investigate influencing factors of the environment on the construction duration.

8 List of References

[Abd-2017] Abdelmegid, M.: Towards a conceptual modeling framework for construction simulation. In: 2017 Winter Simulation Conference (WSC) (2017)

[Abd-2020] Abdelmegid, M. A.; González, V. A.; Poshdar, M.; O'Sullivan, M.; Walker, C. G.; Ying, F.: Barriers to adopting simulation modelling in construction industry. In: Automation in Construction, Jg. 111 (2020), S. 103046.

[Abo-1998] AbouRizk, S. M.; Hajjar, D.: A framework for applying simulation in construction. In: Canadian journal of civil engineering (1998) Nr. 25.3, S. 604–617.

[Abo-2009] AbouRizk, S. M.; Hague, S.: An overview of the COSYE environment for construction simulation. In: Proceedings of the 2009 Winter Simulation Conference (WSC) (2009), S. 2624–2634.

[Abo-2010] AbouRizk; S: Role of Simulation in Construction Engineering and Management (2010) Journal of construction engineering and management, 2010, 136. Jg., Nr. 10, S. 1140-1153.

[Abo-2011] AbouRizk, S.; Halpin, D.; Mohamed, Y.; Hermann, U.: Research in Modeling and Simulation for Improving Construction Engineering Operations. In: Journal of Construction Engineering and Management, Jg. 137 (2011) Nr. 10, S. 843–852.

[Aga-1998] Agapiou, A.; Clausen, L. E.; Flanagan, R.; Norman, G.; Notman, D.: The role of logistics in the materials flow control process. In: Construction Management and Economics, Jg. 16 (1998) Nr. 2, S. 131–137.

[Ail-2008] Ailland, K.; Bargstädt, H.-J.: [Workday-related Schedule Monitoring on Construction Sites Using Simulation] Taggenaues Termincontrolling auf Baustellen mit Hilfe der Simulation. In: Advances in Simulation for Production and Logistics Applications (2008), S. 169–178.

[Akh-2013] Akhavian, R.; Behzadan, A. H.: Knowledge-Based Simulation Modeling of Construction Fleet Operations Using Multimodal-Process Data Mining. In: Journal of Construction Engineering and Management, Jg. 139 (2013) Nr. 11, S. 4013021.

[Arb-2004] Arbulu, R.; Ballard, G.: Lean Supply Systems in Construction. In: International Group for Lean Construction (2004), S. 1–13.

[Ast-2013] Astour, H.; Franz, V.: [Simulation-based crane deployment planner for building construction projects] Simulationsgestützter Kraneinsatzplaner für Hochbauprojekte. In: Simulation in Produktion und Logistik (2013), S. 515–524.

[Baj-2017] Bajjou, M. S.; Chafi, A.; En-Nadi, A.: A Comparative Study between Lean Construction and the Traditional Production System. In: International Journal of Engineering Research in Africa, Jg. 29 (2017), S. 118–132.

[Baj-2021] Bajjou, M. S.; Chafi, A.: Lean construction and simulation for performance improvement: a case study of reinforcement process. In: International Journal of Productivity and Performance Management, Jg. 70 (2021) Nr. 2, S. 459–487.

[Bal-2012] Ballard, G.; Tommelein, I.: Lean management methods for complex projects. In: Engineering Project Organization Journal, Jg. 2 (2012) Nr. 1-2, S. 85–96.

[Bam-2019] Bamana, F.; Lehoux, N.; Cloutier, C.: Simulation of a Construction Project: Assessing Impact of Just-in-Time and Lean Principles. In: Journal of Construction Engineering and Management, Jg. 145 (2019) Nr. 5, S. 5019005.

[Ban-2010] Banks, J.; Carson J.S.; Nelson, B. L.; Nicol, D. M.: Discrete-Event System Simulation. Prentice Hall, 2010.

[Bar-2015] Bargstädt, H.-J.; Feine, I.: Performing scenario simulations in construction by using standard software (2015)

[BBR-2020] Bundesinstitut für Bau-, Stadt- und Raumforschung (BBSR) im Bundesamt für Bauwesen und Raumordnung (BBR): Strukturdaten zur Produktion und Beschäftigung im Baugewerbe – Berechnungen für das Jahr 2019. BBSR-Online-Publikation 15/2020, Bonn, 2020.

[Beh-2015] Behzadan, A. H.; Menassa, C. C.; Pradhan, A. R.: Enabling real time simulation of architecture, engineering, construction, and facility management (AEC/FM) systems: a review of formalism, model architecture, and data representation. In: ITcon (2015) Nr. 20, p. 1–23.

[Ber-2013] Berner, F.; Kochkine, V.; Habenicht, I.; Spieckermann, S.; Vath, C.: Simulation in manufacturing planning of buildings. In: 2013 Winter Simulations Conference (WSC) (2013), S. 3306–3317.

[Bla-2008] Blakey, R.: An Introduction to Lean Construction. In: Design and Construction (2008), S. 33–35.

[Boe-2003] Boenert, L.; Blömeke, M.: [Logistics concepts in turnkey construction to increase cost leadership] Logistikkonzepte im Schlüsselfertigbau zur Erhöhung der Kostenführerschaft. In: Bauingenieur, Jg. 78 (2003), S. 277–283.

[Boe-2006] Boenert, L.; Blömeke, M.: [Cost reduction through centralized logistics management] Kostensenkung durch ein zentrales Logistikmanagement. In: Clausen, U. (Hrsg.): Baulogistik – Konzepte für eine bessere Ver- und Entsorgung im Bauwesen. Verlag Praxiswissen, Dortmund, 2006, S. 29–41.

[Bro-2013] Brodetskaia, I.; Sacks, R.; Shapira, A.: Stabilizing Production Flow of Interior and Finishing Works with Reentrant Flow in Building Construction. In: Journal of Construction Engineering and Management, Jg. 139 (2013) Nr. 6, S. 665–674.

[Cha-2005] Chahrour, R.; Utsch, J. H.; Franz, V.: [Computer simulation in construction operations - ways to innovation -] Computersimulation im Baubetrieb - Wege zur Innovation -. In: Tagungsband 18. ASIM Symposium Fortschritte in der Simulationstechnik (2005)

[Den-2020] Dengler, J.: Entwicklung eines Berechnungsmodells zur Simulation und Optimierung der Materiallogistik im Hochbau, Hochschule Biberach, 2020.

[Fei-2016] Feine, I.; Smarsly, K.; Bargstädt, H.-J.: Scenario simulations for improved production planning in construction engineering using standard simulation software. In: The 16th International Conference on Computing in Civil and Building Engineering (ICCCBE) (2016)

[Gom-2016] Gomez-Cabrera, A.; Paez, H.; Alvarado, Y. A.: Digital Simulation as a Tool for Transforming the Construction Industry. In: Proceedings of the VII Elagec (2016), S. 577–587.

[Gut-2014] Gutfeld, T.; Jessen, U.; Wenzel, S.; Laroque, C.; Weber, J.: A technical concept for plant engineering by simulation-based and logistic-integrated project management. In: Proceedings of the Winter Simulation Conference 2014 (2014)

[Gut-2015] Gutfeld, T.; Jessen, U.; Wenzel, S.; Akbulut, A.; Laroque, C.; Weber, J.: [Final report on the IGF project simject - Simulation-supported logistics-integrated project management in plant engineering and construction] Schlussbericht zu dem IGF-Vorhaben simject - Simulationsgestütztes logistikintegriertes Projektmanagement im Anlagenbau (2015)

[Haj-2002] Hajjar, D.; AbouRizk, S. M.: Unified Modeling Methodology for Construction Simulation. In: Journal of Construction Engineering and Management, Jg. 128 (2002) Nr. 2, S. 174–185.

[Hal-1977] Halpin, D. W.: CYCLONE–method for modeling job site processes. In: Journal of the construction division (1977) Nr. 103, S. 489–499.

[Ham-2007] Hamzeh, F.; Tommelein, I. D.; Ballard, G.; Kaminsky, P. M.: Logistics Centers to Support Project-Based Production in the Construction Industry. In: Proceedings of the 15th Annual Conference of the International Group for Lean Construction (IGLC 15) (2007), S. 181–191.

[Hsu-2018] Hsu, P.-Y.; Angeloudis, P.; Aurisicchio, M.: Optimal logistics planning for modular construction using two-stage stochastic programming. In: Automation in Construction, Jg. 94 (2018), S. 47–61.

[Jeo-2016] Jeong, W.; Chang, S.; Son, J.; Yi, J.-S.: BIM-Integrated Construction Operation Simulation for Just-In-Time Production Management. In: Sustainability, Jg. 8 (2016) Nr. 11, S. 1106.

[Kam-2003] Kamat, V. R.; Martinez, J. C.: Validating complex construction simulation models using 3D visualization. In: Systems Analysis Modelling Simulation (2003) Nr. 43.4, S. 455–467.

[Kir-2013] Kirchner, J.; Krämer, T.: [Constraint-based discrete-event simulation of construction schedules using extended Petri nets] Constraintbasierte Discrete-Event Simulation von Bau-Terminplänen mit Hilfe von erweiterten Petri-Netzen. In: Proc. des 25. Forum Bauinformatik (2013), S.155–168.

[Kön-2007] König, M.; Beißert, U.; Bargstädt, H.-J.: Visual Simulation - An Appropriate Approach to Support Execution Planning in Building Engineering. In: 7th International Conference on Construction Applications of Virtual Reality (2007), S. 189–197.

[Kon-2012] Konig, M.; Koch, C.; Habenicht, I.; Spieckermann, S.: Intelligent BIM-based construction scheduling using discrete event simulation. In: Proceedings of the 2012 Winter Simulation Conference (WSC) (2012), S. 1–12.

[Kön-2015] König, M.; Rank, E.; Bletzinger, K.-U.; Borrman, A.; Smarsly, K.; Huhnt, W.: [Current developments and challenges in construction informatics] Aktuelle Entwicklungen und Herausforderungen der Bauinformatik. In: Bauingenieur, Jg. 90 (2015) Nr. 7/8

[Kos-1992] Koskela, L.: Application of the new production philosophy to construction. Stanford university, 1992.

[Kug-2008] Kugler, M.; Franz, V.: [Use of simulation to increase the efficiency of production processes in the construction industry] Einsatz der Simulation zur Effizienzsteigerung von Produktionsprozessen im Bauwesen In: Rabe, M. (Hrsg.): Advances in Simulation for Production and Logistics Applications (2008), S. 151–160.

[Kug-2012] Kugler, M.: [CAD-integrated modeling of agent-based simulation models for construction process simulation in structural engineering] CAD-integrierte Modellierung von agentenbasierten Simulationsmodellen für die Bauablaufsimulation im Hochbau. Kassel Univ. Press, Kassel, 2012.

[Law-2015] Law, A. M.: Simulation Modeling and Analysis, Fifth Edition. McGraw-Hill Education, New York, 2015.

[Lee-2013] Lee, S.; Behzadan, A. H.; Kandi, A.; Mohamed, Y.: Grand Challenges in Simulation for the Architecture, Engineering, Construction, and Facility Management Industries. In: Computing in Civil Engineering (2013), S. 773–785

[Lei-2016] Leite, F.; Cho, Y.; Behzadan, A. H.; Lee, S.; Choe, S.; Fang, Y.; Akhavian, R.; Hwang, S.: Visualization, Information Modeling, and Simulation: Grand Challenges in the Construction Industry. In: Journal of Computing in Civil Engineering, Jg. 30 (2016) Nr. 6, S. 4016035.

[Lin-2013] Lindén, S.; Josephson, P.-E.: In-housing or out-sourcing on-site materials handling in housing? In: Journal of Engineering, Design and Technology, Jg. 11 (2013) Nr. 1, S. 90–106.

[Lip-1999] Lipsmeier, K.; Ghabel, M.: [Waste management systems in construction practice] Abfallmanagementsysteme in der baubetrieblichen Praxis – Der recyclingorientierte Baustellenbetrieb für den Hochbau. Bautechnik, Jg. 76 (1999) Nr. 5, S. 362–367

[Lu-2018] Lu, H.; Wang, H.; Xie, Y.; Wang, X.: Study on construction material allocation policies: A simulation optimization method. In: Automation in Construction, Jg. 90 (2018), S. 201–212.

[Mar-1994] Martinez, J. C.; Ioannou, P. G.: General purpose simulation with stroboscope. In: Proceedings of Winter Simulation Conference (1994), S. 1159–1166.

[Mar-2010] Martinez, J. C.: Methodology for Conducting Discrete-Event Simulation Studies in Construction Engineering and Management. In: Journal of Construction Engineering and Management, Jg. 136 (2010) Nr. 1, S. 3–16.

[Mos-2007] Mossman, A.: Lean logistics: Helping to create value by bringing people, information, plant, equipment and materials together at the workface. In: International Group for Lean Construction (2007), S. 198–211.

[Mou-2021] El Moussaoui, S.; Lafhaj, Z.; Leite, F.; Fléchard, J.; Linéatte, B.: Construction Logistics Centres Proposing Kitting Service: Organization Analysis and Cost Mapping. In: Buildings, Jg. 11 (2021) Nr. 3, S. 105.

[Nin-2017] Ningshuang, Z.; Dichtl, M.; König, M.: A scenario-based simulation framework of on-and off-site construction logistics. In: 2017 Winter Simulation Conference (WSC) (2017), S. 2348–2359.

[Ohn-1988] Ohno, T.: Toyota production system: beyond large-scale production. CRC Press, 1988.

[Oso-2020] Osorio-Sandoval, C. A.; Tizani, W.; Pereira, E.; Koch, C.; Fadoul, A.: Discrete-Event Simulation and Building Information Modelling Based Animation of Construction Activities, Jg. 98 (2020), S. 285–294.

[Pit-2011] Pitsch, H.: [Simulation of unique processes] Simulation von Unikatprozessen. (2011)

[Pos-2016] Poshdar, M.; Gonzalez, V.; O'Sullivan, M.; Shahbazpour, M.: The Role of Conceptual Modeling in Lean Construction Simulation. In: Proc. 24th Ann. Conf. of the Int'l. Group for Lean Construction (2016), S. 63–72

[Ran-2005] Randolph, T. H.; Riley, D. R.; Messner, J. I.: Fundamental Principles of Site Material Management. In: Journal of Construction Engineering and Management (2005) Nr. 131, S. 117–153.

[Sam-2013] Samkari, K.; Franz, V. (Hrsg.): A Petri net-based simulation model for the flexible modelling and analysis of building construction processes. Heinz-Nixdorf-Inst. Univ. Paderborn, Paderborn, 2013.

[Sep-2016] Seppänen, O.; Peltokorpi, A.: A New Model for Construction Material Logistics. In: Annual Conference of the International Group for Lean Construction (2016)

[Sob-2005] Sobotka, A.; Czarnigowska, A.: Analysis of supply system models for planning construction project logistics. In: Journal of Construction Engineering and Management, Jg. 11 (2005) Nr. 1, S. 73–82.

[Spi-2010] Spiekermann, S.; Habenicht, I.; Zeller, G.; Zimmermann, J.: [Simulations for testing assembly and logistics processes] Simulationen zur Prüfung von Montage- und Logistikabläufen. SimPlan AG. Maintal (2010)

[Sri-2008] Srisuwanrat, C.; Ioannou, P. G.; Tsimhoni, O.: Simulation and optimization for construction repetitive projects using promodel and simrunner (2008), S. 2402–2412.

[Ste-2010] Steinhauer, D.; König, M.: [Concepts for the effective construction of simulation models for the production of unique specimens] Konzepte zum effektiven Aufbau von Simulationsmodellen für die Unikatproduktion. In: Integrationsaspekte der Simulation (2010), S. 157–164.

[Tis-2013] Tischer, A.; Besiou, M.; Graubner, C.-A.: Efficient waste management in construction logistics: a refurbishment case study. In: Logistics Research, Jg. 6 (2013) Nr. 4, S. 159–171.

[Tom-1999] Tommelein, I.; Weissenberger, M.: More just-in-time: location of buffers in structural steel supply and construction processes. In: Proceedings IGLC (1999) Nr. 7, S. 109.

[Tri-2014] Trivedi, J.; Kumar, R.: Optimisation of construction resources using lean construction technique. In: International Journal of Engineering Management and Economics, Jg. 4 (2014) Nr. ¾, S. 213.

[VDI-3633] Verein deutscher Ingenieure: Simulation of systems in materials handling, logistics and production - Fundamentals. VDI Nr. 3633 Page 1, 2000.

[Voi-2008] Voigtmann, J. K.; Bargstädt, H.-J.: [Simulation of construction logistics processes in outfitting] Simulation von Baulogistikprozessen im Ausbau (2008)

[Voi-2010] Voigtmann, J. K.; Bargstädt, H.-J.: Construction Logistics Planning by Simulation. In: Proceedings of the 2010 Winter Simulation Conference (2010), S. 3201–3221.

[Voi-2014] Voigtmann, J. K.: [Simulation of construction logistics processes in outfitting] Simulation baulogistischer Prozesse im Ausbau, Bauhaus-Universität Weimar, 2014.

[Vri-2000] Vrijhoef, R.; Koskela, L.: The four roles of supply chain management in construction. In: European Journal of Purchasing & Supply Management, Jg. 6 (2000) Nr. 3-4, S. 169–178.

[Web-2007] Weber, J.: [Simulation of logistics processes on construction sites based on 3D CAD data] Simulation von Logistikprozessen auf Baustellen auf Basis von 3D-CAD Daten, Universität Dortmund, 2007.

[Weg-2001] Wegelius-Lehtonen, T.: Performance measurement in construction logistics. In: International Journal of Production Economics, Jg. 69 (2001) Nr. 1, S. 107–116.

[Wen-2013] Wenzel, S.; Laroque, C.: [Methodology for simulation-based logistics-integrated project management in plant construction] Methodik für ein simulationsgestütztes logistikintegriertes Projektmanagement im Anlagenbau. In: Dangelmaier, W.; Laroque, C.; Klaas, A. (Hrsg.): Simulation in Produktion und Logistik. W.V. Westfalia Druck GmbH, Paderborn, 2013, S. 537–547.

[Whi-2018] Whitlock: BIM for Construction Site Logistics Management. In: Journal of Engineering, Project, and Production Management, Jg. 8 (2018) Nr. 1, S. 47–55.

[Wic-2020] Wickramasekara, A. N.; Gonzalez, V. A.; O'Sullivan, M.; Walker, C. G.; Poshdar, M.; Ying, F.: Exploring the Integration of Last Planner® System, Bim, and Construction Simulation (2020), S. 1057–1068.

[Xu-1999] Xu, J.; AbouRizk, S. M.: Product-based model representation for integrating 3-D CAD with computer simulation. In: WSC'99. 1999 Winter Simulation Conference Proceedings (1999) Nr. 2, S. 971–977.

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A Appendix

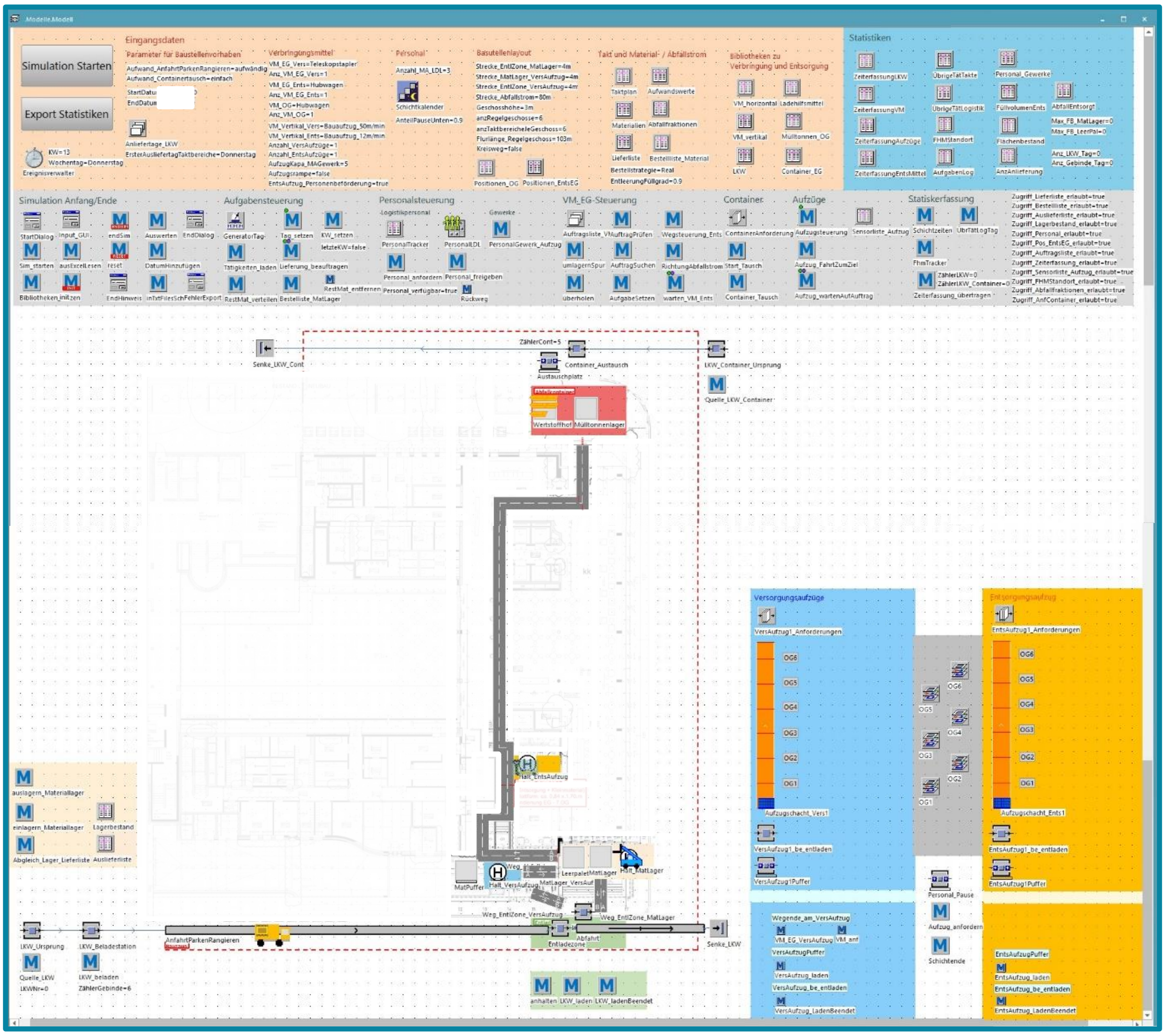

Figure A-1: *Screenshot ground floor (example project)*

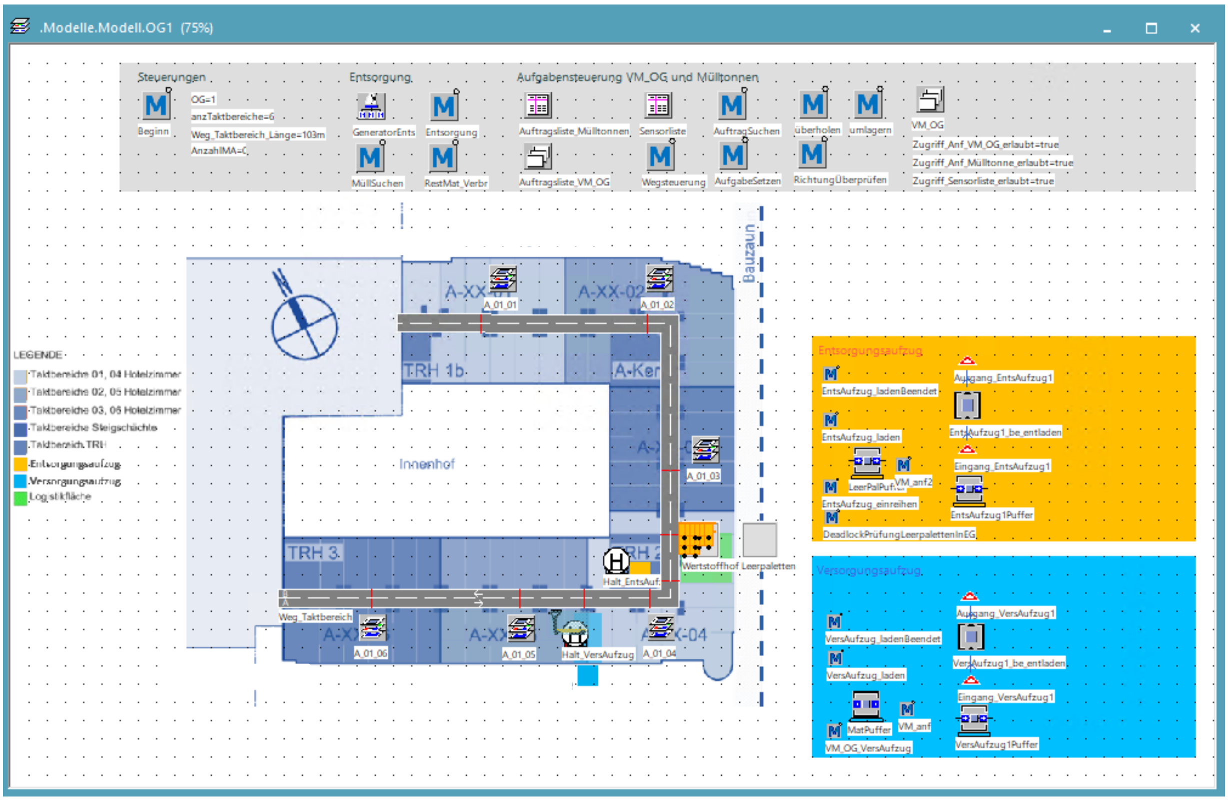

Figure A-2: Screenshot standard floor (example project)

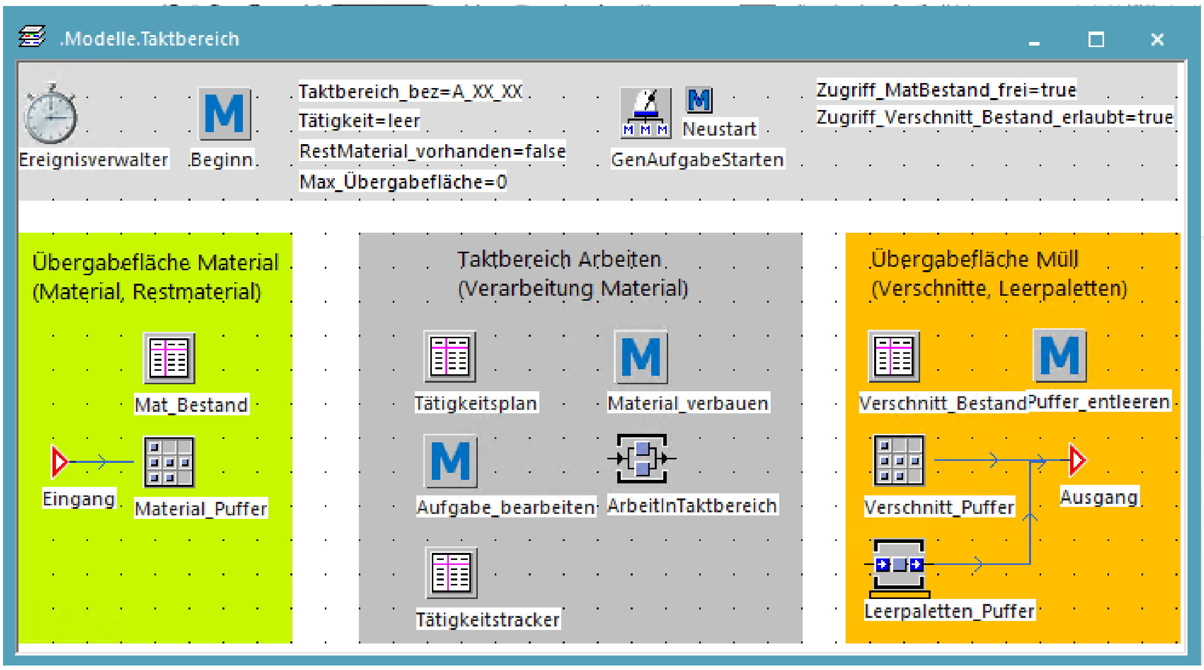

Figure A-3: Screenshot takt area

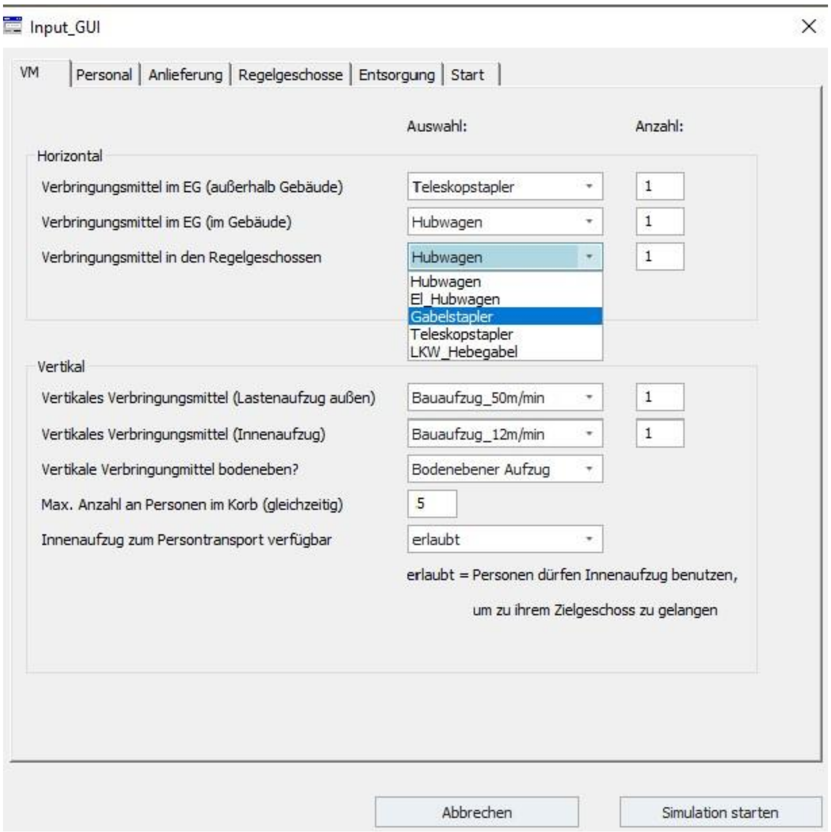

Figure A-4: *Parameter GUI*

Table A-1: *Current state of simulation library - horizontal transportation means (adapted from [Den-2020])*

Transporation means	Specified parameters
Lift truck Electric lift truck Forklift Telehandler Lifting fork on truck	Speed depending on load: - Simple load (< 250 kg, <= euro pallet) - Normal load (250-1000kg, overlength/-heigths/ unstable/limited view) - Heavy load (>1000kg, shunting necessary) - Not loaded Unloading time per handling unit from truck: - Euro pallet/Pallet cage - Disposable pallet - Package/bundle Loading time of a handling unit on an elevator Time for picking up a handling unit Time for putting down a handling unit Costs per operating hour

Table A-2: Current state of simulation library - vertical transportation means (adapted from [Den-2020])

Transporation means	Specified parameters
Elevator (12 m/min) Elevator (24 m/min) Elevator (50 m/min) Elevator (100 m/min) Scissors lift	Speed depending on load: - Loaded - Not loaded Time to open lift door Costs per operating hour

Table A-3: Current state of simulation library - trucks (adapted from [Den-2020])

Transporation means	Specified parameters
Supply truck	Time to arrive, shunt, and park: - Simple environment (direct arrival) - Normal environment (arrival with small issues, a bit of shunting) - Elaborate environment (removing fence or bollard, significant shunting)
Container truck	Time to exchange a full container by a new one: - Simple (empty container next to full container without further movements) - Normal (empty container on place of full container) - Elaborate (Multiple movements of containers)

Table A-4: Current state of simulation library - bins

Disposal means	Specified parameters
Bin 240l Bin 660l	Loading area Maximum capacity [m³] Time to unload full bin into corresponding container Time to load bin on an elevator Average speed if pushed

Table A-5: Current state of simulation library - container

Disposal means	Specified parameters
Container 10m³ Container 9 m³ Container 12 m³	Loading area Maximum capacity [m³]

Table A-6: Current state of simulation library - container

Disposal means	Specified parameters
Container 10m³ Container 9 m³ Container 12 m³	Loading area Maximum capacity [m³]

Table A-7: Current state of simulation library – handling units

Handling unit	Specified parameters
Euro pallet Disposable pallet Plasterboard pallet Package Paket Piece	Hight Length Width Loading area Disposable/reusable

Table A-8: Current state of simulation library – material

Material	Specified parameters
Aluminum door Floor CD-profile CW-profile Raised floor Fancoil Color Windowsill Gypsum filler GKBI – plasterboard GKF – plasterboard Cabel reel Lamp Mineral wool 50mm Mineral wool 80mm Nonius hanger Floor filler Dry plaster Plaster Wall paper Door frame Door panel Socket Filler for painters	Handling unit Number of units per handling unit Separation of handling unit allowed Loading area per handling unit (important if piece) Waste fraction Blend [%] Volume (to simulate blend volume) Time to load a unit of blend

B Appendix

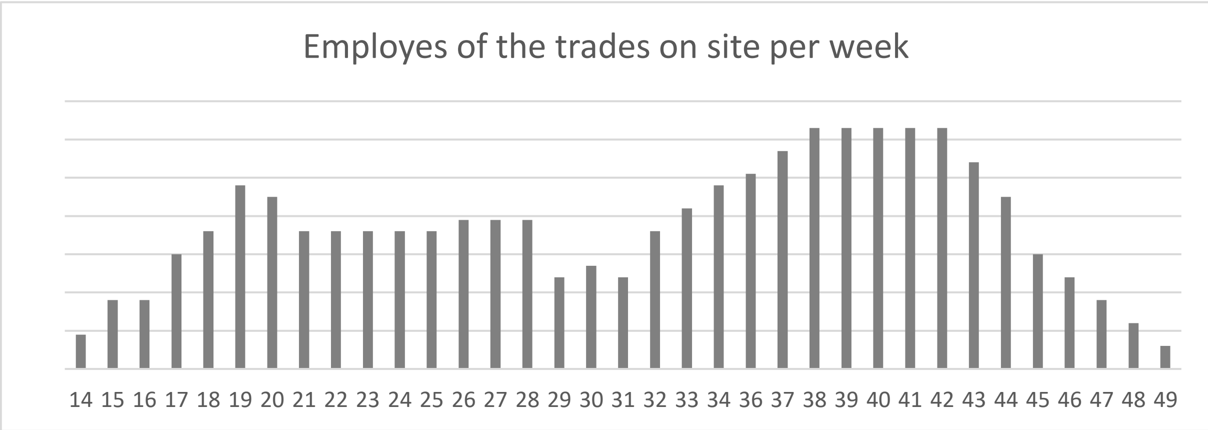

Figure B-1: Number of employees of the trades per week throughout the construction project

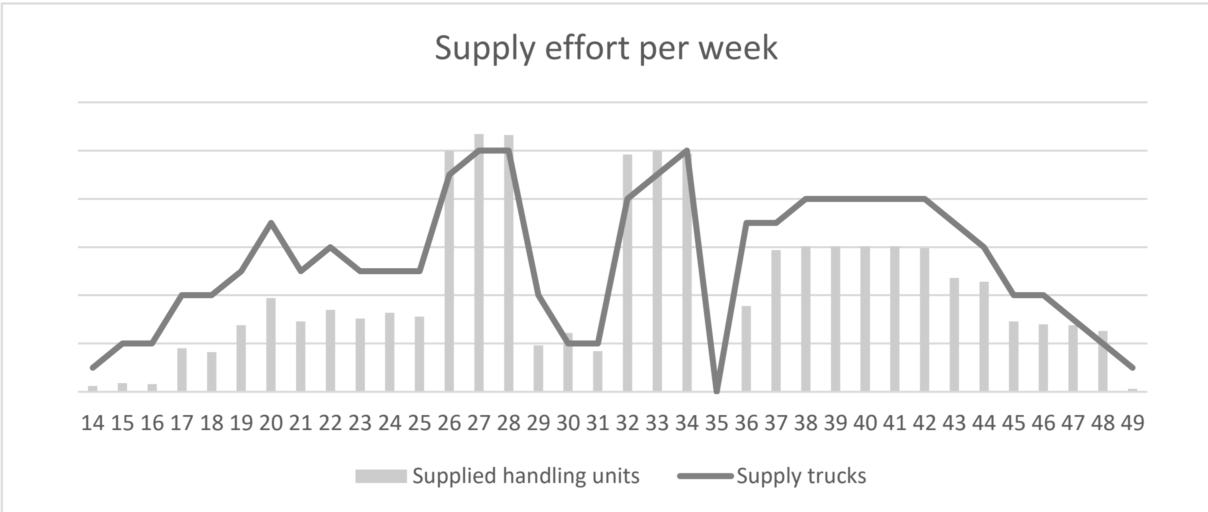

Figure B-2: Number of supplying trucks and supplied handling units per week throughout the construction process

Erklärung

Ich versichere hiermit, dass ich die von mir eingereichte Abschlussarbeit selbstständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

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Ort, Datum, Unterschrift