

ENHANCING INTERNAL VERTICAL LOGISTICS FLOWS IN HIGH-RISE CONSTRUCTION: AN EXPLORATORY STUDY

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ABSTRACT

Vertical logistics systems are important for enhancing production performance in high-rise buildings (HRBs). However, researchers studying vertical logistics have focused on examining the flow of individual resources in isolation. Only a few studies adopt a holistic approach to optimizing the flow of resources. For example, research on the combined effect of the number, characteristics, and rules of elevators uses and break rooms' location on the production system's performance remain scarce. Methods and tools like agent-based modelling (ABM) and simulation could be used to study and predict vertical logistics systems' performance holistically. This research uses hypothetical strategies to investigate opportunities to enhance performance and develop more effective vertical logistics systems. The proposed agent-based model and simulation is validated with a simple, hypothetical takt plan. The simulation results show that the logistic system's performance varies when changing parameters like the number of elevators and the location of break rooms. This research's main contribution is a new way to study these systems and potentially enhance their performance. Furthermore, possibilities to maximize performance and remove logistical bottlenecks are suggested.

KEYWORDS

Vertical transportation systems, internal logistics, simulation, agent-based, production planning and control.

INTRODUCTION

Effective high-rise construction depends on the vertical transportation system's performance. The system can substantially affect the production schedule as it limits the

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time available for work or delays the transportation of the resources (Jung et al. 2017; Park et al. 2013). A vertical transportation system is used to move workers to their work locations during working hours. Elevators are also used for moving other resources such as materials and equipment consumed by production tasks. Increased performance of vertical transportation systems is necessary to minimize waste.

One essential peculiarity in construction, compared to plant-based manufacturing, is that instead of product flowing through the production line, the productive resources flow through the product (Sacks 2016). That is, the planning, coordination, and organization of productive resources, in addition to production operations, to flow through the building is very important. It is especially relevant in high-rise construction projects, where the physical distance of travel and associated time is significantly higher than in other building types.

Although there is previous work on high-rise logistics, they tend to focus on an individual strategy such as elevator zoning (e.g., Jung *et al.*, (2017)). In real high rise projects, a combination of strategies is required, and to the authors' knowledge, there is no previous work that has attempted to identify and include. This study explores vertical flows as an emergent property of takt based construction production plan. An agent-based model is used to study the interactions between these flows. The model could be used in high rise projects to study, pre-plan and determine the performance of hypothetical strategies for vertical transportation systems. The model may bring insights for the construction planners to examine the role of changing combinations of system variables, including, for example, the number of elevators, the site working policy, and when the material elevator can be used to transport workers, on system performance. As such, it may be used by companies and planners to update their current planning methods and produce better plans.

BACKGROUND

SIMULATION OF VERTICAL LOGISTICS SYSTEMS IN HIGH-RISE BUILDING

This study focuses on the internal phase of construction production. The vertical logistics during the internal construction phase is achieved through different means, including elevators and cranes. It is important to select the right number of elevators with the appropriate speed, capacity and manage the elevators' control rules, including the service range, zones, usage, and methods of calling the elevators, to optimize vertical transportation.

Vrijhoef et al. 2018 simulated workers' time usage and examined five strategies that could affect workers' productive time. One strategy included increasing the number of restrooms by one and the elevators by one. These interventions helped to increase the productive time on site. However, the role of material delivery, traffic on different floors and the impact of changing the break rooms' locations were not considered.

Jung *et al.*, (2017) used ABM to study the effects of zoning and sky-lobby control strategies on the performance of vertical transportation systems. The main finding was that there is no one best strategy suitable for all kinds of traffics and that the design of the elevator system should vary according to the construction project phase. The study did not, however, examine how the location of breakrooms, number of lifting elevators, and material lifting strategies affect the site traffic.

There are many metrics to assess the elevator system's performance in the building's operation phase, however, these metrics are not suitable for the construction phase

because no particular patterns for traffic exist (Jung *et al.*, 2017). Also, these metrics ignore workers waiting time, queuing length, and the total travel time when workers' traffic exceeds the vertical transportation system's capacity (Siikonen, 1997).

Moreover, it is important in construction to evaluate each elevator operation efficiency separately and manage the traffic accordingly. This is particularly evident when the performance, service range, and elevators' characteristics are different. This limitation stresses the need to emphasize the worker's time to arrive at their destination, mainly during peak time traffic. If the workers spend more time arriving at their destination, their overall productivity decreases accordingly. Thus, a measure for vertical transportation system performance should consider assessing the time needed by every worker to reach their destination.

One of the challenges in studying vertical transportation is that the historically used methods for evaluating vertical transportation, like deterministic simulation, or discrete event simulation, fall short in modelling the site conditions. The usage of complex science methods like ABM can help to overcome these limitations.

RESEARCH METHODS

As the main output of this research is an agent-based simulation model for construction vertical transportation systems, the design science research methodology is chosen (Holmström *et al.* 2009). The selected methodology assumes gradual and iterative development and evaluation of the artefact, i.e., the simulation model in this research. After each development iteration, focus group interviews were organized to collect feedback from researchers and practitioners to develop the model further.

ABM is a computer simulation technique used to examine how system rules and patterns emerge from individual agents' behaviours (Epstein *et al.* 1996). ABM is a suitable tool to describe complex systems' behaviour. It employs a "bottom-up" approach and creates artificial agents representing entities with the ability to perceive and interact with each other and their environment. In other words, in ABM, the interaction of system components or agents' behaviours determines the whole system's behaviour. The agent could be an autonomous individual or an entity that recognizes each other as heterogeneous rather than identical. They evolve and adapt to their surrounding environment. Also, they can communicate, make autonomous decisions, and behave stochastically.

Few recent works have used ABM to bring insights to construction. For example, ABM is used to assess the impact of production control methods and information flow on production (Ben-Alon and Sacks 2015). Also, ABM has been used to study the design workflow at the intersection of social and process aspects (Hattab and Hamzeh 2016). Furthermore, ABM helped the project controller simulate a project's status within the Weekly Work Plan (WWP) to achieve the desired performance (Shehab *et al.* 2020).

This model is built using Python open-source programming language and Python library for Agent-based modeling (MESA), which rely on object-oriented programming concepts. The results of each step of simulation are extracted as data frame (table-like data structure) and then plotted using Python data analysis and visualization libraries, including Pandas, Seaborn, and NumPy.

A simple takt plan to illustrate the progress of HRB production was used for this purpose. The takt plan contains information on the simplified structural, exterior, and interior phases of a 40-floor HRB (see Figure 1). The authors created the plan based on a hypothetical HRB case with hypothetical values for variables. These initial values were

validated in workshops with industry representatives and provided a basis to assess the proposed concept's feasibility. These variables will be further validated in future studies.

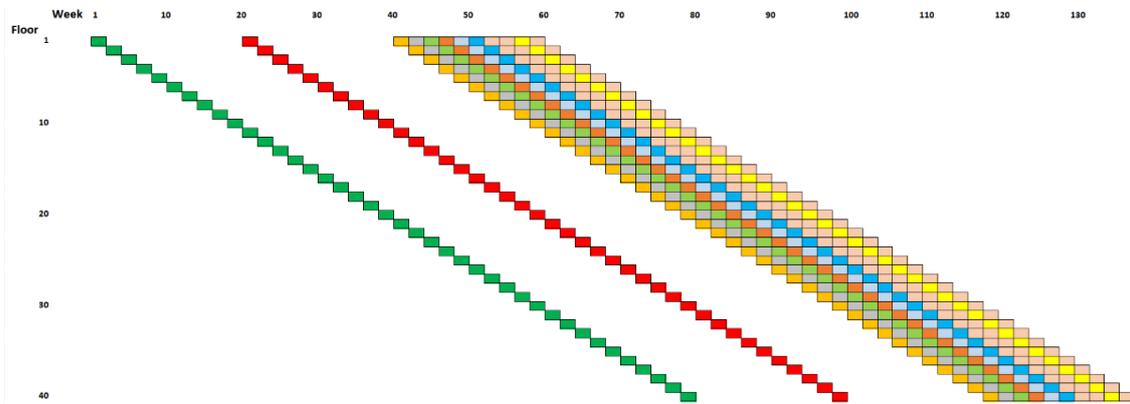


Figure 1 Takt plan with floors on the vertical axis and time (weeks) on the horizontal axis.

DEVELOPING A PROOF OF CONCEPT MODEL THROUGH A TAKT PLAN

The simulation presented in this paper focuses on building a proof of concept and demonstrates the utility of using the agent-based methodology for decision-making. The designed model was used to assess the impact of combinations of strategies, including the number and locations of elevators and break rooms and material delivery strategies in HRB. The parameters that are integrated to develop ABM model for different strategies are shown in Table 1.

As the metrics used to assess elevators' efficiency in the operational building are inappropriate for the construction stage, a new metric called system latency is suggested in this study. We define it as the average time required by the transportation system, including elevators and staircases, to fulfil workers' intentions, e.g., the time taken to reach a break room since that intention was declared.

This also means that intentions and the status of workers have been distinguished from each other. The statuses are the states that workers go through to fulfil their intentions. For example, if the worker is on the first floor and wants to go to a breakroom on the fifth floor, the worker intends to reach the breakroom. However, the worker has many different states to fulfil this intention, including waiting for the elevator, getting in the elevator, waiting for the breakroom's availability (space). The utilization rate index is also used to assess the average percentage of time workers' spent in their working location.

Table 1 Parameters to construct different scenarios of vertical logistics strategies.

ID	Parameters	Explanation
1	Number and type of lifts	The number of installed elevators at a given time.
2	Elevators range	Which floors are served with each elevator?
3	Elevator's usage	Materials/logistics or people
4	Material lifting strategies.	As part of the structural works cycle in weekends
4	Break room's locations	On every 5th and 10th floor breakrooms in site
5	Elevators ordering options.	One button for each elevator or other methods
6	Waste production	Consideration for waste flow
7	Probability of using the elevator	i.e., faster elevators or elevators with more range
8	Location of material storage	One floor or many
9	Location of waste disposable	One floor or many
10	Height: 10, 30 and 50 floors	By changing the time wagons move up.

With 40 takt areas (1 floor equals 1 takt area.), 12 takt wagons, 10-day takt time, and 10-story buffer between structural, exterior, and interior phases, the total duration of the hypothetical project is 138 weeks. The information on work wagons, their need for material logistics, and the number of workers for each wagon are presented in Table 2. The logistics represent a roughly estimated number of material packages that can fit in one elevator needed per one week of work per wagon. A correction factor of 1.2 was included to consider other workforce and visitors to the site, such as supervisors and client representatives.

Table 2 Work distribution within wagons

Wagon	Wagon Description	Logistics	Workers	Correction Factor
1	Structure	0	20	1,2
2	Exterior	0	12	1,2
3	Drywall both sides & HVAC, ELEC, ceilings	6	10	1,2
4	Floor screeding	4	4	1,2
5	Wall levelling and painting	2	4	1,2
6	Ceiling equipment, sockets and switches,	2	5	1,2
7	Kitchen wall & floor tiling	6	4	1,2
8	Floor laminate installation, door and floor	4	4	1,2
9	ELEC, Household equipment installation and	6	5	1,2
10	Cleaning, Supervisor inspection	6	3	1,2
11	Functionality checks	2	2	1,2
12	Handover	0	1	1,2

The construction phase after structure erection, when the vertical logistics rely mostly on elevators, is evaluated. That is, the evaluation of the cranes' role is neglected. On average, the elevator can accommodate 10 people at a time or one person carrying a material package. The elevator takes one minute (one simulation step) to move from one floor to another, considerably slower than in reality. This simplification was made to ease the simulation for the pilot study. The simulation step is connected with the elevator speed (1 step = 1 minute), and simulated elevators move up or down in every step, depending on the elevator demand. Workers also go up/down using stairs with the speed of 1 floor/min. The worker uses the elevator if they are carrying a material package and cannot use the

staircase. These parameters were determined in workshops with industry representatives who had experience in takt planning and worked on Finnish high-rise construction sites.

The primary information and agents that are modelled include:

- The model itself, acting as a container of all other agents, time, and spaces.
- Workers for each wagon
- Materials needed for each wagon
- Elevators
- Break rooms: On every 5th and 10th floor versus break rooms in the site office
- Number and type of lifts and rules of lift
- Number and location of storage areas

The values of parameters that are used in the HRB are shown in Table 3. Breakrooms are mainly used during lunch and coffee breaks. The number of these areas and their locations are considered variable. The time spent on the break was assumed to follow a triangular distribution with a mean of 12 min for a coffee break, 30 minutes for a lunch break, and 10 minutes for other types of breaks. Thus, the simulation's distinctive areas depict workspace, storage, elevators, break areas, and lunch areas.

Table 2 Parameters used in the model.

ID	Parameter Name	Value	Max	Min	Unit	Probability
1	Probability of going to nearest	50 %				
2	Elevator capacity	10			persons	
3	Elevator speed	1			floors/min	
4	Storage room capacity	6			persons	
5	Break room capacity	unlimited			persons	
6	Lunch break duration	30	25	45	minutes	triangular distribution
7	Lunch break start	240	210	270	minutes	triangular distribution
8	Coffee break duration	12	10	30	minutes	triangular distribution
9	Coffee break start	120	100	150	minutes	triangular distribution
10	Coffee break2 start	420	400	450	minutes	triangular distribution
11	Picking material duration	15	35	10	minutes	triangular distribution
12	Break duration	15	5	30	minutes	triangular distribution
13	Floors by stairs	3	1	5	floors	triangular distribution
14	Work duration	120	5	180	minutes	triangular distribution
15	Workday steps	510			minutes	-

RESULTS

In total, 54 simulation runs in two iterations were conducted in this pilot study. The generated data were analyzed and visualized. KPIs were calculated after simulating one week per scenario. The investigated 27 scenarios are formed from the combinations of the following parameters:

- The numbers of elevators: two, four, and six.

- The break rooms' locations: only ground floor, every fifth floor, and every 10th floor
- Simulation starting days are 200, 400 and 600

The strategy titled 2EV – Br5th in Figure 2 means that the site has two elevators and break rooms on every fifth floor. Similarly, the 4EV-BrGr site strategy has four elevators and one break room on the ground floor. All other strategies visualized in Figure 2 are encoded similarly.

System latencies ranged from 1 minute to a maximum of 8 minutes. On average, since the announcement of their attention, most workers reached their destinations in less than two minutes. There are only a few instances where the system took more than 8 minutes to fulfil intentions.

As the wagons move up, the system latency increases. The increase in the physical distance from the ground floor increased the reliance on elevators and caused increased latency. The maximum system latency is around 8.5 minutes when the structure wagon is on the 60th floor, and the building had two working elevators with one break room on the ground floor. When the structure wagon is on the 20th floor, many other wagons are close to the ground floor, and according to our previously explained assumptions, some workers will use the stairs more frequently. This reduces the reliance on elevators and reduces system latency significantly. In the same way, the utilization rates increase when the wagons are close to the ground floor. For all strategies with the structure wagon on the 20th floor, the utilization rate ranges between less than 70% to around 75%.

When the structure wagon is on floor 40th, the maximum utilization rate is achieved by having four elevators and break rooms every 5th floor (6EV-Br5th) with materials delivery out of working hours with an average utilization rate, from two iterations, close to 68 %. This also applies when the structure wagons are on floors 20th and 60th. The model estimates an increment in utilization rate by around 20% compared to the strategy with two elevators and one break room on the ground floor. Adding elevators and break rooms also reduced the latency time tremendously. For example, when the structure wagon is on the 40th floor, adding four elevators and break out rooms on every 5th floor reduced the latency time 8 times from an average of ~4 to ~0.5 minutes, as shown in the figure (2EV-BrGr vs 6EV-Br5th).

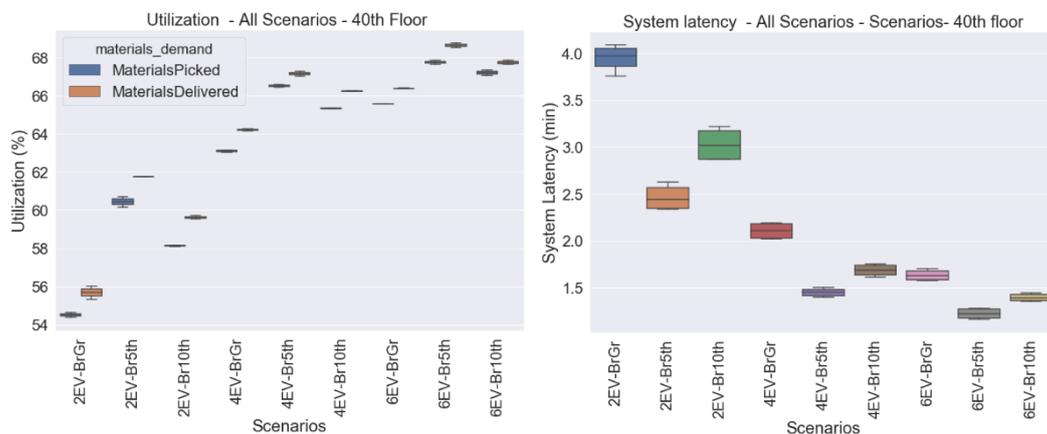


Figure 2 System latency and utilization rate when structure wagon is on 40th floor.

DISCUSSION

The system's performance was studied by changing one parameter or a combination of parameters as part of the strategy. The results showed a significant correlation between system variables and the overall performance of the vertical transportation system. It was possible to increase the utilization rate ca 18% by changing the system's variables. The simulation model helped to quantify the impact of these changes on system performance. This could provide construction planners better understanding and tangible evidence regarding the importance of each variable.

It was found that the method of material delivery affects the overall utilization rate. For example, the utilization rate increased about 2% for the strategy 2EV-Br10th when materials are delivered out of working hours. Overall, it was found that delivering materials outside working hours increased the utilization rate and decreased system latency. However, the addition of elevators had a more significant impact.

Adding elevators increased the utilization rate for all scenarios. The increase in the utilization rate was not linear. For example, compared to the 2EV-BrGr, the utilization rate for the strategy 4EV-BrGr was around 9% higher and, when compared to the 6EV-BrGr, the utilization rate for the 2EV-BrGr was 2.8% higher, signifying the difference between adding 2 and 4 elevators. The impact of adding elevators on system latency was similar to the utilization rate. The system latency decreased in none linear manner as the number of elevators increased. The optimal number of elevators can be determined based on evaluating and balancing the expected gains against the costs. Also, adding break rooms enhanced the performance of the system. Adding break rooms had a lower impact on system performance than the number of elevators but more than the selected material delivery method.

An interesting finding is cases where more elevators rendered equal or even less the overall performance than the cases with fewer elevators. This is evident in the cases 4EV-Br5th vs 6EV-BrGr also in 4EV-Br10th vs 6EV-BrGr. According to this, the planner can further build on this result to decide between the best strategies.

The magnitude of the impact of each variable on cost and waste can be evaluated against the estimates. For example, assuming that workers spend 5 hours in their workplace, an increase of 18 % in utilization rate would account for an approximate reduction in time wasted out of working place by 54 minutes for each worker. If the site has 40 workers, this accounts for 36 hours total reduction in the wasted transportation time in one day and 7200 hours in 200 days. Suppose this time is value-adding, and considering that the cost of worker/h is ten euros, this sums up to 72000 euros of savings. This amount could then be compared, i.e., with the cost of elevators and installing the elevators.

LIMITATIONS

The proof-of-concept model is subject to several limitations to be addressed in future research. For example, no distinction between external and internal elevators was made. The external elevator must have an operator and his time of operating the elevator is by definition non-value adding. Also, the speed of elevators in this research is considered all equal and slow for construction elevators. In reality, speeds differ, and elevators are faster. Similarly, the speed 1 floor/min of workers using the stairs is also slow. The metrics like system latency and utilization represent the average values for all floors. Distinguishing system performance based on the height of floors is important to have better and more accurate understanding for the results.

In the current model, the simulation time is one week, per which the average performance is calculated. However, this approach averages out the performance during the peak times and different types of traffic, i.e., upward, downward, and mixed traffic. In future research, it is critical to consider the system's performance at peak times in addition to the average performance.

The model parameters and values, including the hypothetical takt project case, were evaluated through workshops with industry partners. In future research, the model should be implemented in real case projects both in the pre-planning phase, where the model could be used to investigate alternative vertical transportation strategies, and the construction phase, where the existing logistics system's performance is monitored. Data from elevators and resource positioning systems could be collected in high-rise building projects to track the performance.

FUTURE RESEARCH

ABM and simulation were used to evaluate complex vertical logistics systems and predict hypothetical systems' performance. The model generated results that were validated in workshops with industry participants by visualizing the agents' movements. Also, the results were validated internally and numerically by comparing the generated numbers and metrics with those in real projects. However, further internal and external validation is needed. External validation should be made with the industry partners by comparing the model results with a real case study.

Other parameters could be integrated and tested to understand their impact on the overall performance. For example, the simulation model could be developed to quantify the effect of changing takt times or takt strategy. The impact of errors and omissions in design could also be studied as workers move to seek more information from other trades or supervisors.

The model should be flexible and configurable for a specific actual project and before the elevators are installed. This could be done by iterating through strategies with multiple elevators' schedules and characteristics of elevators. We have already started using the model to support decision-making in two real high-rise construction projects. Our initial experience from two ongoing case studies indicates that it is possible to get data for calibrating the model. This will include analyzing the time spent by workers on each space throughout the day and waiting after elevators, as suggested by our industry partners. The model could form a basis for a digital twin of logistics process where parameters are updated in real or close to real time based on the system's actual behavior.

CONCLUSION

Construction processes embody complex systems' behaviours. Simulation is one of the methods used to understand complex systems, yet it is not often utilized in construction research. This work has created and implemented a simple simulation model that can predict some performance metrics for vertical construction logistics systems despite the limited work done under this scope. The proof of concept showed promising results that do not deviate much from reality. The model is expected to help the construction teams in their decision-making and quantify the impact of different decisions and policies. Such an approach to decision-making is expected to result in savings and benefits.

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