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A Vertical Transportation Analytical Tool For the Construction of Tall Buildings

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Oscar Savage works for Multiplex Construction Europe on its 22 Bishopsgate project in London. Continuing his life-long passion for building, he studied construction management at the Royal Melbourne Institute of Technology. In the final year of his studies, he won the CIOB Global Student Challenge. This allowed him to explore international employment opportunities; he has since joined the Multiplex team in London. Savage enjoys a challenge and tackles problems with an innovative, hands-on approach.

Abstract

The construction phase of 22 Bishopsgate, London, presented many challenges, but one of the greatest issues to overcome was the requirement to ensure comfortable and efficient labor movements, material deliveries, and waste disposal, as well as plant and equipment transportation throughout its construction. This study introduces the Vertical Logistics Planning System (VLPS), an innovative real-world solution developed to overcome this challenge, demonstrating how the construction-phase vertical transportation strategy was assessed and optimized on the project. It is hoped that this paper will catalyze the development of further advancements in this field, assisting the transfer from an experiential approach to a predictive, data-driven methodology.

Keywords: Construction, Vertical Transportation

Introduction

The successful delivery of tall building projects is inextricably linked to the efficiency of construction-phase vertical transportation strategies. Although it is a widely-known challenge, vertical transportation during construction has attracted limited attention in academic and industrial literature to date. Presently, the construction industry relies on anecdotal evidence to plan for such critical operations. While these experiential methods are well-established and are often perceived to provide suitable guidance, they seldom facilitate a detailed understanding of the time-based supply/demand profiles, leaving projects greatly exposed to significant delays and unnecessary lifting infrastructure costs.

Limitations of Existing Methods

Current methods for conceiving and planning the vertical logistics strategies for tall building construction projects are broadly based on intuition and experience, and often fail to address the specific needs of a construction site, leading to potential inefficiencies in the distribution of labor, materials and equipment throughout the building. A typical set of assumptions for vertical logistics calculations (Shin, Cho & Kang 2010) can be found in Table 1.

Existing traditional methods present three main weaknesses:

1. They often lack numerical back-up and are largely based on anecdotal evidence
2. They are short-sighted, only considering peak demands, while other phases of the construction might prove to be more critical
3. They lack flexibility and adaptability over time and do not match supply to demand in any intelligible way

The approach to optimizing the vertical logistics strategy at 22 Bishopsgate, London, consisted of an extensive data-backed model, which provided the project team with an overall view of challenges over time and granted the team the necessary flexibility to re-assess needs at any given time. It also allowed "what-if" questions to be asked and answered, and for multiple scenarios to be assessed with one click.

> "The devised system integrated the project's labor histogram, expressing demand as a function of the number of operatives present on the construction site throughout its duration."

Phase description	Formula	Remarks
Transportation frequency (*Ft*)	*a* x *b*	*a*: transportation frequency per unit area based on historical data of similar project *b*: gross areas of actual project
Transportation frequency per day (*Fd*)	*Ft*/*n*	*n*: total construction duration, days
Average height of transportation (*Ha*)	*H* x (1 + *c*)	*H*: height of building *c*: charged rate for handicap
Cycle time of transportation (*Tc*)	*T1* + *T2* + *T3* + *T4*	*T1*: time of loading *T2*: time of dumping *T3* (= *Ha*/*v*): time for lifting up *T4* (= *Ha*/*v*): time for lifting down *v*: speed of hoist
Available transportation frequency per day (*Ta*)	(*Tw*/*Tc*) x *d*	*Tw*: available work time per day *d*: operation ratio of temporary hoist
The adequate number of temporary hoists	*Fd*/*Ta*	

Table 1. An example of a typical ad-hoc construction hoist planning formula. Source: Shin 2011.

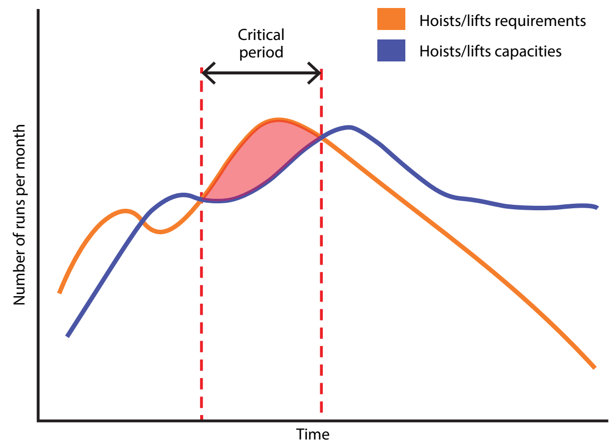

Figure 1. Graph illustrating the team's initial thinking behind the Vertical Logistics Planning System (VLPS).

As an example, the project was expected to experience its peak construction traffic in October 2018 with approximately 1,700 workers coming to site every morning of the month. October 2018 was also expected to be the busiest month for material deliveries as well, with almost 4,000 pallets requiring delivery to the relevant floors. While these statistics would be significant in any construction project, their importance increases tenfold when applied to a tall building construction project.

However, those peaks weren't necessarily going to be the most critical periods in the construction phase, and it was proved that the construction team had to be focused on different phases. The overall understanding of the challenges through time allowed the team to make informed adjustments that permitted increasing the efficiency of the temporary hoisting infrastructure by approximately 30%, which saved the project a significant portion of its hoisting budget, without penalizing the demand on-site. The remainder of this paper focuses on establishing an efficient, flexible, and data-backed predictive solution to plan vertical transportation during the construction phase of any tall building project, based on the 22 Bishopsgate example.

Vertical Logistics Planning System (VLPS)

The Vertical Logistics Planning System (VLPS) developed at 22 Bishopsgate, consists of an adaptable data-driven model, using known inputs to generate a time-based interpretation of the supply and demand profile throughout the construction phase. Figure 1 illustrates the initial thinking behind the model. The orange curve shows the project's requirements (demand) in terms of labor movement and material, waste, plant, and equipment (MWPE) transportation, while the blue curve describes its hoisting/lifting capacity (supply) over time. Both sets of data were to be expressed in the same unit: the number of lift runs required on a monthly basis. Each time the "requirements curve" is above the "capacity curve", it shows that the project is going to suffer from potential under-capacity. The specifics of the project, as well as the intricacy of the inputs, led the team to develop a model with slightly more complex outputs, but the essence remained the same. This bespoke model facilitated the holistic testing of a variety of scenarios, with the primary focus of identifying and understanding the variety of known and unknown constraints associated with the vertical transportation of labor, materials and plant. The model outputs are presented in an intelligible way, allowing the user to quickly identify, and respond to, under- or over-capacities in the vertical logistics supply profile.

Understanding Vertical Transportation Requirements

To produce the demand curve shown on Figure 1 shown in orange, the first step of the study was to fully understand the requirements over time in terms of labor, and MWPE transportation for each trade. This exercise was conducted in close collaboration with package managers and planners, to understand both the assumptions of each trade and the detailed program. Once established, the data inputs were gathered and inserted into the model.

Labor requirements

Grasping the main trends of labor movement throughout the duration of the project is essential to a well-functioning vertical transportation strategy for a construction site. During the development of these strategies, which are often conceived at the tender stage, it is common for the author to make a series of informed decisions based on anecdotal evidence, as opposed to firm data. The VLPS overcomes this issue through integrating the project's labor histogram, expressing demand as a function of the number of operatives present on the construction site throughout its duration. To ensure robust outputs, the model was designed to utilize simple inputs, including;

- The average number of operatives per active floor on any given day

- The daily demand for vertical transportation (*x* per day)
- The capacity of the vertical transportation system (number of operatives per lift/hoist)

The program is often not detailed enough at tender stage to make this determination at the outset. So, it is crucial to have a model that can be easily adjusted as the program gets further developed. Once analyzed, the outputs of the model provided a clear direction as to the demand for vertical transportation – which operatives were required to move between which floors (see Table 2) as well as an overall understanding of requirements throughout the construction phase (see Figure 2). By way of example, Figure 3 identifies the quantity of operatives, and locates the peak demand. The graph demonstrates a clear peak in October 2018, with an average of approximately 1,700 workers on-site on any given day of the month (conservative estimate), mostly caused by the peak of one of the trades: M&E CAT-A (Mechanical & Electrical, Category A) (see Figure 3).

Material, waste, plant, and equipment (MWPE) requirements

Understanding the MWPE movements was as important as understanding the labor requirements, if not more so. Indeed, while the labor demand can naturally adjust by implementing a requirement for operatives to walk between certain levels, the MWPE demand requires every single relevant floor to be accessible by a hoist or lift. To avoid material congestion on the ground floor and/or in a potential off-site consolidation center, the MWPE vertical transportation needs to be planned out with an even greater level of detail and precision. Reflecting the approach taken for understanding the labor demand, the MWPE profile was assessed using the following assumptions:

- Material, plant and equipment demand for each trade on each floor (expressed in terms of the number of lift runs) throughout the height of the building
- Waste movement requirements, expressed as a percentage of the material movement demand

Once aligned with the construction program, and thereafter analyzed, it was possible to discern the demand profile for each floor (see Table 3) and present that demand visually as a function of each sub-contract trade, over time (see Figure 4). This month-by-month analysis allowed the team to better comprehend material movements throughout the building and to make sure

	Jan 2018	Feb 2018	Mar 2018	…
…	…	…	…	…
Floor 9	427	371	203	…
Floor 8	427	371	203	…
Floor 7M	443	154	138	…
Floor 7	475	162	138	…
Floor 6	451	251	339	…
…	…	…	…	…

Table 2. Vertical transportation requirements per floor (on monthly basis, expressed as the number of lift runs needed during the course of a month).

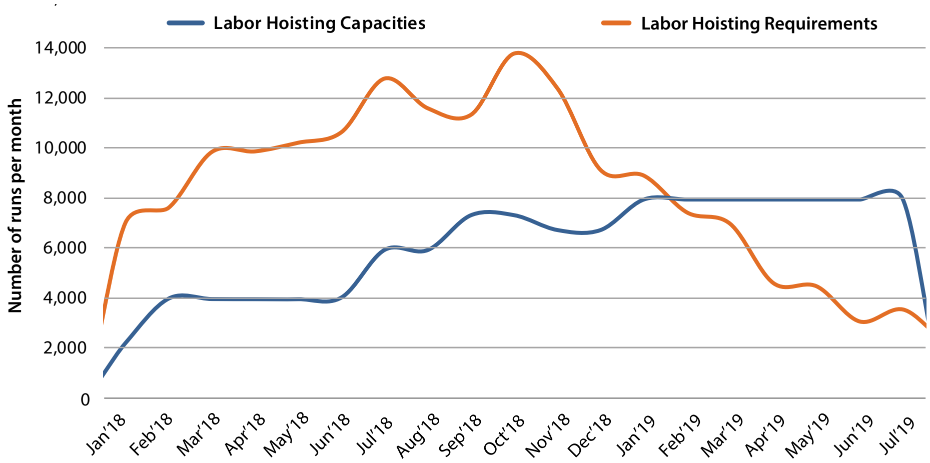

Figure 2. Aggregated labor vertical transportation requirements projected against aggregated labor lifting capacity (monthly basis).

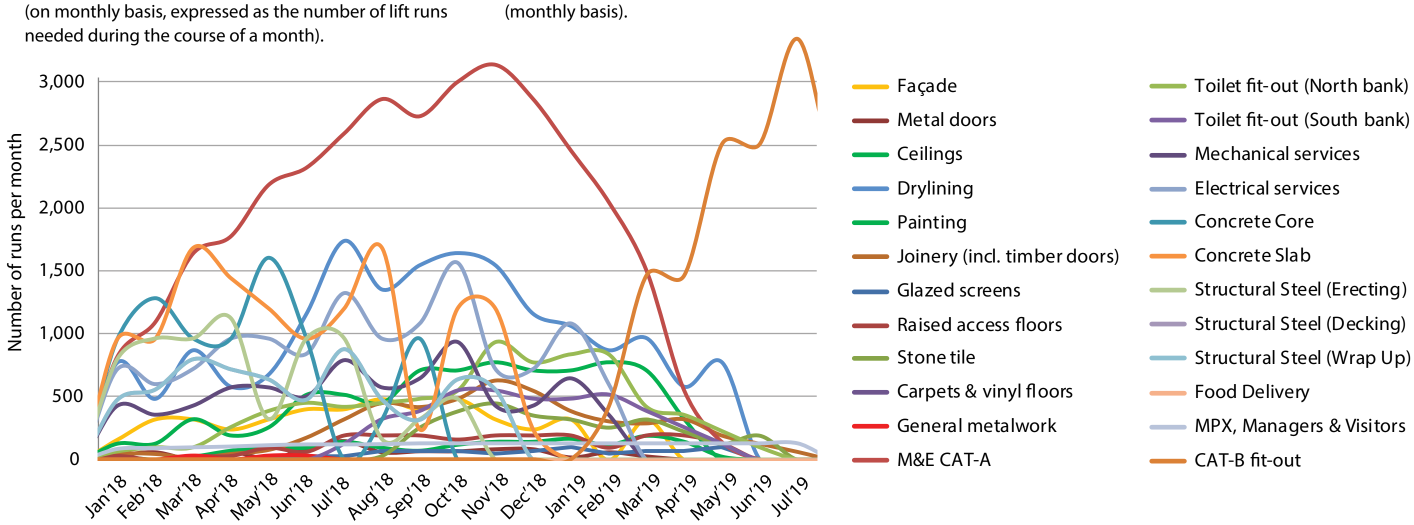

Figure 3. Labor vertical transportation requirements split into each trade (monthly basis).

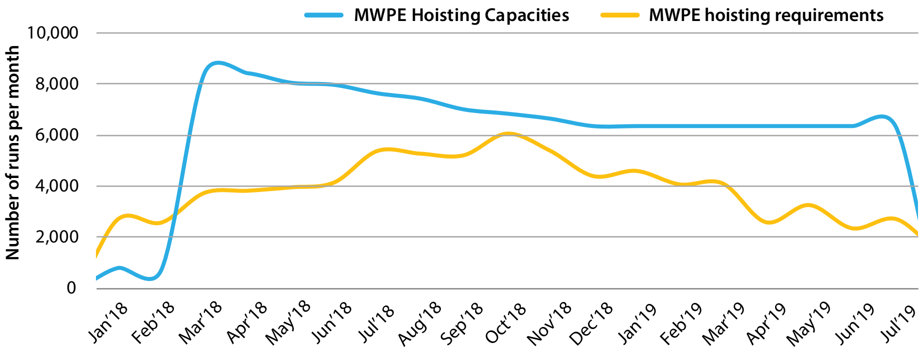

Figure 4. Aggregated MWPE vertical transportation requirements projected against aggregated MWPE lifting capacity (monthly basis).

	Jan 2018	Feb 2018	Mar 2018	…
…	…	…	…	…
Floor 9	242	217	168	…
Floor 8	258	233	183	…
Floor 7M	417	178	174	…
Floor 7	374	183	174	…
Floor 6	362	216	251	…
…	…	…	…	…

Table 3. MWPE vertical transportation requirements per floor (monthly basis, expressed in terms of number of lift runs needed per month).

	…	Jun 2018	Jul 2018	Aug 2018	…
…	…	…	…	…	…
Floor 53	…	-2	-323	-243	…
Floor 52	…	-162	-162	-197	…
Floor 51	…	-162	-162	-197	…
Floor 50	…	-323	-348	44	…
Floor 49	…	-323	-348	44	…
…	…	…	…	…	…

XX No access

XX Access, but under capacity

XX Access and sufficient capacity

Table 4. Summary tab showing under- and over-capacities per floor for the vertical transportation of MWPE (monthly basis).

the site (including the pit lane, access routes, ground floor arrangement, etc.) was capable of taking this inflow. However, it was not until requirements were projected against lifting capacities that the team could fully grasp the challenges and opportunities ahead.

Understanding Vertical Transportation Capacities

After having established the demand curve of the preliminary assessment (see Figure 1), the next task consisted of drawing its supply equivalent (the blue curve). This required understanding each month's capacity in terms of number of lift runs. This exercise was conducted in close collaboration with the project's planners and vertical logistics manager, to ensure precise predictions of lifting capacity throughout the construction phase. The supply profiles were calculated using the following metrics:

- Lifts/hoists install, commissioning, and dismantling dates
- Lifts/hoists allocation to either Labor or MWPE profiles
- Speeds
- Cabin capacities
- Floor openings
- Average number of stops per trip
- Average distances
- Load in/out timing

The VLPS thereafter provided a holistic assessment of the overall vertical transportation supply and demand, throughout the construction phase, facilitating a deeper understanding of various aspects of the strategy, and allowing an understanding of how the strategy must respond (see Figures 3 and 4). In essence, every time the dark orange line was above the dark blue line, it meant that the lifting infrastructure was going to potentially experience some difficulties moving the required number of operatives to the relevant floors. By way of example, Figure 3 demonstrates a clear case of under-capacity in labor movements between January 2018 and February 2019, with a maximum monthly shortage of 6,866 lift runs during the month of July 2018. Similarly, Figure 4 identifies an undersupply in MWPE capacity during the first two months of 2018, and an oversupply between March 2018 and July 2019.

Output Analysis and Optimization

At this point of the exercise, the team had built the intended two curves of the original sketch (see Figure 2). The VLPS model built for this vertical transportation strategy now presented the supply and demand profiles in an intuitive way, immediately highlighting under- and over-capacities. Put another way, it identified challenges and opportunities. In addition, an immense value-add lay in its flexibility over time. Indeed, every time any assumptions changed, the model automatically adapted and allowed the team to react in real time to any major shift in the project's construction strategy, testing the outputs as a function of overall gains in the efficiency of the construction-phase vertical transportation strategy.

Identifying gaps

As explained previously, the first step of the analysis consisted in making sure that the lifting/hoisting infrastructure provided access to all the required floors, especially for the MWPE requirements. A detailed gap examination (see Table 4) helped illustrate that certain floors suffered from under-capacities and sometimes wouldn't be accessible at all. The same exercise was conducted for labor. Based on these discoveries, the logistics team could take measures where required to respond to these critical gaps.

Optimizing hoist/lift allocations

Once it was established that every relevant floor was accessible by hoist or lift, the second step of the optimization process consisted of understanding the bottlenecks and the overcapacities of the project as a whole to efficiently allocate each lift/hoist to the right function. As described previously, labor suffered from a clear under-

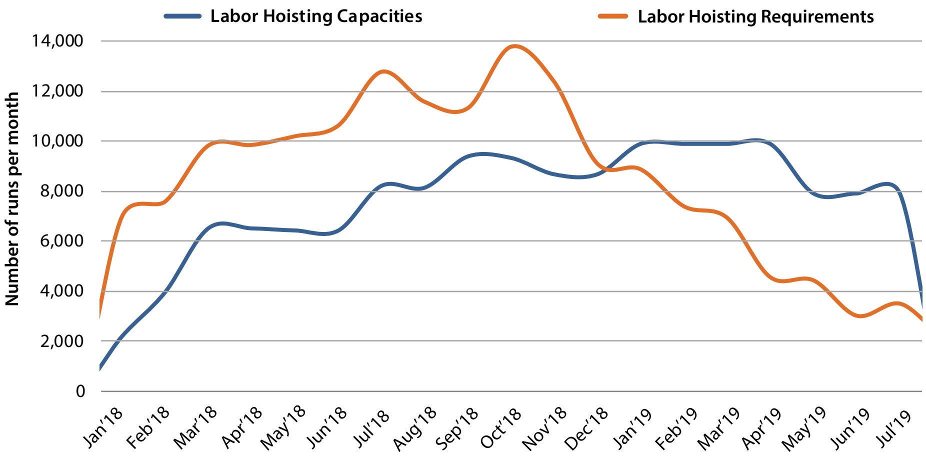

Figure 5. Aggregated labor vertical transportation requirements projected against post-intervention aggregated labor lifting capacity (monthly basis).

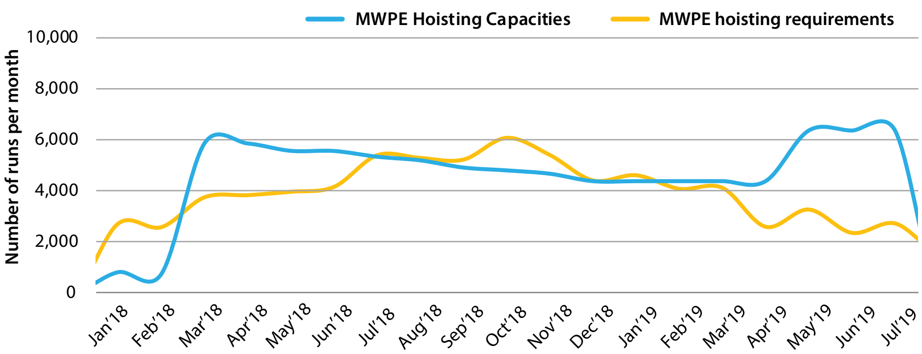

Figure 6. Aggregated MWPE vertical transportation requirements projected against post-intervention aggregated MWPE lifting capacity (monthly basis).

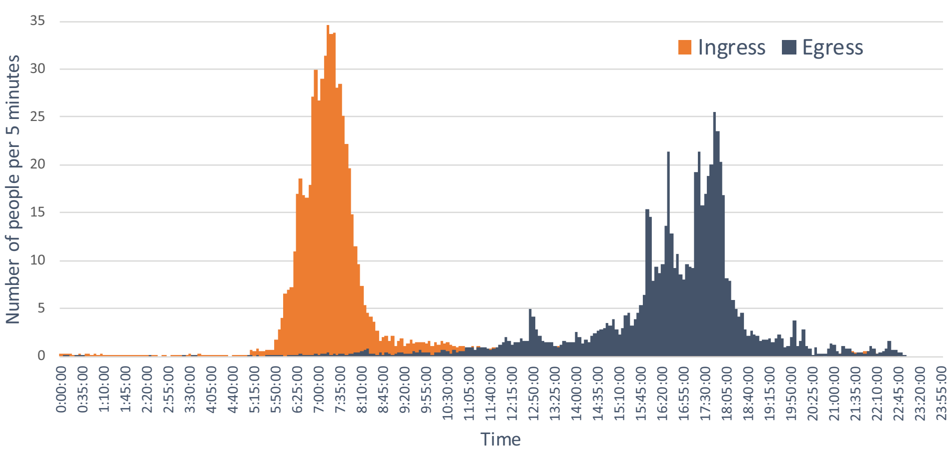

Figure 7. Turnstile records analysis: morning arrival pattern. © Movement Strategies Ltd.

> “Due to information provided by the model, the team was able to eliminate two external hoists originally in the budget.”

capacitybetween January 2018 and February 2019, while MWPE benefited from an over-capacity between March 2018 and July 2019. Such discrepancies were overcome through modifying the supply profile accordingly; i.e. reassigning which lifts or hoists serve which levels, and when. The idea of reallocating one of the MWPE hoists/lifts to the labor demand became evident, but a series of other measures were implemented to bring the two curves of each graph as close as possible. Once more, this scenario-testing was easily conducted thanks to the great adaptability of the VLPS model and its ability to proactively answer "what-if" questions. After dozens of iterations, the team was most satisfied with the scenario represented in Figures 5 and 6.

Translating theory into practice

While based on a series of known assumptions, naturally the VLPS model lacked the necessary level of detail to fully understand the practical challenges of implementing the strategy on site. However, it did highlight the most critical phases on which the team needed to focus. In this case, July 2018 appeared to be a particularly challenging one for the project in terms of labor transportation. Hence, amongst other subjects of focus, it was decided to conduct a detailed-crowd simulation study, linking the VLPS model to the physical daily constraints of the construction site.

It was vital to guarantee smooth access to and from work areas during peak time periods on any given day during the project – particularly those periods throughout which the demand profile was the furthest away from the supply profile, typified by the highest levels of physical congestion and discomfort for the construction operatives.

Historical turnstile site entry and egress data was gathered and post-processed, allowing an understanding of the arrival and departure patterns of the construction team. Figure 7 displays the morning arrival pattern, showing a clear peak between 6:30 and 8:30 a.m. This distribution curve was applied to a condensed time slot between 7:00 a.m. and 8:00 a.m. to run a conservative analysis. An

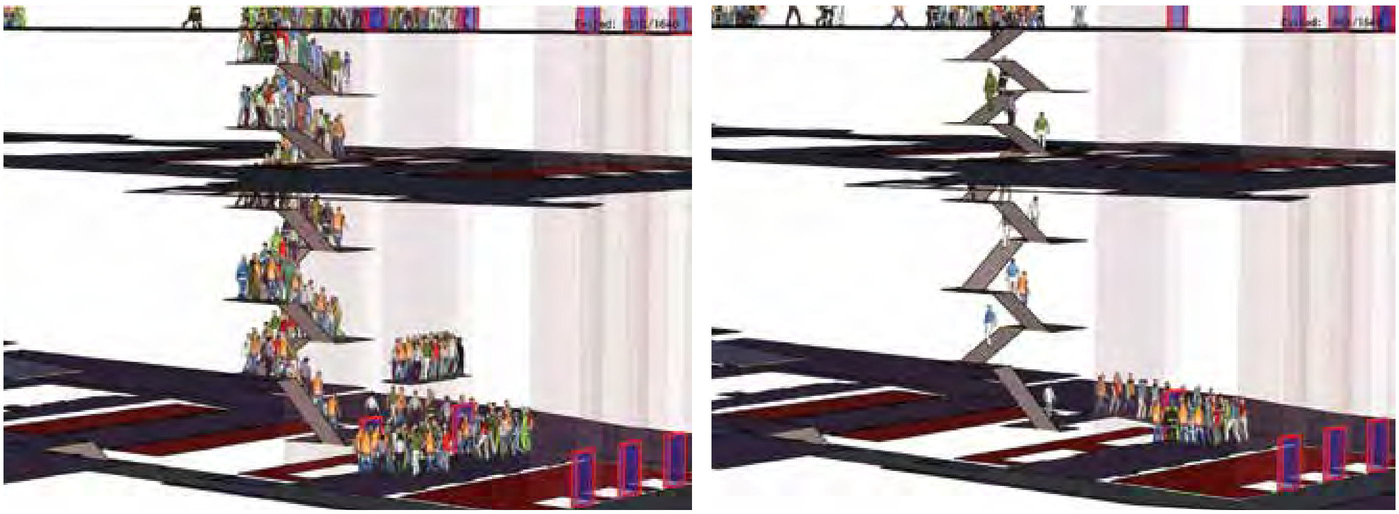

Figure 8. Bottleneck identified through the crowd movement simulation study – pre-correction (left) and post-correction (right). © Movement Strategies Ltd.

extensive 3D model was then extracted from the project's Revit BIM model to create a framework for the simulation. The simulation of workers arriving via the main entrance to the site was then run through the model. The vertical transportation speeds and capacities, as well as the natural behavior of the workers, were incorporated into the model. Testing several scenarios allowed the team to understand the weaknesses of its logistics strategy and to identify potential critical bottlenecks on site (see Figure 8). Additional adjustments to the vertical transportation strategy based on the results of this crowd-simulation study were then made to allow for the smoothest labor flow possible.

Conclusion/Next Steps

Throughout the construction phase, using predictive analytics from the VLPS allowed the team to detect multiple problems well in advance, with a high level of confidence in delivery success; therefore giving the team the ability to act and correct those issues prior to their appearance. The VLPS model also allowed the identification of numerous opportunities and potential gains, improving the efficiency of the project vertical transportation strategy. A good example of the latter: due to information provided by the model, the team was able to eliminate two external hoists originally in the budget – representing a significant savings from its original hoisting budget. Another key insight of the study was the revelation that the goods lifts had to be allocated to labor traffic for certain months of the construction phase.

At some point in the project, the construction program was partially revised to reflect a new sequence of events in the project's construction strategy. As planned, the model was easily updated and immediately highlighted the new opportunities and challenges ahead, based on this set of new assumptions. Exactly as conducted the first time, the team was again able to ask the model "what-if" questions that allowed us to set the grounds for the optimum vertical transportation strategy.

It is absolutely essential to understand a project's vertical transportation requirements (demand) in depth, and to match these with the project's hoisting/lifting capacity (supply) before making irreversible decisions. The earlier this happens, the better the logistics manager can anticipate and plan for an infrastructure that reflects the optimal strategy. The second crucial element is for the project/logistics manager to be able to adapt the strategy to the changing program and assumptions without spending too much time conducting the analysis. Indeed, the construction phase of a project is filled with unexpected events and unplanned delays, and every project/logistics manager spends a great portion of his or her time adapting to these impromptu changes. The authors believe that the VLPS helps address these two points in an intuitive and innovative way, and takes vertical transportation planning to the next level by supporting historical experience with a more robust and comprehensive data-driven approach.

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