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BUILDING BEYOND THE BOOTH: IMPROVING LOGISTICS FOR THE CONSTRUCTION OF TRADE FAIR

MASTER THESIS

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Preface

Dear reader,

Thank you for taking the time to read my thesis. It marks the end of the Transport, Infrastructure and Logistics program, and my student years at the TU Delft. Although this thesis took longer than anticipated to complete, I look back on it with pride and fulfillment.

Of course, I could not do this alone. I would first like to thank Mark ten Oever, for giving me the opportunity to do this project at RAI Amsterdam. It has been a great experience, that I will not forget any time soon. I also want to thank everyone at the RAI for welcoming me and taking their time to introduce me to the wonderful world of trade fairs. Your insights and patience have helped me to grasp the complexities of the trade fair construction process and made this a very enjoyable experience.

I also want to thank Yousef Maknoon and Mark Duinkerken for their guidance and feedback. It was not easy to find the right direction for this project, but your trust and the time you made available to guide me through this have been fundamental to making this thesis a success. It would not be near to where it is now without your insights, ideas and enthusiasm which has helped me more than once to improve and further my work.

And last, but certainly not least, I would like to thank my friends and family for their care and support. Despite writing this thesis alone, I did not once feel lonely in this experience. I would like to thank my friends for hearing me out about my thesis for the past 8 months, my fellow thesis writing students for the enjoyable study days together and roommates for their support. And I would most of all like to thank my family who have supported me unconditionally throughout all of my academic journey.

Enjoy the read!

Maaike Tjeerdsma
Delft, November 2024

Abstract

Trade fairs bring together suppliers from specific industries or fields, offering them a valuable platform to showcase their products, gather information on competitors, and find potential partners. During construction, materials that are not yet in use are often stored in pathways. When multiple stands are under construction simultaneously, pathways can get increasingly congested, resulting in stands becoming inaccessible, safety risks and delays. Despite the importance of managing these issues, no scheduling method has been developed to address these challenges to date. To fill this gap, this research introduces a Mixed Integer Linear Programming (MILP) model designed to improve the construction scheduling process at trade fairs by incorporating the predicted impact of scheduled workspace availability on delays as a factor in scheduling decisions. A case study at RAI Amsterdam was performed to collect data and validate the model. The improved schedules proposed by the MILP model are estimated to reduce average aisle material storage by 3.1%, variance in material storage density by 38.9%, and workspace interferences by 18.0%. When accessibility constraints were relaxed, even greater gains were achieved, with reductions up to 10.7% in material storage and 64.6% in interferences. Simulation runs with varying input variables showed that the degree improvement varied by hall layout, stand density, and available construction time, with island layouts and additional setup time yielding the best results. The most recurring and clear scheduling strategy applied by the model was letting stands furthest away from the accessible safety paths start first, followed sequentially by closer stands. Overall, the model provides a practical scheduling approach to reduce congestion and enhance safety, offering a useful tool for trade fair organizers.

Keywords: Mixed Integer Linear Programming (MILP), scheduling optimization, trade fairs, construction logistics, workspace management, event logistics

Contents

1

Introduction

1.1 Background

Trade fairs are events that bring together suppliers from specific industries or fields, offering them the opportunity to showcase and market their products or services to potential buyers (Bathelt et al., 2014, Gębarowski, 2012). Companies use these trade fairs to present their innovations, learn about user needs, gather information on competitors, and find potential partners (Gębarowski, 2012, Bathelt, 2017). Trade fairs have a long history, dating back to biblical times, yet they continue to play a significant role in today's business landscape (Palumbo et al., 2002). Their importance is evident in both their economic impact and global expansion (Geigenmüller, 2010). The global trade fair industry hosts approximately 31,000 exhibitions annually, attracting 4.4 million exhibitors and 260 million visitors (UFI, 2014).

Most trade fairs are held in purpose-built conference and exhibition centers. The exhibition halls consist of vast open spaces, offering a blank canvas for each event. The venues furthermore offer good service roads, large dock doors, and high floor loading limits and ceiling heights, such that large equipment or high volumes of materials can easily be brought into the halls (Nolan, 2020).

1.1.1 Construction characteristics

In case a trade fair is hosted at the venue, the exhibitors' stands need to be constructed in the venue hall before its opening. Usually 2-5 days are available for construction, during which all stands need to be constructed. The construction conditions at trade fairs are different from those of regular construction project and can be characterized by the following:

- Stands are constructed simultaneously, and can therefore be seen as multiple construction projects being undertaken at the same time, instead of one project.
- There is a strict deadline for completion. Each stand must be finished by the opening of the fair
- The layout of the fair is determined beforehand. Although the layout has an effect on the construction logistics, it is not created with construction logistics in mind,

but rather by the sizes of the stands and by the proximity/distance that exhibitors want from their competitors.

- A team of standbuilders can start construction of a stand once its materials are delivered and unloaded at the venue.
- Only a limited amount of trucks can be unloaded at the venue at the same time, and therefore a limited number of stands start construction simultaneously.
- Stand builders only use the assigned stand location and its surrounding pathways as workspace
- Materials that are not used yet, are stored in the pathways. In case other stands are adjacent to the same pathways, the storage space of the pathways is shared.

1.2 Problem statement

All stands within the venue hall need to be fully constructed by the time the fair opens. Not only is this time window limited, stand builders also need to construct their stand within a limited space. Aside from the assigned stand location and its surrounding pathways, little space is available. This space can get even more limited due to several standbuilders storing their materials in the same aisles (see figure 1.1). As a result, three things happen:

1. Stands become inaccessible and materials can not be brought to the stand
2. Too densely stacked materials create safety risks
3. Construction work is done in too limited spaces, which causes delays.

Figure 1.1: *Examples of materials stored in the aisles. Source: Author.*

The effects of limited or congested workspaces on productivity and safety have long been recognised as a problem in construction logistics (Dawood et al., 2006, Thabet et al., 1994, Thomas et al., 2006). In a case study on a £6 million construction site, it was found that about 30% of time on site was unproductive due to the lack of a detailed planning of space (Mallasi et al., 2001). Others found an even higher effect, up to a 65% productivity loss Sanders et al., 1991). Thomas Jr et al. (1990) suggested that $19m^2$ per person is needed on a construction site and when this is declined to 10.4 m^2, 50% more man-hours are required. The minimum of workspace was found to be 9.4 m^2. Maximum productivity was reached at 30.2 m^2.

Especially during the construction of trade fairs, where workspaces are highly limited, safety risks and productivity decreases are significant. Yet, no research has been done to date on how to improve the workspace conditions at trade fairs, or on how to effectively schedule the construction start times of stands, in order to minimize these effects.

1.3 Research goal and methods

The aim of this research is to construct a scheduling model for the start of stand constructions, such that:

- The excess stored material density caused by stands using the same pathways for storage is reduced, by letting neighbouring stands start construction earlier or later
- Stands that are likely to become inaccessible are scheduled earlier, such that all stands are accessible when their materials are delivered.
- Stands are provided sufficient time to finish construction before the opening of the fair.

The research specifically focuses on scheduling the unloading times of trucks, because construction of a stand can only start once its materials are delivered. The layout of the fair is left out of consideration, since it is predetermined.

To this end, a Mixed Integer Linear Programming (MILP) model will be formulated to find an improved schedule. The model will be tested in several simulation runs, where the layout, stand sizes, available construction time and truck unloading capacity will be changed. Data for the model will be collected using a timelapse at a trade fair. Also, a case study will be performed to provide insights in the workings of the model when applied in practice.

1.4 Research questions

The main research question for this research is as follows:

In what way can a scheduling model for the unloading of trucks at a trade fair improve storage of materials in aisles, minimise workspace interferences and improve accessibility during construction?

In order to answer this question, the following sub research questions are formulated:

RQ1: How does the construction of trade fairs currently work?
RQ2: What models found in literature are most suitable for solving the scheduling problem at trade fairs?
RQ3: How can the scheduling problem be represented in a mathematical model?

RQ4: How can the duration of construction and the volumes of materials per stand best be estimated?

RQ5: How does the performance of the scheduling model vary under different input conditions?

RQ6: To what extent can the scheduling model improve the overall storage of materials at a trade fair?

RQ7: What strategies does the scheduling model apply under different input conditions?

1.5 Case study

To address these research questions, a case study will be performed at RAI Amsterdam, to provide insights in the construction of a trade fair. RAI Amsterdam is the largest exhibition venue in the Netherlands, hosting around 500 events annually. The company started as an association for the bicycle industry back in 1893, located in the southern disctrict of Amsterdam. Over the course of the years, it slowly evolved into the largest event centre in the Netherlands with over 110.000m^2 and 12 multi functional halls (see figure 1.2). While hosting various congresses, concerts and shows, its primary focus is on trade fairs.

Due to its high frequency of events, and the location of the venue in a busy and compact district of the city, the RAI is frequently faced with challenges in the logistics of its fairs. By performing a case study at the RAI, the company provides insights into the workings of the construction of trade fairs, as well as provide data and opportunities for interviews.

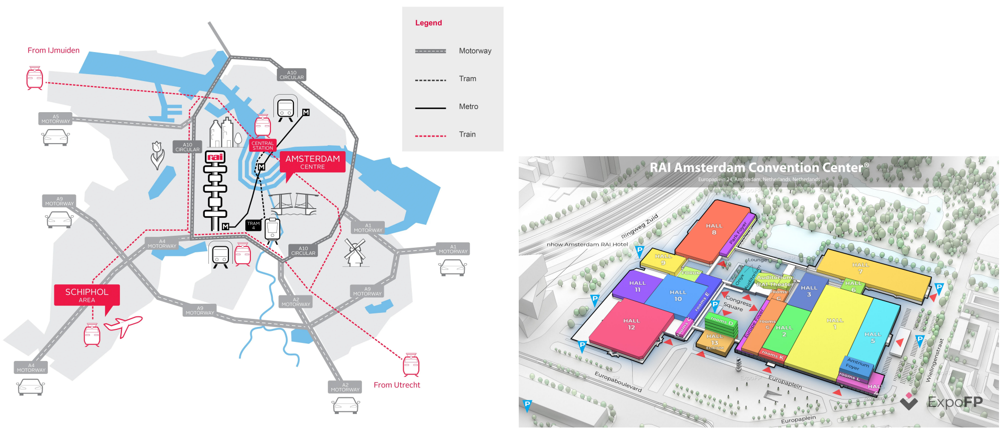

Figure 1.2: *Location and accessibility of RAI Amsterdam (left), map of the halls in RAI Amsterdam (right). Source: RAI, n.d.*

1.6 Document structure

This document is structured as follows: first, in order to understand the workings of a trade fair, an analysis and description is given in chapter 2 to answer RQ 1. In order to find a suitable method, a literature review is given in on trade fair and construction logistics in chapter 3, answering RQ 2. Then, the scheduling problem will be represented as a mathematical problem in chapters 4, answering RQ 3. After this, RQ 4 is answered in chapter 5, where the construction duration and material volumes are estimated using data, followed by a test of the model under different input conditions in chapter 6, to see how the model responds to different inputs, and deduce its strategies, which answers RQ 5 and RQ 7. This is followed by a case study in chapter 7, that presents potential improvements that can be obtained by implementing the schedule proposed by the model, where RQ 6 and 7 are answered. Lastly, a conclusion and discussion are given in 8 and 9, where the main research question is answered.

2

Description of the construction of trade fairs

This chapter aims to answer the first research question: "*How does the construction of trade fairs currently work?*". Although venues generally have the same approach, the results found in this chapter are specific to the RAI. Other venues may have slightly deviating structures.

When hosting a trade fair, there are four main parties involved. These are the venue, the organizer, the exhibitors and the standbuilders. This organizational structure of a trade fair will be explained in section 2.1, followed by an explanation of the types of stands in section 2.2. Standbuilders have a different approach for different stand types. These differences will be discussed in 2.3, after which the delivery appointment system is explained in section 2.4, followed by an overview of the entire construction planning in 2.5. In section 2.6 a conclusion is given, answering the sub-question.

2.1 Organizational structure

2.1.1 The venue

The venue is responsible for the rental of the venue, the safety, and for the provisioning of some services to the organizer. In consultation with the organizer, the venue decides which halls can be rented out for a certain time period. A rental period consists of construction days, event days and dismantling days. Usually the venue provides the logistical planning for the construction and dismantling days.

2.1.2 The organizer

The organizer is the party in charge of the fair. It arranges the venue rental, promotion, and attracting exhibitors to the event. Although some organizers host a fair only once, most fairs are held (bi-)annually at the same venue.

Once the organizer has secured the venue rental, it can sell spots in the halls to exhibitors. The organizer will contact potential companies for the purchase of square meters in the hall. Aside from the size of the area, the position can also be important. Some bigger companies can have strong preferences on the size and position of their stand, in order to make the best impression on the visitors. On the other hand, not all stand sizes and configurations fit within the dimensions of the venue halls. The organizer determines the final layout.

2.1.3 The exhibitor

The exhibitor is a company that is present at the trade fair, in order to showcase its products or services, make new contacts with other companies in the same industry, or get updated on new developments and innovations. An exhibitor at a fair rents an area in the hall, which is then used for the construction of a stand. Although the exhibitor is present during the fair itself, it often outsources the construction of its stand to a third party. This is either the venue, where it rents a stand, or a standbuilding company that creates a personalized design. The design and the size of the stand depends on both the budget and the intention of the exhibitor. In section 2.2, a more elaborate discussion will be given on the possible stand designs.

2.1.4 Standbuilder

The standbuilders are the people who construct the stands in the venue. These standbuilders have different working methods, based on the type of stand they construct. What these differences are and how standbuilders work, will be further explained in 2.3.

2.2 Types of stands

There are two types of stands available at fairs: rented stands, and free-build stands. The rented stands can be further divided in uniform build stands (UB) and modular stand design (MSD). Both are constructed by the venue. On the other hand, free build stands are constructed by an exhibitor's own team of stand builders. An example of each stand type can be found in figure 2.1.

2.2.1 Rented stands

Uniform build (UB)

A UB stand is a shell scheme stand, with a simple design. It is an industry wide standardised design, that is characterised by its white panels, a small banner and functional furniture. Some changes to the design can be made, such as altering the wall decorations or the furniture. The UB stands are well suited for small areas and are often used by companies with limited budgets, or companies that are new to the industry and whose main priority at the fair is to make connections with other companies, rather than to impress.

Figure 2.1: *Different stand stypes. Left: UB stand. Middle: MSD stand. Right: Free build stand. Source: Aquatech (n.d.), KOPExpo (n.d.)*

Modular stand design (MSD)

The MSD stand is in many ways similar to the UB stand, but allows for a more customized design. The colouring of the panels, the poster and the layout is more advanced than the uniform build stands. These designs are suited for stands up to 30m^2, and are often rented by exhibitors who want a more elaborate showcasing than the uniform build stand.

2.2.2 Free build

The other stand type is the free build stand. As the name suggests, the exhibitor has more freedom in the stand design. They are often custom made, and have complex designs such as two-storey stands, or artistic constructions. These stands are often bought by larger companies that want to make an impression on the trade fair visitors. These companies also have the budgets to rent bigger stand areas and buy more elaborate stand designs. Oftentimes, the stands are reused at different fairs, and are either stored, or transported to the next fair. The exhibiting companies often do not design these stands themselves, but hire a specialised stand building company.

2.3 Standbuild approach

2.3.1 Rented stand standbuilders

At each fair, there are multiple exhibitors that rent a stand. Instead of sending in a separate team for each stand, the venue hires one team to do all the rigging, one team for all the floors, one team for all the walls, etc. Standbuilders for rented stands therefore have a specific part of the stand, which they construct for all rented stands. In order to do this, they move around the hall, taking their materials with them. This material is often very little, and since it is moved around, it only blocks aisles very briefly. Besides, rented stand standbuilders can often enter the halls one or more days earlier, so that their stands are already constructed before the free build standbuilders enter. Since these stands do not create the safety risks, delays and inaccessibility problems mentioned in section 1.2, they are left out of further consideration.

2.3.2 Free build standbuilders

These standbuilders are hired by exhibitors to build a free build stand. Before construction, the design is approved with the exhibitor, and materials are collected for the stand. The standbuilder then books a timeslot at the venue's delivery appointment system, which determines when the standbuilder can unload its materials at the venue. Once there, the materials are brought into the hall, where they are stored around the stand. From here, the standbuilders start constructing. They start with the rigging (if the stand has any), followed by the flooring, after which the walls are constructed, electronics are connected, and the stand gets decorated. At each step, required materials are taken from the aisles, and put on the stand. At the end of construction, the stand is cleaned and delivered to the exhibitor.

2.4 Delivery appointment system

Venues often work with a delivery appointment system. In this system a standbuilder can book a timeslot for unloading its materials, and picking up its empty packagings. The number of timeslots available depend on the size of the working terrace. The working terrace is the area outside the hall that is used for (un)loading vehicles. This space is limited, and therefore, the number of vehicles that can enter the working terrace depends on the vehicle sizes. For example, more small passenger cars fit on the working terrace than large trucks.

By introducing an appointment system, the venue spreads the deliveries over the entire day, instead of only the morning. Vehicles arrive at their appointed time, and therefore do not queue in front of the venue, at the start of the construction period. This reduces waiting times at the gates (see the interview in Appendix H.1).

2.5 Construction planning

The entire construction period is characterized by different construction days. These are as follows:

1. **Technical buildup days (1-4 days):** During the technical buildup, the preparatory work for all stand construction is done. This consists of:
   - Marking the outlines of the stands
   - Marking the yellow safety pathways, that need to be passable and free of materials at all times
   - Installing electricity, IT and water services at the stands
   - Preparing the rigging points from the roof
   - (If possible) An early start for the construction of the UB and MSD stands
2. **Regular buildup days (1-4 days):** During the regular buildup days, the halls are open for the construction of all the stands. The stand builders of the free build

stands can start constructing their stand after the arrival and unloading of their truck. In case the construction of UB and MSD stands have not been finished during the technical buildup days, construction will continue during the regular buildup days.

3. **(If possible) Decoration days (1 day):** The last buildup day can be designated as a decoration day. On this day, no construction work is permitted; only furnishing, decorating, and cleaning of the stands are allowed.

2.6 Conclusion

This chapter aimed to answer the research question *"How does the construction of trade fairs currently work?"*. Starting with the organizational structure, there are several parties involved in the organization of a trade fair, namely the venue, the organizer, the exhibitor and the standbuilder.

The exhibitor can choose between renting a stand and building their own stand. Rented stands are often of a more simple design, and are constructed by the venue. The venue hires one team for a specific component of a stand, which the team then constructs for all rented stands. They bring little materials with them into the halls. For this reason, they do not cause the problems stated in section 1.2, and do not need to be further considered.

The second type are the free build stands. Each stand is constructed by a designated team, that delivers the materials for the stand to the venue. Free build standbuilders can start their construction, once their trucks are unloaded during their delivery appointment. Materials are then brought into the hall, and stored in the aisles. This way, the problems mentioned in 1.2 are created. Therefore, this research will further focus on free build stands.

The venue can regulate the construction process by changing the number of regular buildup days, as well as the available timeslots in the delivery appointment system. This can set boundaries to the start time of stand constructions and their deadlines.

3

Literature review

3.1 Introduction

In this chapter, a literature review will be given on scheduling models for trade fairs and events, as well as scheduling of construction projects and construction logistics. The aim of this chapter is to answer the research question "*What models found in literature are most suitable for solving the scheduling problem at trade fairs?*". First, literature on event logistics will be discussed in section 3.2, followed by a review on workspace planning in 3.3, and methods on assigning unloading slots 3.4.

3.2 Trade fairs and events

3.2.1 Event logistics

Events, such as sport events, music events, theaters or festivals, or congresses, share similarities with trade fairs regarding preparations, venues and size. However, most papers focus on the general management of events, and write little details on the on-site construction logistics or preparations for these events (e.g. Allen et al., 2022; Bonet et al., 2018; Caciur, 2012; Herold et al., 2020a; Herold et al., 2020b; Jalil et al., 2019; Masterman, 2014; Váncza et al., 2010). More has been published on the logistics of special events such as the Olympic Games and World Exposition, although the main recommendations of these works call for a smooth logistics process, with a good balance between internal and external staff, using data from previous events, robust planning and securing infrastructure early on (Creazza et al., 2015; Minis et al., 2006). These results can however not be applied on the problem stated in 1.2, which reuires a more detailed planning procedure.

3.2.2 Trade fair logistics

Literature on trade fairs mostly focuses on the optimal layout of a fair (Velarde, 2017), how to design a stand (Neidoni et al., 2017; Søilen, 2013), how the experience for visitors can be improved (Jiménez-Guerrero et al., 2020; Pencarelli et al., 2018) or on how companies can create business opportunities at trade fairs (Alberca et al., 2018; Gębarowski, 2012; Siegfried, 1970). Agalianos et al. (2020) and Harjes et al. (2014) explored new ways for integrating IT systems in event logistics to automate asset tracking and logistics.

To the author's knowledge, only one research has been performed on formally analyzing bottlenecks at trade fair constructions. Sad (2013) simulated the arrival of delivery trucks using queuing theory and focused on the supply logistics at a trade fair. The complexities of the internal logistics were not considered. The unique logistical challenges at the organization of events have therefore not yet been researched in the event logistics research field (Creazza et al., 2015).

3.3 Workspace planning

3.3.1 Workspace conflicts

Over the past 70 years, a substantial body of literature has emerged on planning techniques for construction sites (Sriprasert et al., 2003). This field focuses on planning resources, activities, equipment, and personnel. The objectives of these planning methods can vary from minimizing total time, to minimizing costs, safety risks, or a combination of these factors. Also the constraints, such as the physical, resource, informational or contractual limitations, differ per construction project, as well as the scale.

Construction projects can be subject to limited resources. These resources are not only materials, equipment, and personnel, but also space. Space can be seen as a renewable resource, that is released again after an activity is completed. Task execution space on a construction site is therefore dynamic. Not only do teams with different tasks move through the space and occupy different areas at different times, but the space also changes when, for instance, walls are constructed or floors are laid (Winch et al., 2006).

In case the same workspace is occupied by two or more activities simultaneously, a workspace conflict occurs (Tao et al., 2020). In literature there are two types of strategies to deal with these conflicts: the site layout problem and the space scheduling problem.

3.3.2 Site layout problem

The site layout problem focuses on the optimal arrangement of temporary facilities at the construction sites, such as equipment, storage areas, worker accommodations and pathways (Roofigari-Esfahan et al., 2017). As mentioned, the layout of a trade fairs can differ, but is fixed for a specific trade fair, and is therefore not considered for optimization.

3.3.3 Workspace scheduling problem

The space scheduling problem involves the planning of the activities and their related workspaces (Pasupathy et al., n.d.). There are two methods for approaching this scheduling problem: reactive and proactive methods.

Reactive methods

In reactive methods, an initial schedule is created, which is then scanned for workspace conflicts. These are resolved using heuristic rules (Tao et al., 2020). The premise of these strategies is to create a schedule that is eliminated of all potential workspace conflicts. Most of the studies in this area have used rule-based heuristics (e.g., Thabet et al., 1994, Guo, 2002, Kassem et al., 2015) in combination with 4D CAD (Hosny et al., 2020, Kassem et al., 2015, HyounSeok Moon et al., 2014). Other studies used GIS (Bansal, 2011) or BIM (Choi et al., 2014) for visualising and detecting workspace interferences. Other approaches include the usage of singularity functions to model the progress of activities in space, and detect workspace interferences in a 3D schedule representation (Isaac et al., 2017, Lucko et al., 2014).

Although the heuristics are effective at creating these conflict free schedules, the strategy of adjusting baseline schedule often results in suboptimal schedules (Tao et al., 2020). Still, these methods remain popular in construction projects where no workspace interferences can be tolerated, and where only one schedule needs to be made. However, workspace interferences are tolerated at trade fair constructions. Besides, finding an (near) optimal schedule is highly desirable. Therefore, reactive methods do not suffice for solving the proposed problem.

Proactive methods

In proactive methods, the scheduling problem is optimized by minimizing workspace conflicts rather than to eliminating them. Research in this topic has resulted in promising models that include an optimization element that was absent in reactive methods, yet studies in this topic are surprisingly sparse (Tao et al., 2020). However, there are still several valuable studies in this area. Dang et al. (2013) for example solved a multi-objective space scheduling problem by using an evolutionary algorithm. Rohani et al. (2018) combined reactive and proactive methods in a 5D CAD model (3D model, including a time and costs dimension), by first optimizing the schedule using a Genetic Algorithm, and then solving detected workspace clashes using heuristics.

Chua et al. (2010) quantified the spatio-temporal congestion in workspace interferences by introducing the dynamic space interference (DSI) variable and a congestion penalty indicator (CPI). Although the CPI was a good quantification of a linear penalty costs of workspace congestion, the congestion was not translated to an actual delay of the activities. Roofigari-Esfahan et al. (2017) also looked at costs in the form of linear productivity losses due to time and space constraints, and added an uncertainty buffer by using constraint programming and a fuzzy interference system. However, the end time of activities was fixed in their model, so that a lower productivity did not result in a longer activity execution time. Rather, a lower productivity rate at the start of an activity would be compensated with a higher one later on. Tao et al. (2020), on the other hand, introduced a nonlinear delay factor. Productivity loss and delays occurred during work space interferences, but were taken at random and were not linked to the severity or duration of the interference. The scheduling of activities were not altered by this, although distinctions between acceptable and unacceptable interferences were included.

So although efforts have been done to include the delay effects of workspace interferences in the optimization of workspace scheduling, the link between the severity and duration of the interference is absent in current studies. The intensity and penalty of the interference have been well captured in the DSI and CPI variables, as introduced in Chua et al. (2010), and delays and productivity rates have been addressed in Tao et al. (2020). However, no study has been performed in which the intensity has been linked to delays, and no study has included the changes in activity duration due to these delays.

3.4 Assigning unloading slots

Another approach for finding a scheduling model, is through focusing on the assignment of unloading slots.

Although this initially seems to be a Truck Appointment Scheduling (TAS) problem, TAS research primarily aims to determine the optimum appointment quote per timeslot, the length of the timeslots, and evaluate the performance of a container terminal once a TAS has been implemented (Abdelmagid et al., 2022). However, since these are presumed to be fixed at trade fairs, research on this field is not relevant for the mentioned problem. Instead, this research requires optimizing the assignment of trucks to timeslots, which aligns more closely with the field of Parallel Job Shop Scheduling Problems (PJSSP).

3.4.1 Parallel Job Shop Scheduling Problem (PJSSP)

A PJSSP is a special case of a Job Shop Scheduling problem (JSSP). This is a manufacturing problem where a set of jobs need to be processed on a set of machines as efficiently as possible. Each machine functions as a manufacturing station, and each job consists of a series of tasks that need to be performed in a specific order on a designated machine. The goal of this is to find the most efficient schedule of assigning tasks to machines. An example of a Job Shop Scheduling Problem is the manufacturing of two types of t-shirt (jobs), for which materials need to cut, sewed, dyed and packaged (tasks) at the corresponding cutting, sewing, dying and packaging stations (machines) (Hajibabaei et al., 2021).

In case there are multiple identical machines available, tasks can be processed simultaneously. This is a PJSSP, where the identical machines work in parallel, and allow for more flexibility in the scheduling of tasks (Joo et al., 2012). A PJSSP covers two sub-problems: first, the assignment of each operation to one of the alternative machines, and secondly, the ordering of the operations on each machine. When looking at the scheduling problem of trade fairs, a PJSSP can be seen in the assignment of timeslots, where the quota of the timeslot is the number of parallel machines, and where the task is to construct the stands. Construction durations of stands are not the same for all stands. It is dependent on obvious reasons like size, complexity of the stand, the number of people building the stand, but also due to the limited workspaces in the venue. How limited this space is depends not only on the time, but also on the chosen sequence of the starting times. The duration of the construction is therefore both time and sequence dependent.

Sequence and time dependent set-up time JSSP have been well studied in literature. The set-up time of a task refers to the time that is needed to prepare a machine for the processing of a particular job. In case this setup time is sequence dependent, it varies based on the job previously processed on that machine. When the setup time is time dependent, it changes based on the starting time of the job.

Sequence dependent set-up times

The sequence dependent set-up time problem has been well studied in literature. A framework for minimising the total tardiness of a parallel machine sequence-dependent setup times scheduling problem was provided by Lee et al. (1997) using simulated annealing. Ramezani et al. (2015) aimed to minimize the maximum completion time of jobs with no wait inbetween tasks using a weed optimization, variable neighborhood search and simulated annealing. Others have also minimized the makespan using hybrid genetic algorithm (Kim et al., 2021) or a tabu search algorithm (Hajibabaei et al., 2021, Shen et al., 2018). Rossi et al. (2007) chose an Ant Colony Optimization approach, and included transportation time and routing flexibility in the problem. Joo et al. (2012) minimized the weighted sum of the setup times, delay times and tardy times with a genetic algorithm and a new evolutionary method called Self-Evolution Algorithm (SEA).

Although these studies provide useful insights in how to formulate and optimize parallel job-shop scheduling problems, processing times in these studies only depend on the task sequence on a single machine. The processing times on the second machines (the second jobs) are not influenced by the sequence of tasks on the first ones. This means that, if this were to be applied on the scheduling at trade fairs, the sequence in which stands start construction, does not influence the duration of construction. However, in practice it should have an influence, due to the effects on the available workspaces. To date, no study has captured this dependency to date.

Time dependent set-up times

In time-dependent machine scheduling problems, the processing times depend on the starting times of the jobs. There are many variations of this problem, varying from general variants to dedicated machine variants, in which the processing time also depends on the assigned machines (Gawiejnowicz, 2020). Some variations on the general model are the works of Zimmermann et al. (1997), who introduced proportionally deteriorating processing times according to a function that was common for all jobs. Mel'Nikov et al. (1979) (as cited in Gawiejnowicz (2020)) as well as Cai et al. (1998) introduced a model of nonlinear deteriorating job processing times. Alidaee (1990) was the first to introduce exponential job processing times. However, all these studies only let processing times be influenced by the starting time of a job. No study was found in which processing time was influenced by both the starting time and the sequence or starting times of other jobs.

3.5 Conclusion

In this literature review, it was found that literature on event logistics is highly limited. No studies have been performed on scheduling problems at trade fairs or similar events to date. The complexity of scheduling starting times for stand constructions at trade fairs, lies within the dependency between the starting times of the stands, the materials in the pathways and its effects on productivity. Studies on scheduling tasks with shared workspaces mainly focused on removing any workspace interferences from a schedule, rather than optimizing a schedule in which some workspace interferences are accepted. Studies on this aspect have been limited. While Chua et al. (2010) and Roofigari-Esfahan et al. (2017) introduced linear productivity rates, and Tao et al. (2020) addressed delays, the impact of shared workspace intensity on delays has not yet been linked or considered in scheduling processes.

The availability of workspace depends on both the time and sequence of the construction starting times of stands. Although studies are performed on time and sequence dependent PJSSP separately, no studies was found on the combination of the two. As a result, no study has yet captured the complex dependencies between start times and construction durations in similar construction projects.

This creates a gap in the literature regarding scheduling models that account for the complex dynamics of workspace interferences and associated delays. Consequently, current scheduling practices are often suboptimal, failing to consider the workspace dynamics that occur on the work floor. Addressing this gap is important, because optimized scheduling can lead to more efficient resource use, reduced delays, and minimized congestion, ultimately improving productivity and safety. By incorporating these dynamics into scheduling models, more realistic and effective approaches to planning in high-density, shared work environments can be achieved.

4

Mixed Integer Linear Programming model

4.1 Introduction

This chapter aims to create the MILP formulation, and answer the research question: *"How can the scheduling problem be represented in a mathematical model?"*.

In this model, the venue hall is seen as a 2D-space, in which each stand has a construction space and a storage. This is done in a similar way to the approach of Hyounseok Moon et al. (2014), where 2D-grid projections were used to project overlapping work spaces. In their work, each work space has a surrounding buffer space. Here, these buffer spaces are seen as the storage spaces. This will be further discussed in section 4.2.

After this, a Mixed Integer Linear Programming (MILP) formulation of the problem will be given in section 4.3. Three policies will be introduced. First, the **no delay policy** will be discussed in section 4.4, where productivity is assumed to be linear and constant, inspired by the works of Chua et al. (2010) and Roofigari-Esfahan et al. (2017). After this, a **delay policy** is introduced in 4.5, where the previous policy will be expanded upon by adding a delay factor, similar to the works of Tao et al. (2020). Lastly, an **accessibility policy** will be discussed in 4.6, that expands upon the ideas of Chua et al. (2010) that there is accessible and "dead" work space, and accessibility paths can be flexible, by introducing an accessibility graph, and adding accessibility constraints to the MILP model.

An overview of the sets, parameters and decision variables used in this chapter can be found in table 4.1.

4.2 Venue layout analysis

4.2.1 2D grid

Similar to the works of HyounSeok Moon et al. (2014), the layout of the venue is given as a 2D-space. Instead of seeing this space as the continuous Euclidean plane, it can

Table 4.1: *Sets, parameters and decision variables for the no delay, delay and accessibility policy. Source: author.*

Sets	
S	Set of stands
X	Set of steps in the x-axis direction in the grid, := $\{0, \ldots, X_{max}\}$
Y	Set of steps in the y-axis direction in the grid, := $\{0, \ldots, Y_{max}\}$
T	Set of timesteps
Parameters	
B_s	Set of nodes, adjacent to stand s
$c_{s,(x,y)}$	Binary indicator, = 1 if (x, y) is in the construction space of s, = 0 else
D_s	The expected duration of construction of stand s, assuming no delays
$\delta_{s,(x,y)}$	Binary indicator, = 1 if (x, y) is in the storage space of s, = 0 else
E	Set of edges in G. When two aisle sections are adjacent, their nodes are connected by an edge
G	Graph of the floor plan of the hall, $G = (N^t, E)$
h	Allowed height of storage of materials per m^2, in m.
I_s	Set of stands $s' \in S$ with a shared storage space, i.e. $\Omega_{s,s'} \neq \emptyset$
$I_{s,\sigma}$	Set of tuples (s', σ') of stands $s' \in S$ and their respective side σ' that overlaps with stand s at side σ.
m_s	Total amount of materials required for the construction of stand s, in m^3
μ_s	The density of materials from stand s at the start of its construction
N^t	Nodes of graph G.
Ω_s	Set of squares (x, y) that are in the storage space of stand s.
$\Omega_{s,s'}$	Set of squares (x, y) that are in the storage space of both s and s'
L	Length of the pathway outside the construction area available for material storage
$\Omega_{s,\sigma}$	Set of squares (x, y) that are in the storage space of stand s at side σ
P_s^t	Set of paths from stand s to the yellow path
$p_s^{t,k}$	kth path from stand s to the yellow path at time t.
Φ_s	Set of tiles (x, y) that are in the construction space of stand s
S'	Set of stands, adjacent to the yellow path
S''	Set of stands, not adjacent to the yellow path
τ_{max}	Indicates the maximum number of stands that can start at a given timeslot
$v(\Omega_s)$	Volume of space Ω_s
w_s	Weight of the effect of material density in the surrounding aisles on the productivity of stand s
X_{max}	The number of squares in the x-direction of the grid
$\mathcal{Y}$	Set of nodes, adjacent to the yellow path
Y_{max}	The number of squares in the y-direction of the grid
$y_s^l, x_s^l, y_s^u, x_s^r$	Bottom, left, upper and right boundary of stand s respectively
Decision variables	
τ_s^t	Binary, equals 1 when stand s starts construction at time t, equals 0 otherwise
ρ_s^t	$\in [0, 1]$. Average resource density of materials from stand s at Ω_s at time t
$\rho_{s,\sigma}^t$	$\in [0, 1]$. Resource density of materials from stand s at side σ at time t
$\alpha_s^{t,k}$	Binary variable, = 1 if path $p_s^{t,k}$ is passable at time t, = 0 else

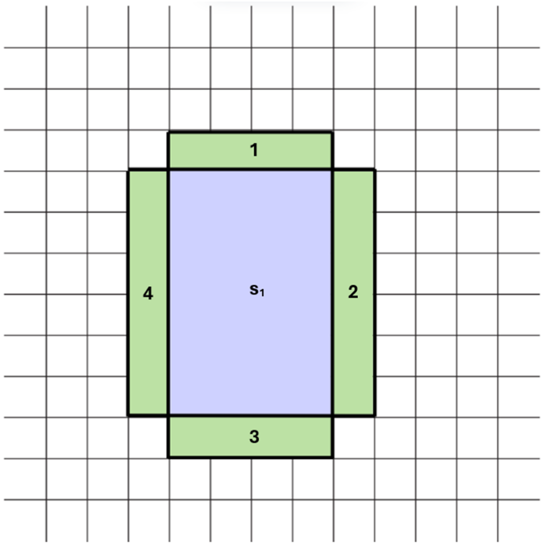

Figure 4.1: *Example of a stand's construction space (blue) and storage space (green). Source: author.*

be discretised in a grid $X \times Y$, where $X := \{0, 1, \ldots, X_{max}\}$ and $Y := \{0, 1, \ldots, Y_{max}\}$. Here, $\times$ defines the cartesian product between X and Y. The value of $X_{max}, Y_{max} \in \mathbb{N}$ correspond to the width and length of the venue respectively. Where Hyounseok Moon et al. (2014) used integers to indicate work spaces, buffer spaces, and overlapping spaces, here binary indicators will be used in order to keep the spaces separated and identifiable per stand.

4.2.2 Construction and storage space of a stand

Each stand has two types of spaces. The first is the construction space, which indicates the area where that the stand will occupy once it is fully constructed. The second is the storage space, which is the space around a stand that is used for the storage of construction materials. An example of the construction space (in blue) and storage space (in green) of a stand, can be found in figure 4.1.

Construction space

Let S be the set of stands that need to be constructed. For each stand, the construction space is known beforehand, and is given by a left, right, lower and upper bound: x^l_s, x^r_s, y^l_s, and y^u_s respectively. In figure 4.2, an example of a small venue layout can be found, where the construction spaces of the stands are given in blue. The boundaries of s_1 are $y^l_{s_1} = 1, x^l_{s_1} = 1, y^u_{s_1} = 6$ and $x^r_{s_1} = 5$.

Now, the binary indicator $c_{s,(x,y)}$ for each square of the grid can be defined. $c_{s,(x,y)}$ indicates the construction space of s and $c_{s,(x,y)} = 1$ if (x, y) is in the construction space of s, and 0 else. $c_{s,(x,y)}$ can be defined as:

$$c_{s,(x,y)} := \begin{cases} 1 & \text{if } x^l_s \leq x < x^r_s \wedge y^l_s \leq y < y^u_s \\ 0 & \text{else} \end{cases} \tag{4.1}$$

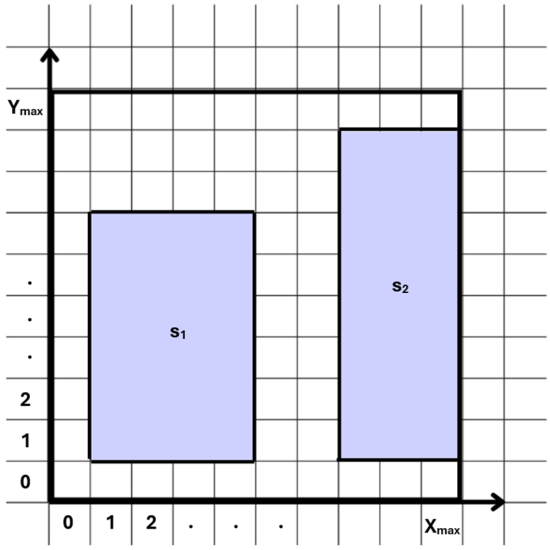

Figure 4.2: *Example of a simple venue layout. Source: author*

The total construction space of s is then given by:

$$\Phi_s := \{(x, y) | c_{s,x,y} = 1\} \tag{4.2}$$

Storage space

Each stand has an area surrounding it, which can be used for storage of materials. A square (x, y) can be used for storage for stand s, when the distance between that square and the construction area is less than parameter L. L indicates the width of the pathway that can be used for material storage by the neighbouring stands. When L is small, materials can only be stored close to the stand, but when L is larger, a bigger portion of the pathway can be used.

In figure 4.3 an example can be found with $L = 1$ and $L = 2$. When $L = 1$, the stands can use up to one square outside their construction space for materials. Since the pathway between s_1 and s_2 is two squares wide, the storage areas do not overlap. When $L = 2$, the stands can use up to a distance of two squares outside their construction space. s_1 now has a bigger storage space on its upper and right side, while its lower and left side can not expand due to the walls of the venue hall. In a similar fashion s_2 expands its storage area to the left. The two now share an overlapping storage area, overlap between the two storage areas is given in dark green.

The corner squares of the stands are not included in the storage areas. This is done, because it was found that in practice corners are not often used for storage. Most stands prefer to use the pathways along the edges of their stand, since corner points are often intersections of pathways that are frequently used by people moving around the venue. Obstructing these corner points causes more disruption than blocking regular pathways. As an additional advantage, the chances three stands sharing the same storage space is greatly reduced. Although this is still possible, the occurrence of this is negligible,

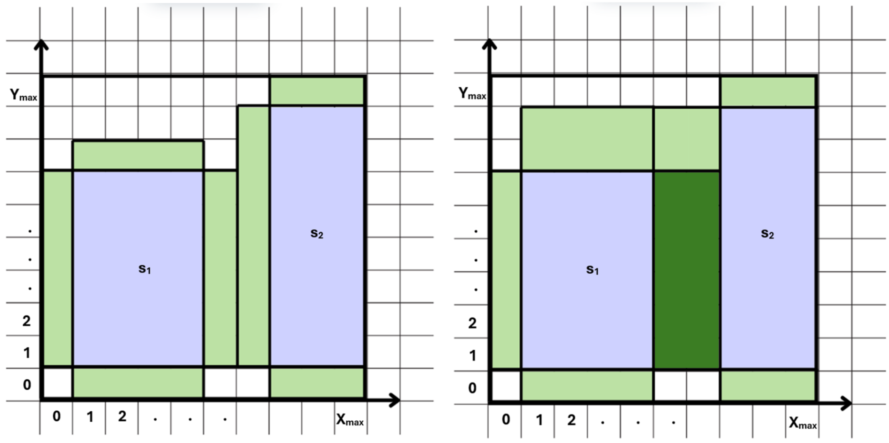

Figure 4.3: *Example of storage areas (in green). Left: $L = 1$, right: $L = 2$. Dark green indicates the area of overlapping storage area of stand s_1 and s_2. Source: author*

since these spaces are very small and L is not greater than the pathway width. The binary variable $\delta_{s,(x,y)}$ captures the availability of a square (x, y) for storage by stand s. $\delta_{s,(x,y)} = 1$ if (x, y) can be used for storage, and 0 else. Aside from the value of L, the availability of a square for storage is also determined by whether a square is already used construction by another stand. The definition of $\delta_{s,(x,y)}$ can be found in appendix B.

Let Ω_s be the total storage space of stand s, such that:

$$\Omega_s := \{(x, y)|\delta_{s,(x,y)} = 1\} \tag{4.3}$$

For each side $\sigma \in \{1, 2, 3, 4\}$, the storage space of stand s can be defined by:

$$\Omega_{s,\sigma} := \{(x, y)|\delta_{s,(x,y)} = 1 \wedge (x, y) \text{ on side } \sigma \text{ of } s\} \tag{4.4}$$

In figure 1.1 one can see the numbering of the sides of a stand. So here, $\Omega_{s,2}$ indicates the storage space on the right of the stand.

Storage spaces can overlap between stands (indicated by $\Omega_{s,s'} := \Omega_s \cap \Omega_{s'}$). The set of stands s' that have overlapping storage space with stand s, can be defined as:

$$I_s := \{s' \in S|\Omega_s \cap \Omega_{s'} \neq 0\} \tag{4.5}$$

Now for each side $\sigma \in \{1, 2, 3, 4\}$, the overlap with other stands is given in:

$$I_{s,\sigma} := \{(s', \sigma')|s' \in S \setminus s, \sigma' \in \{1, 2, 3, 4\}, \Omega_{s,\sigma} \cap \Omega_{s',\sigma'} \neq 0\} \tag{4.6}$$

4.3 Problem definition

The first step of creating a MILP for the problem is to define the objective function. Let ρ_s^t be the density of materials around stand s and time t, where $\rho_s^t = 1$ means that the aisles are completely full, and $\rho_s^t = 0$ means the aisles are completely empty. Instead of seeing time as continuous, it is discretised into timesteps of 1 hour, where $T := \{1, \dots, T_{max}\}$ is the set of timesteps. The objective is to minimize the average density of all aisles at all times $t \in T$. Let $v(\Omega) := |\Omega|$ be the volume of space Ω, then the objective function can be formulated as:

$$\text{Minimize } Z = \frac{\sum_{t\in T}\sum_{s\in S}\rho_s^t \cdot v(\Omega_s)}{(\sum_{s\in S} v(\Omega_s)) * T_{max}} \tag{4.7}$$

First, a basic MILP is introduced that models the construction of the stands, but in which no delays are taken into account. This model will be called the **no delay policy** and will have the following conditions:

1. Each stand must have a starting time
2. Each stand must be finished by the end of the construction period (T_{max}).
3. Only a limited amount of stands can start construction per timeslot. This maximum is given by τ_{max}.
4. The overall density of stored materials around a stand s at time t, given by ρ_s^t, can not be higher than 1.
5. The combined density of materials from stand s and s' at their combined storage space $\Omega_{s,s'}$ can not be higher than 1.
6. The overall density of stored materials around a stand s decreases linearly over time.

These conditions serve as the basis for constructing the constraints for the MILP.

After this, the **delay policy** is introduced, in which the effect of the material storage on the productivity is taken into account. In this policy, the decrease of material density per timestep now depends on the material density around the stand.

Lastly, the **path accessibility policy** is introduced, in which it is ensured that each stand is accessible at the time of its start of construction. This way, materials can still be brought to the stand, without being blocked by materials of other stands.

4.4 No delay policy

In this section, the constraints for the delay policy will be discussed in more detail.

Each stand must have a starting time

In order to develop a constraint that makes sure that each stand has a starting time, binary variable τ_s^t is introduced. This variable will indicate whether stand s starts construction at time t ($\tau_s^t = 1$) or not ($\tau_s^t = 0$). Since each stand must have exactly one starting time, a first estimate for a constraint would be:

$$\sum_{t\in T} \tau_s^t = 1 \qquad \forall s \in S \tag{4.8}$$

Each stand must be finished by T_{max}

Let D_s be the duration of construction of stand s. Since each stand must finish construction before T_{max}, the starting time of s must be before $T_{max} - D_s$. Therefore, constraint 4.8 can be rewritten as:

$$\sum_{t=1}^{T_{max}-D_s} \tau_s^t = 1 \qquad \forall s \in S \tag{4.9}$$

$$\sum_{t=T_{max}-D_s+1}^{T_{max}} \tau_s^t = 0 \qquad \forall s \in S \tag{4.10}$$

A limited amount of stands can start construction per timeslot

Let τ_{max} be the maximum number of stands that can start construction per timeslot. Then, no more than τ_{max} stands can start construction when adding the following constraints:

$$\sum_{s \in S} \tau_s^t \leq \tau_{max} \qquad \forall t \in T \tag{4.11}$$

The overall density of stored materials around a stand s at time t can not be higher than 1

Let ρ_s^t be the density of the materials of stand s over its storage area Ω_s at time t. Note that this does not include the density of materials of other stands that are stored in the same space.

ρ_s^t can be defined as:

$$\rho_s^t := \sum_{\sigma \in \{1,2,3,4\}} \rho_{s,\sigma}^t \frac{v(\Omega_{s,\sigma})}{v(\Omega_s)} \tag{4.12}$$

where $\rho_{s,\sigma}^t$ is the density on area $\Omega_{s,\sigma}$. Then, $\rho_s^t \in [0,1]$ for all $s \in S, t \in T$ when:

$$\rho_{s,\sigma}^t \in [0,1] \qquad \forall s \in S, \sigma \in \{1,2,3,4\}, t \in T \tag{4.13}$$

The combined density of materials from stand s and s' at $\Omega_{s,s'}$ can not be higher than 1

At storage space $\Omega_{s,s'}$ both stand s and s' can store materials. The density of these materials are given by $\rho_{s,\sigma}^t$ and $\rho_{s',\sigma'}^t$ respectively, for $(s',\sigma') \in I_{s,\sigma}$. The total material density at $\Omega_{s,s'}$ is given by $\rho_{s,\sigma}^t + \rho_{s',\sigma'}^t$, and can not exceed 1. In order to ensure this, the following constraints should be added to the model:

$$\rho_{s,\sigma}^t + \rho_{s',\sigma'}^t \leq 1 \qquad \forall s \in S, \sigma\{1,2,3,4\}, (s',\sigma') \in I_{s,\sigma}, t \in T \tag{4.14}$$

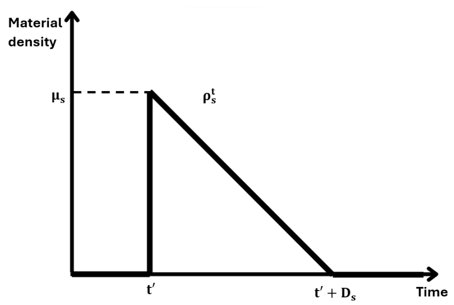

Figure 4.4: *Linear reduction of ρ_s^t. Source: author*

The overall density of stored materials around a stand s decreases linearly over time

The linear decrease approach is similar to the works of Roofigari-Esfahan et al. (2017) and Chua et al. (2010). The sigmoid function in Tao et al. (2020) is not used, in order to comply with the linearity demand for MILP.

In order to let the overall density of stored materials around stand s (ρ_s^t) decrease linearly over time, first the density at the start of construction needs to be determined. Let m_s be the total amount of materials for stand s in m^3, and let h be the maximum allowed height for storage of materials per m^2, given in m. Then:

$$\mu_s := \frac{m_s}{h * v(\Omega_s)} \quad \forall s \in S \tag{4.15}$$

This is a constant per stand, and indicates the starting density of stand s. Let $t' \in T$ be such that $\tau_s^{t'} = 1$. Then $\rho_s^{t'} = \mu_s$, and $\rho_s^{t'+D_s} = 0$ due to the linear decrease (see figure 4.4). Note that $\rho_s^t = 0$ when $t < t' \vee t \geq t' + D_s$. ρ_s^t reaches 0 in D_s number of timesteps after t', and therefore reduces by $\frac{1}{D_s} \cdot \mu_s$ each timestep. ρ_s^t is given by:

$$\rho_s^t = \sum_{t'=t-D_s}^{t} \left(\mu_s \cdot \tau_s^{t'} - \frac{1}{D_s} \cdot \mu_s \cdot \tau_s^{t'}(t - t') \right) \qquad \forall s \in S, t \in T \tag{4.16}$$

Clearly, the value of μ_s must be ≤ 1 for the model to be feasible. The values of μ_s found in real life will be further discussed in section 5.3.

4.4.1 No delay policy MILP

Now that the sets, parameters, decision variables and constraints have been introduced, the full model can be established.

$$\text{Minimize } Z = \frac{\sum_{t\in T}\sum_{s\in S}\rho_s^t \cdot v(\Omega_s)}{(\sum_{s\in S} v(\Omega_s)) * T_{max}} \tag{4.17}$$

$$\text{s.t.} \tag{4.18}$$

$$\sum_{t=1}^{T_{max}-D_s} \tau_s^t = 1 \qquad \forall s \in S \tag{4.19}$$

$$\sum_{t=T_{max}-D_s+1}^{T_{max}} \tau_s^t = 0 \qquad \forall s \in S \tag{4.20}$$

$$\sum_{s\in S} \tau_s^t \leq \tau_{max} \qquad \forall t \in T \tag{4.21}$$

$$\rho_s^t = \sum_{\sigma\in\{1,2,3,4\}} \rho_{s,\sigma}^t \frac{v(\Omega_{s,\sigma})}{v(\Omega_s)} \qquad \forall s \in S, t \in T \tag{4.22}$$

$$\rho_{s,\sigma}^t + \rho_{s',\sigma'}^t \leq 1 \qquad \forall s \in S, \sigma \in \{1,2,3,4\}, (s',\sigma') \in I_{s,'}, t \in T \tag{4.23}$$

$$\rho_s^t = \sum_{t'=t-D_s}^{t} \mu_s \cdot \tau_s^{t'} - \frac{1}{D_s} \cdot \mu_s \cdot \tau_s^{t'}(t-t') \qquad \forall s \in S, t \in T \tag{4.24}$$

$$\tau_s^t \in \{0,1\} \qquad \forall s \in S, t \in T \tag{4.25}$$

$$\rho_{s,\sigma}^t \in [0,1] \qquad \forall s \in S, \sigma \in \{1,2,3,4\}, t \in T \tag{4.26}$$

4.4.2 Example

In this section, an example of the model will be discussed. The example of figure 4.3 will be used where $L = 2$, and:

$$v(\Omega_{s_1}) = 30 \tag{4.27}$$

$$v(\Omega_{s_2}) = 22 \tag{4.28}$$

$$v(\Omega_{s_1,s_2}) = 12 \tag{4.29}$$

Let $m_{s_1} = h \cdot v(\Omega_{s_1})$ and $m_{s_2} = h \cdot v(\Omega_{s_2})$, such that $\mu_{s_1} = \mu_{s_2} = 1$. Let $D_{s_1} = D_{s_2} = 4$.

For these parameters, the optimised objective value for the model would be 10, with

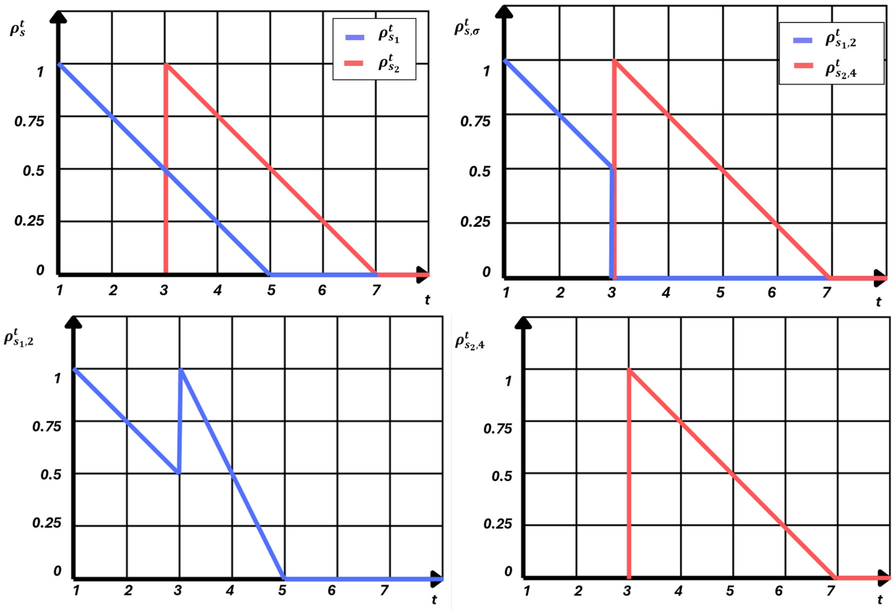

Figure 4.5: *Progression of densities for $L = 2$, $D_s =$, $\mu_{s_1} = \mu_{s_2} = 1$ for the example of figure 4.3. Source: author*

$\tau_{s_1}^1 = 1$, and $\tau_{s_2}^3 = 1$.

This result can be explained by the following reasoning: One of the stands will start construction at the earliest time possible, $t = 1$. Since $\mu_{s_1} = \mu_{s_2} = 1$, for both the stands the density of construction spaces would be one. Since their construction spaces overlap, and the density on this part can not exceed 1, the other stand can only start construction at time t when the remaining materials of the construction stand can be fully stored on the other three sides, so that the overlapping side is fully available for the second stand. Storing everything on the other three sides is possible at time $t \in T$ only if $\rho_{s_1}^t < \frac{v(\Omega_{s_1,1})+v(\Omega_{s_1,3})+v(\Omega_{s_1,4})}{v(\Omega_{s_1})}$ or $\rho_{s_2}^t < \frac{v(\Omega_{s_2,1})+v(\Omega_{s_2,2})+v(\Omega_{s_2,3})}{v(\Omega_{s_2})}$. Since $\frac{v(\Omega_{s_1,1})+v(\Omega_{s_1,3})+v(\Omega_{s_1,4})}{v(\Omega_{s_1})} > \frac{v(\Omega_{s_2,1})+v(\Omega_{s_2,2})+v(\Omega_{s_2,3})}{v(\Omega_{s_2})}$ (namely $0.6 > 0.45$), Ω_{s_1,s_2} can be cleared earlier when s_1 starts construction. Because $D_{s_1} = 4$, construction will be halfway at $t = 3$, i.e. $\rho_{s_1}^3 = 0.5$. Now $\rho_{s_1}^3 < 0.6$, meaning that $\Omega_{s,s'}$ can be cleared and stand s_2 can start construction. The results can be found in 4.5 The objective value is 0.313.

4.5 Delay policy

In this policy, the effect of material storage on the productivity will be taken into account. The higher the density of materials stored around the stand, the less workspace the stand builders have, and the more the construction delays. Therefore, construction duration will now be variable, instead of the fixed construction duration D_s, in a similar way to the works of Tao et al. (2020). First, the new constraints will be introduced, after which the full MILP will be presented

4.5.1 Delay policy constraints

Construction is completed before T_{max}

Completion of the construction in the no-delay policy was first ensured by constraint 4.19. However, since duration has now become variable, this is no longer enough. It is now possible for a stand to start construction before $T_{max} - D_s$, but be delayed during construction such that completion takes place after T_{max} (i.e. $\rho_s^{T_{max}} > 0$). To avoid this, the following constraints are added to the model:

$$\rho_s^{T_{max}} = 0 \qquad \forall s \in S \tag{4.30}$$

Delay constraints

The effect of materials on the productivity can be captured in the material density variable ρ_s^t. When productivity is high, ρ_s^t reduces more per timestep than when producivity is low. ρ_s^t was defined in the no-delay policy as:

$$\rho_s^t = \sum_{t'=t-D_s}^{t} \left(\mu_s \cdot \tau_s^{t'} - \frac{1}{D_s} \cdot \mu_s \cdot \tau_s^{t'}(t - t') \right) \qquad \forall s \in S, t \in T \tag{4.31}$$

Let $t' \in T$ again be the construction starting time of stand s, such that $\tau_s^{t'} = 1$, then ρ_s^t can also be rewritten as:

$$\rho_s^t = \begin{cases} 0 & \text{if } t < t' \\ \mu_s & \text{if } t = t' \\ \rho_s^{t-1} - \frac{\mu_s}{D_s} & \text{if } t \in (t', t' + D_s] \\ 0 & \text{if } t > t' + D_s \end{cases} \tag{4.32}$$

This is equivalent to the following formulation:

$$\rho_s^t = \tau_s^t \cdot \mu_s + \rho_s^{t-1} - \left(\sum_{t'=1}^{t-1} \tau_s^{t'} \right) \frac{\mu_s}{D_s} \qquad \forall t \in \{2, \ldots, T_{max}\} \tag{4.33}$$

$$\rho_s^1 = \tau_s^1 \cdot \mu_s \qquad \forall s \in S \tag{4.34}$$

The factor $\left(\sum_{t'=1}^{t-1} \tau_s^{t'} \right)$ is introduced so that ρ_s^t is only reduced with $\frac{\mu_s}{D_s}$ when construction has already started (so $\sum_{t'=1}^{t-1} \tau_s^{t'} = 1$).

Adding a delay factor means that the productivity reduces and that ρ_s^t in the delay policy should be greater than or equal to the ρ_s^t in the no delay policy. In this case, some penalty should be given to the $-\left(\sum_{t'=1}^{t-1} \tau_s^{t'} \right) \frac{\mu_s}{D_s}$ factor. The delay can be measured by the density should depend on all the materials stored around (i.e. $\rho_s^t + \sum_{\sigma \in \{1,2,3,4\}} \sum_{(s',\sigma') \in I_{s,\sigma}} \rho_{s',\sigma'}^t \cdot \frac{v(\Omega_{s,s'})}{v(\Omega_s)}$, so the total sum of a stands own materials and the materials of others placed around it), multiplied with some weight factor w_s. The definition of w_s will be discussed in 4.5.1. ρ_s^t can now be reformulated as:

$$\rho_s^t \geq \tau_s^t \cdot \mu_s + \rho_s^{t-1} - \left(\sum_{t'=1}^{t-1} \tau_s^{t'}\right)\left(\frac{\mu_s}{D_s} - w_s \cdot \left(\rho_s^t + \sum_{\sigma\in\{1,2,3,4\}} \sum_{(s',\sigma')\in I_{s,\sigma}} \rho_{s',\sigma'}^t \cdot \frac{v(\Omega_{s,s'})}{v(\Omega_s)}\right)\right) \qquad \forall s \in S, t \in \{2,\ldots,T\} \tag{4.35}$$

$$\rho_s^1 = \tau_s^1 \cdot \mu_s \qquad \forall s \in S \tag{4.36}$$

The equality sign has been replaced by a $\geq$ sign, since the additional delay penalty may cause ρ_s^t to drop below 0 otherwise. Since this should not be possible, the $\geq$-sign has been introduced. However, the model will still minimize ρ_s^t, because its objective function will minimize the value of all ρ's. Therefore, the $\geq$-sign can be interpreted as an equality sign for all timesteps before the stands completion time.

Equation 4.35 is not yet in the right form for a MILP model, since it multiplies decision variables with each other. Therefore, the equation can first be reformulated to:

$$\rho_s^t \geq \tau_s^t \cdot \mu_s + (1+w_s)\rho_s^{t-1} - (\sum_{t'=1}^{t-1} \tau_s^{t'})\frac{\mu_s}{D_s} + w_s \cdot \left(\sum_{\sigma\in\{1,2,3,4\}} \sum_{(s',\sigma')\in I_{s,\sigma}} \sum_{t'=1}^{t-1} \rho_{s',\sigma'}^{t-1} \cdot \tau_s^{t'} \cdot \frac{v(\Omega_{ss'})}{v(\Omega_s)}\right) \qquad \forall s \in S, t \in \{2,\ldots,T\} \tag{4.37}$$

Introducing variable $\psi_{(s,\sigma),(s',\sigma')}^{t',t} = \rho_{s',\sigma'}^t \cdot \tau_s^{t'}$, the following MILP constraints can be formulated:

$$\psi_{(s,\sigma),(s',\sigma')}^{t',t} \leq \tau_s^{t'} \qquad \forall s \in S, t \in T, \sigma \in \{1,2,3,4\}, (s',\sigma') \in I_{s,\sigma}, t' \in \{1,\ldots,t-1\} \tag{4.38}$$

$$\psi_{(s,\sigma),(s',\sigma')}^{t',t} \leq \rho_{s',\sigma'}^t \qquad \forall s \in S, t \in T, \sigma \in \{1,2,3,4\}, (s',\sigma') \in I_{s,\sigma}, t' \in \{1,\ldots,t-1\} \tag{4.39}$$

$$\psi_{(s,\sigma),(s',\sigma')}^{t',t} \geq \rho_{s,\sigma}^t - (1-\tau_s^{t'}) \qquad \forall s \in S, t \in T, \sigma \in \{1,2,3,4\}, (s',\sigma') \in I_{s,\sigma}, t' \in \{1,\ldots,t-1\} \tag{4.40}$$

Using $\psi_{(s,\sigma),(s',\sigma')}^{t',t}$, 4.37 can now be reformulated as:

$$\begin{aligned}\rho_s^t \geq\, & \tau_s^t \cdot \mu_s + (1+w_s)\rho_s^{t-1} \\ & - (\sum_{t'=1}^{t-1} \tau_s^{t'})\frac{\mu_s}{D_s} + w_s \cdot \left(\sum_{\sigma\in\{1,2,3,4\}} \sum_{(s',\sigma')\in I_{s,\sigma}} \sum_{t'=1}^{t-1} \psi_{(s,\sigma),(s',\sigma')}^{t',t} \cdot \frac{v(\Omega_{ss'})}{v(\Omega_s)}\right) \qquad \forall s \in S, t \in \{2,\ldots,T\}\end{aligned} \tag{4.41}$$

Factor w_s

As can be seen from equation 4.41:

$$w_s \cdot (\rho_s^{t-1} + \left(\sum_{\sigma\in\{1,2,3,4\}} \sum_{(s',\sigma')\in I_{s,\sigma}} \sum_{t'=1}^{t-1} \psi_{(s,\sigma),(s',\sigma')}^{t',t} \cdot \frac{v(\Omega_{ss'})}{v(\Omega_s)}\right)) < \frac{\mu_s}{D_s} \qquad \forall s \in S \tag{4.42}$$

Otherwise, no reduction could take place. Note that $\rho_s^{t-1} + \left(\sum_{\sigma\in\{1,2,3,4\}} \sum_{(s',\sigma')\in I_{s,\sigma}} \sum_{t'=1}^{t-1} \psi_{(s,\sigma),(s',\sigma')}^{t',t} \cdot \frac{v(\Omega_{ss'})}{v(\Omega_s)}\right)) \leq 1$, and therefore:

$$w_s \leq \frac{\mu_s}{D_s} \qquad \forall s \in S \tag{4.43}$$

In chapter 1 it was mentioned how Thomas Jr et al., 1990 found that reduction from $19m^2$ to $10.4m^2$ in construction space per person led to an increase of 50% in man-hours. Because the number of persons working on a stand, and the stand size itself differs, this statement is generalised to a reduction of 50% of workspace leading to a 50% longer construction duration. The total workspace of a stand consists of its construction space ($|\Phi_s|$) and its aisle space ($|\Omega_s|$): $|\Phi_s| + |\Omega_s|$. The materials are only stored in the aisles, and therefore only affect $|\Omega_s|$. When $\rho_s^t = 1$, a stands workspace is reduced by a portion of $\frac{|\Omega_s|}{|\Omega_s|+|\Phi_s|}$. So when workspace is reduced by 50%, $\rho_s^t \cdot \frac{|\Omega_s|}{|\Omega_s|+|\Phi_s|} = 0.5$. Productivity should at the same time also be reduced by 50%, so $w_s \cdot (\rho_s^{t-1} + \left(\sum_{\sigma\in\{1,2,3,4\}} \sum_{(s',\sigma')\in I_{s,\sigma}} \sum_{t'=1}^{t-1} \psi_{(s,\sigma),(s',\sigma')}^{t',t} \cdot \frac{v(\Omega_{ss'})}{v(\Omega_s)}\right)) = 0.5 \cdot \frac{\mu_s}{D_s}$. The effect can be assumed to be linear, and therefore it can be concluded that:

$$w_s := \frac{|\Omega_s|}{|\Omega_s| + |\Phi_s|} \cdot \frac{\mu_s}{D_s} \tag{4.44}$$

4.5.2 Delay policy MILP

In this section, the full MILP for the delay policy will be presented. Changes to the no-delay policy are given in bold.

$$\text{Minimize } Z = \frac{\sum_{t\in T}\sum_{s\in S}\rho_s^t \cdot v(\Omega_s)}{(\sum_{s\in S} v(\Omega_s)) * T_{max}} \tag{4.45}$$

s.t.

$$\sum_{t=1}^{T_{max}-D_s} \tau_s^t = 1 \qquad \forall s \in S \tag{4.46}$$

$$\sum_{t=T_{max}-D_s+1}^{T_{max}} \tau_s^t = 0 \qquad \forall s \in S \tag{4.47}$$

$$\sum_{s\in S} \tau_s^t \leq \tau_{max} \qquad \forall t \in T \tag{4.48}$$

$$\rho_s^t = \sum_{\sigma\in\{1,2,3,4\}} \rho_{s,\sigma}^t \frac{v(\Omega_{s,\sigma})}{v(\Omega_s)} \qquad \forall s \in S, t \in T \tag{4.49}$$

$$\rho_{s,\sigma}^t + \rho_{s',\sigma'}^t \leq 1 \qquad \forall s \in S, \sigma \in \{1,2,3,4\}, (s',\sigma') \in I_{s,\sigma'}, t \in T \tag{4.50}$$

(4.51)

$$\rho_s^t \geq \tau_s^t \cdot \mu_s + (1+w_s)\rho_s^{t-1} - (\sum_{t'=1}^{t-1} \tau_s^{t'})\frac{\mu_s}{D_s} + w_s \cdot \left(\sum_{\sigma\in\{1,2,3,4\}} \sum_{(s',\sigma')\in I_{s,\sigma}} \sum_{t'=1}^{t-1} \psi_{(s,\sigma),(s',\sigma')}^{t',t} \cdot \frac{v(\Omega_{ss'})}{v(\Omega_s)} \right) \quad \forall s \in S, t \in \{2,\dots,T\} \tag{4.52}$$

$$\rho_s^1 = \tau_s^1 \cdot \mu_s \quad \forall s \in S \tag{4.53}$$

$$\rho_s^{T_{max}} = 0 \quad \forall s \in S \tag{4.54}$$

$$\psi_{(s,\sigma),(s',\sigma')}^{t',t} \leq \cdot \tau_s^{t'} \quad \forall s \in S, t \in T, \sigma \in \{1,2,3,4\}, (s',\sigma') \in I_{s,\sigma}, t' \in \{1,\dots,t-1\} \tag{4.55}$$

$$\psi_{(s,\sigma),(s',\sigma')}^{t',t} \leq \rho_{s',\sigma'}^t \quad \forall s \in S, t \in T, \sigma \in \{1,2,3,4\}, (s',\sigma') \in I_{s,\sigma}, t' \in \{1,\dots,t-1\} \tag{4.56}$$

$$\psi_{(s,\sigma),(s',\sigma')}^{t',t} \geq \rho_{ss'}^t - (1-\tau_s^{t'}) \quad \forall s \in S, t \in T, \sigma \in \{1,2,3,4\}, (s',\sigma') \in I_{s,\sigma}, t' \in \{1,\dots,t-1\} \tag{4.57}$$

$$\tau_s^t \in \{0,1\} \quad \forall s \in S, t \in T \tag{4.58}$$

$$\rho_{s,\sigma}^t, \psi_{s,\sigma}^{t,t'} \in [0,1] \quad \forall s \in S, \sigma \in \{1,2,3,4\}, t \in T \tag{4.59}$$

4.6 Accessibility policy

Lastly, constraints need to be added to the model, regarding the accessibility of stands at the start of construction. As mentioned before, materials can not be brought to stands that have become inaccessible due to the blockage of pathways. Therefore, the model should take into account that a path to the stands should be available at the start of their construction. This idea was already introduced by Chua et al. (2010), where the accessibility of work spaces and path flexibility was introduced. Here, this is further expanded upon by developing a graph for the accessibility and introducing constraints into the MILP model for maintaining an accessible path for the stands.

4.6.1 Yellow pathways

For safety reasons, trade fairs have pathways marked on the floor that serve as emergency paths. These should be kept clear of materials at all times during construction. At the RAI, these are called the yellow paths, and are marked with yellow tape. Because these paths are connected to the entrances, stands do not have to be accessible from the entrance specifically, but could also be accessible from the yellow path. An example of a yellow path can be found in figure 4.6.

4.6.2 Pathway graph

In order to find paths in the venue hall, the layout can first be analysed as a graph $G^t = (N^t, E)$, where N is the set of nodes, and E is the set of edges. In this graph, each

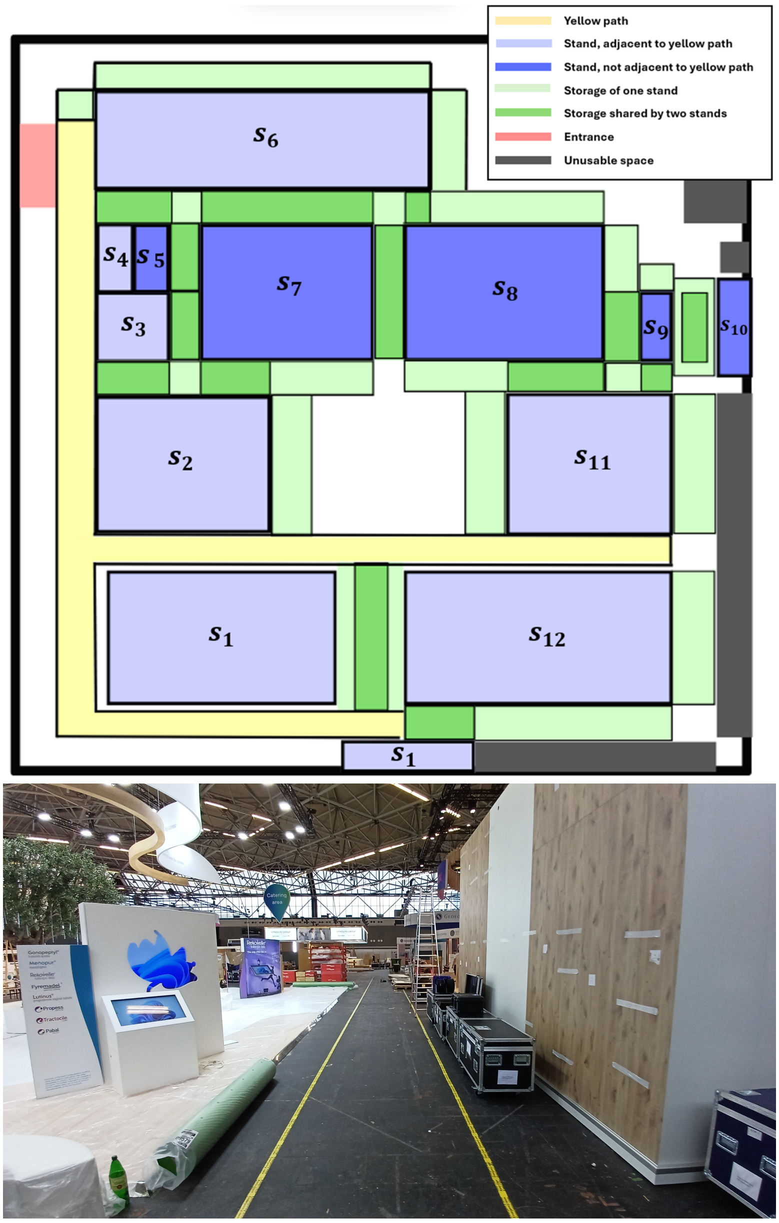

Figure 4.6: *Above: a floor plan of a hall, including the yellow paths. Below: a picture of the yellow path in practice, taken between stands s_1 and s_2. Source: author*

Figure 4.7: *A magnification of the upper left section of the floor plan from 4.6, including the nodes and their respective densities, and the edges (arcs) between them. Source: author*

pathway section is seen as a node. A node can therefore represent a storage area by one stand, two stands or no stands. Each has its own unique density $\rho^t_{s,\sigma}$, $\rho^t_{s,\sigma} + \rho^t_{s',\sigma'}$ or 0 respectively. Therefore, each node can be represented by the corresponding density:

$$N^t := \{0, \rho^t_{s,\sigma}, \rho^t_{s,\sigma} + \rho^t_{s',\sigma'} | \forall s \in S, \forall (s', \sigma') \in I_s, \sigma \in \{1, 2, 3, 4\}\} \tag{4.60}$$

Edges represent the adjacency of pathway sections. When two pathway sections are adjacent to each other, the corresponding nodes are connected with an edge:

$$\begin{aligned} E :=&\{(\rho^t_{s,\sigma}, \rho^t_{s,\sigma} + \rho^t_{s',\sigma'}), (\rho^t_{s,\sigma} + \rho^t_{s',\sigma'}, \rho^t_{s,\sigma} + \rho^t_{s'',\sigma''}), (\rho^t_{s,\sigma}, 0), (\rho^t_{s,\sigma} + \rho^t_{s',\sigma'}, 0) \\ &| \forall s \in S,\ \sigma \in \{1, 2, 3, 4\},\ (s', \sigma'), (s'', \sigma'') \in I_{s,\sigma}, \text{if sections are adjacent}\} \end{aligned} \tag{4.61}$$

In figure 4.7, a magnification of the floor plan of figure 4.6 is given, with the nodes and edges for that section.

4.6.3 Finding paths

Once graph G is created, paths can be sought from each stand. Let B_s be the set of nodes adjacent to stand s:

$$B_s := \{\rho^t_{s,\sigma}, \rho^t_{s,\sigma} + \rho^t_{s',\sigma'} | \forall \sigma \in \{1, 2, 3, 4\}, \forall (s', \sigma') \in I_{s,\sigma}\} \tag{4.62}$$

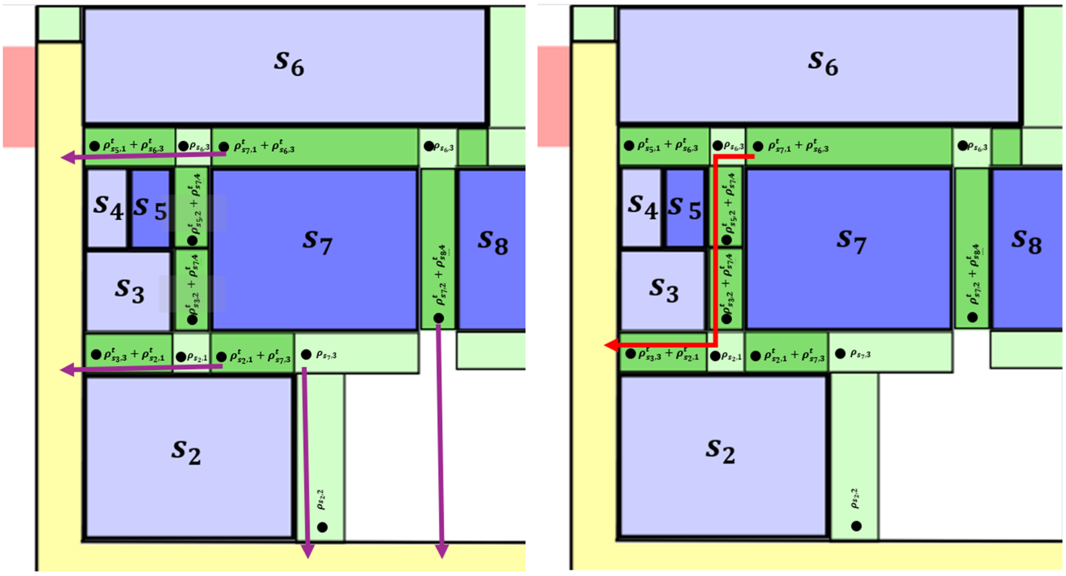

Figure 4.8: *Left: four paths from s_7 to the yellow path. Right: A path that's not considered due to taking turns. Source: author*

Let $\mathcal{Y}$ be the set of nodes adjacent to the yellow path. Then, a path from a stand to the yellow path can be defined as:

$$p_s^{t,k} := (\rho_0^t, \rho_1^t, \ldots, \rho_m^t), \text{ where each } \rho_i^t \in N, (\rho_i^t, \rho_{i+1}^t) \in E, \text{ and } \rho_0^t \in B_s, \rho_m^t \in \mathcal{Y} \quad (4.63)$$

Because of the high inconvenience of moving large materials around corners, standbuilders tend to only move materials in straight lines to the stands. Therefore, only straight paths are considered for stands. 4.8 shows the paths (not) considered for s_7 from figure 4.7.

Let K be the total number of paths from stand s to the yellow path, and let P_s^t be the set of these paths $p_s^{t,k}$:

$$P_s^t := \{p_s^{t,k} | k \in \{1, \ldots, K\}, s \in S\} \quad (4.64)$$

4.6.4 Accessibility constraints

If $\exists \rho_i^t \in N^t$ such that $\rho_i^t \in B_s \wedge \rho_i^t \in \mathcal{Y}$, then s is adjacent to a yellow path. Let S' be the set of stands that is adjacent to a yellow path:

$$S' := \{s \mid \exists \rho_i^t \in N, \text{ s.t. } \rho_i^t \in B_s \wedge \rho_i^t \in \mathcal{Y}, s \in S\} \quad (4.65)$$

And:

$$S'' := S \setminus S' \quad (4.66)$$

such that S'' is the set of stands that are not adjacent to a yellow path. Then stand $s' \in S'$ is accessible at all $t \in T$, while stand $s'' \in S''$ is accessible at time t when there exists a path $p_{s''}^k \in P_{s''}$ such that for all $\rho_{s''}^t \in p_{s''}^k$, the corresponding $\rho_{s'',\sigma''}^t$ or $\rho_{s'',\sigma''}^t + \rho_{s''',\sigma'''}^t$ is sufficiently low so that the path can be passed through.

For a safe and convenient pass through each aisle, it is estimated that 3/4th of the aisle should be passable, and materials should not be stacked higher than 1 meter. With a maximum height of $h = 2$ meters, material density should therefore not exceed 12.5%.

When converting this to a constraint, binary variable α_s^k is introduced. $\alpha_s^k = 1$ when path $p_s^{t,k}$ is accessible at time t, and 0 otherwise. Then, the following constraints need to be added to the model:

$$(1 - 0.875 \cdot \tau_s^t) \geq \rho_i \cdot \alpha_s^k \qquad \forall s \in S, t \in T, k \in \{1, \ldots, K\}, \rho_i \in p_s^{t,k} \tag{4.67}$$

$$\sum_{k \in K} \alpha_s^k \geq 1 \qquad \forall s \in S \tag{4.68}$$

$$\alpha_s^k \in \{0, 1\} \qquad \forall s \in S, k \in K \tag{4.69}$$

(4.70)

4.6.5 Full MILP

In this section, the full MILP model will be presented for the accessibility policy. Changes to the model will be given in bold.

$$\text{Minimize } Z = \frac{\sum_{t \in T} \sum_{s \in S} \rho_s^t \cdot v(\Omega_s)}{(\sum_{s \in S} v(\Omega_s)) * T_{max}} \tag{4.71}$$

s.t.

$$\sum_{t=1}^{T_{max}-D_s} \tau_s^t = 1 \qquad \forall s \in S \tag{4.72}$$

$$\sum_{t=T_{max}-D_s+1}^{T_{max}} \tau_s^t = 0 \qquad \forall s \in S \tag{4.73}$$

$$\sum_{s \in S} \tau_s^t \leq \tau_{max} \qquad \forall t \in T \tag{4.74}$$

$$\rho_s^t = \sum_{\sigma \in \{1,2,3,4\}} \rho_{s,\sigma}^t \frac{v(\Omega_{s,\sigma})}{v(\Omega_s)} \qquad \forall s \in S, t \in T \tag{4.75}$$

$$\rho_{s,\sigma}^t + \rho_{s',\sigma'}^t \leq 1 \qquad \forall s \in S, \sigma \in \{1,2,3,4\}, (s', \sigma') \in I_{s'}, t \in T \tag{4.76}$$

$$\rho_s^t \geq \tau_s^t \cdot \mu_s + (1 + w_s)\rho_s^{t-1} - (\sum_{t'=1}^{t-1} \tau_s^{t'}) \frac{\mu_s}{D_s}$$
$$+ w_s \cdot \left(\sum_{\sigma \in \{1,2,3,4\}} \sum_{(s',\sigma') \in I_{s,\sigma}} \sum_{t'=1}^{t-1} \psi_{(s,\sigma),(s',\sigma')}^{t',t} \cdot \frac{v(\Omega_{ss'})}{v(\Omega_s)} \right) \qquad \forall s \in S, t \in \{2, \ldots, T\} \tag{4.77}$$

$$\rho_s^1 = \tau_s^1 \cdot \mu_s \qquad \forall s \in S \tag{4.78}$$

$$\rho_s^{T_{max}} = 0 \qquad \forall s \in S \tag{4.79}$$

$$\psi_{(s,\sigma),(s',\sigma')}^{t',t} \leq \cdot \tau_s^{t'} \qquad \forall s \in S, t \in T, \sigma \in \{1,2,3,4\}, (s',\sigma') \in I_{s,\sigma}, t' \in \{1,\ldots,t-1\} \tag{4.80}$$

$$\psi_{(s,\sigma),(s',\sigma')}^{t',t} \leq \rho_{s',\sigma'}^t \qquad \forall s \in S, t \in T, \sigma \in \{1,2,3,4\}, (s',\sigma') \in I_{s,\sigma}, t' \in \{1,\ldots,t-1\} \tag{4.81}$$

$$\psi_{(s,\sigma),(s',\sigma')}^{t',t} \geq \rho_{ss'}^t - (1 - \tau_s^{t'}) \qquad \forall s \in S, t \in T, \sigma \in \{1,2,3,4\}, (s',\sigma') \in I_{s,\sigma}, t' \in \{1,\ldots,t-1\} \tag{4.82}$$

$$\boldsymbol{(1 - 0.875 \cdot \tau_s^t) \geq \rho_i^t \cdot \alpha_s^k} \qquad \boldsymbol{\forall s \in S, t \in T, k \in \{1,\ldots,K\}, \rho_i^t \in p_s^{t,k}} \tag{4.83}$$

$$\boldsymbol{\sum_{k \in K} \alpha_s^k \geq 1} \qquad \boldsymbol{\forall s \in S} \tag{4.84}$$

$$\boldsymbol{\alpha_s^k}, \tau_s^t \in \{0,1\} \qquad \forall s \in S, t \in T, k \in K \tag{4.85}$$

$$\rho_{s,0}^t, \rho_{s,s'}^t \in [0,1] \qquad \forall s \in S, s' \in I_s, t \in T \tag{4.86}$$

4.7 Verification and validation

Model verification was done by checking that each constraint in the model behaved correctly and consistently. This involved doing simple test cases with known solutions to confirm that the constraints produced the expected outputs, and temporarily isolating individual constraints to check if they functioned as intended, without interference from others. Also, a sensitivity analysis was done to check that the model was not overly sensitive to minor changes in the input parameters. More details on this can be found in 7.4.

To validate the model, first the progression of ρ_s^t in the model was compared to collected data (see 5.5 for more details). There it was found that the model was close to the real life data. The model was also run using a baseline scenario that closely mirrored real-world conditions, to ensure that its outputs matched actual results. This will be further discussed in chapter 7. Also, discussions and interviews with employees, as well as experiencing construction periods first hand, provided insight in the workings of trade fair constructions. This information helped establish a framework for defining the model's constraints.

4.8 Conclusion

The aim of this chapter was to answer the research question "*How can the scheduling problem be represented in a mathematical model?*". First, the layout of the venue was analysed in a 2D-grid, where the construction and storage spaces of the stands were defined. Then the first MILP policy was introduced as the no delay policy. Here, it was assumed that construction durations were not influenced by the amount of materials stored in a stand's surrounding storage spaces. The density of materials in the aisles was assumed to reduce linearly. This base model was then expanded upon in the delay policy, where a delay effect was introduced. Due to this delay, stands that are surrounded by more materials take longer to complete than stands without any materials. Lastly, the accessibility policy was introduced, where it was ensured that stands are accessible from the yellow path at the start of their construction.

5

Data Collection

5.1 Introduction

Now that the model is set in place, it is time to collect data for the input of the model. The model requires the following input:

1. Layout of the hall
2. Area of a stand
3. Construction duration of a stand
4. m^3 of materials put in aisles per stand.

Here, volume is considered rather than floor occupancy, because the height of the stacking of materials is also of importance. An aisle that is built up to two meters high creates more safety risks than an aisle that is occupied with low stacked materials.

Since the layout of the hall and the area of the stands are predetermined, only the construction duration and the volume of materials per stand need to be found. Finding this input for the model answers the fourth research question: *"How can the duration of construction and the volumes of materials per stand best be estimated?"*. In order to answer this, data was collected from a timelapse of a fair at RAI Amsterdam. During this fair, three halls were in use, with a total of 218 stands. 132 of these stands were UB or MSD stands, and were already constructed at the start of the regular construction days. These stands were left out of further consideration. Of the remaining 86 stands, 6 were omitted, because they were not constructed at all. 3 stands on the map were also left out of further consideration, because they were used for a seating area, an information desk and a brochure holder. This way, there remained 77 stands. There was one early buildup day, and three regular construction days, at which stands could be constructed between 8am and 10pm. Pictures were taken near the aisles of the remaining free build stands at the regular construction days, at 12 different time intervals (day 1: 12pm, 2pm, 4pm, 6pm. Day 2 and 3: 10 am, 1pm, 4pm and 7pm).

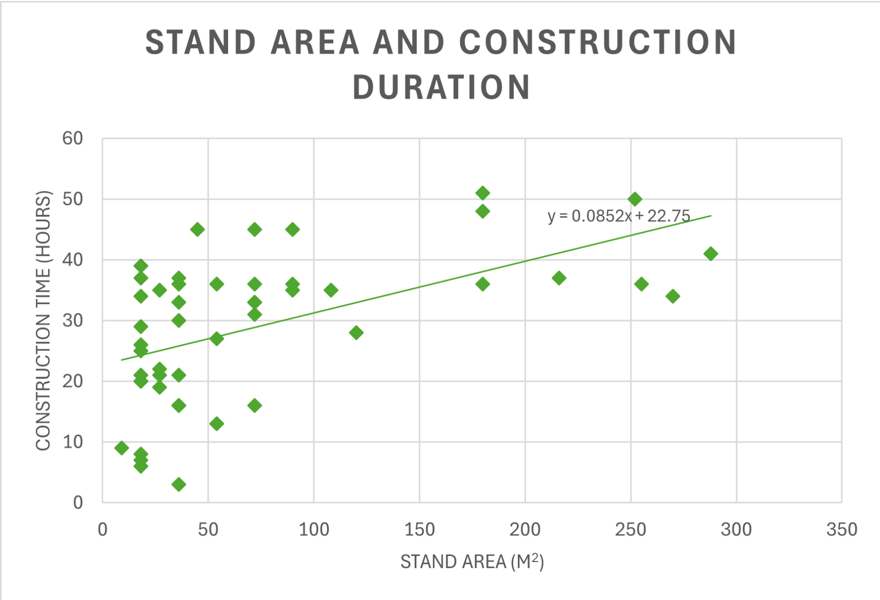

Figure 5.1: *Linear regression of stand area on construction time.* $R^2 = 0.273$, $F(1, 46) = 18.64$, $p < 0.001$. *Source: author.*

5.2 Construction duration

Based on these pictures, starting and finishing times of stands within these time intervals could be determined. For several stands, either the start time could not be verified, or they were build in multiple time sections with large breaks in between, or they were not well visible on the pictures. This led to another 29 stands being omitted.

From the remaining 48 stands, it could be shown that stand area is a significant predictor of construction duration (see figure 5.1) (slope $\beta_1 = 0.085$, $SE = 0.020$, $p = 0.00$; intercept $\beta_0 = 22.75$, $SE = 2.09$, p=0.00). The overall regression explains 27.3% of the variance in construction duration ($R^2 = 0.273$, $F(1, 46) = 18.64$, $p < 0.001$).

5.3 m^3 of materials

Another type of data that is needed for the model, is the amount of m^3 of materials stored in the aisles per stand. This is different from the total amount of m^3 used for construction, because materials are also stored and used on the stand itself. Therefore, search methods for total amounts of m^3 per stand, such as using data made available by standbuilders, or making estimations based on delivering trucks' sizes and fill percentages, can not be used.

Instead, the pictures of the timelapse were used for estimating the amount of m^3 of materials in the aisles. For each stand, the adjacent aisles were analysed per time interval. An estimation was made on the percentage of floor space occupied by materials, and the average height. An example of this can be found in figure 5.2.

Once this is done for all sides and per time interval, the amount of materials can be estimated per time interval. By choosing the maximum over all time intervals, the

Figure 5.2: *Aisle at 4pm, day 2. The stand on the right filled the aisle for 30% (materials on the left belong to the other stand), with an average of 0.5m height. The aisle is 15m long, resulting in 6.75 m^3 of materials on this side. Source: author.*

maximum amount of m^3 in the aisles can be found per stand.

This calculation was done for 24 stands. Stands were not included, because there was a lack of usable pictures on their adjacent aisles, or there was too much uncertainty about materials belonging to one stand or the other. This was mainly due to aisles becoming too clogged to pass through, making it impossible to take pictures at certain locations in the hall. Other reasons were pictures being taken from too far away, visibility on pictures being low due to obstruction by materials, or pictures being taken from the wrong angle.

In figure 5.3, a scatter plot and trendline can be found for the stand area and m^3 of materials for the remaining stands. Stand area proved to be a significant predictor of construction materials in the aisles (slope $\beta_1 = 0.20$, $SE = 0.026$, $p = 0.00$; intercept $\beta_0 = 7.14$, $SE = 3.06$, $p = 0.03$). The regression explained 73% of the variance in the materials in the aisles ($R^2 = 0.733$, $F(1, 23) = 60.4$, $p < 0.001$). Assuming stand areas to be square and accessible from all four sides, it means that the densities at the start of construction will range between 12% and 18% for all stands.

5.4 Delay effects

As mentioned in section 4.5, the model considers a delay factor in construction. In order to find the size of these delay effects according to the model, some calculations need to be made. The construction finish times that were found from the timelapse, are the actual finishing times, that were impacted by the delays due to the limited workspace. The actual construction duration therefore does not represent the construction duration in an ideal scenario, where no aisles are filled.

Therefore, in order to find the initial construction durations, the following was done: first, the total amount of materials around the stands (so both their own and materials from others) at each time interval were calculated. Using the amount of materials stored in the aisles by a stand, and the stands starting time, the decrease in density was

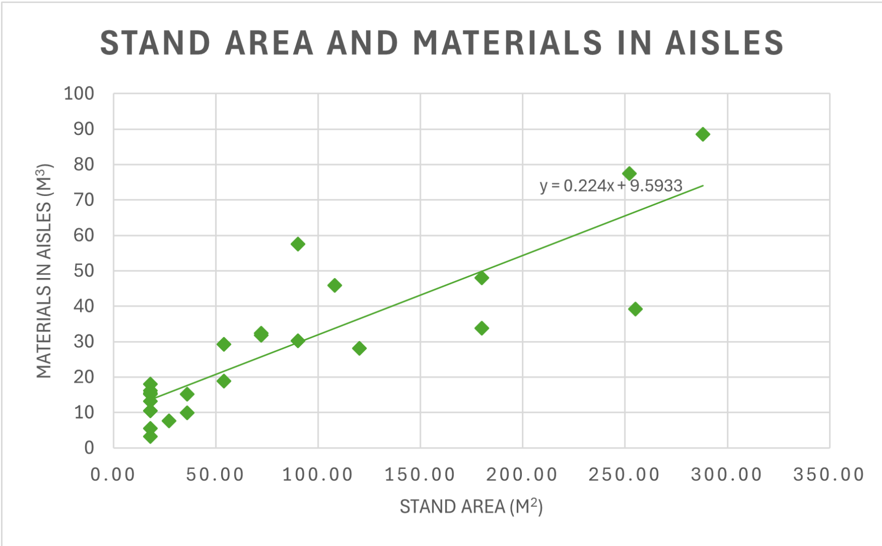

Figure 5.3: *Linear regression of stand area on materials in the aisles.* $R^2 = 0.733$, $F(1, 23) = 60.4$, $p < 0.001$. *Source: author.*

simulated, using the total amount of materials in the aisles for the delay factor. This way, the model's progression of a stands material density is similar to how it is calculated in the MILP model. Using different D_s values, the progression of a stand's ρ_s^t changes for each D_s. For small D_s, ρ_s^t quickly reaches 0, and for high D_s, ρ_s^t is not 0 by the time the stand finishes construction. The highest D_s value for which $\rho_s^t = 0$ at the construction finish time, is the best estimation for the optimal construction duration. At this D_s, the model reaches 0 at the measured finish time, while taking the delays into account.

5.4.1 Example

In this section an example of this calculation is explained. In table 5.1, the results of the density caused by the stands own materials, the total density (also caused by materials of other stands) and the volume of materials from the stand are given. The start and finish time of this stand were 10am on day 1 and 6pm on day 3. Its measured construction duration is therefore 34 hours (14 work hours per day).

In table 5.2, the progression of ρ_s^t is calculated for $D_s = 33$. The measured total density indicates the density that is used in combination with the delay factor to calculate the delay, while the measured own density is used as a reference for the calculated ρ_s^t. The column on the right indicates the error between ρ_s^t and the measured density. Cells in yellow indicate the times at which the density was measured. Because the intervals between measurements are irregular, the values in the inbetween are interpolated and included.

Here it was found that the stand's construction time without delays, D_s, should be 33, while the measured construction duration was 35. This means that there was possibly a delay of 2 hours.

Table 5.1: *Example of the measured material density around a stand, and its material volume. Source: author.*

Hour:	12pm day 1	2pm day 1	4pm day 1	6pm day 1	10am day 2	1pm day 2	4pm day 2	7pm day 2	10am day 3	1pm day 3	4pm day 3	7pm day 3
Own density	0.29	0.25	0.24	0.24	0.23	0.14	0.14	0.14	0.083	0.06	0.023	0
Total density	0.41	0.38	0.28	0.26	0.25	0.14	0.14	0.14	0.083	0.06	0.023	0
Volume materials own stand	15.48	13.68	12.96	12.96	12.6	7.56	7.56	7.56	4.5	3.24	1.26	0

Table 5.2: *Progression of ρ_s^t for $D_s = 33$, and the difference between the calculated density (ρ_s^t) and the measured density. Cells in yellow indicate the moments where the density was measured. At other cells, density was interpolated. Source: author.*

Day	**Hour**	**Volume of materials (m^3)**	**Calculated ρ_s^t**	**Measured total density**	**Measured own density**	**Difference between calculated and measured density**
Day 1	10am	15	0.29			0
	11am		0.28			0
	12pm		0.27	0.41	0.29	-0.017
	1pm		0.26	0.40	0.27	-0.0085
	2pm		0.25	0.38	0.25	-0.00013
	3pm		0.24	0.33	0.25	-0.0018
	4pm		0.24	0.28	0.24	-0.0035
	5pm		0.23	0.27	0.24	-0.012
	6pm		0.22	0.26	0.24	-0.020
	7pm		0.21	0.26	0.24	-0.028
	8pm		0.20	0.26	0.24	-0.035
	9pm		0.19	0.26	0.24	-0.042
Day 2	8am		0.19	0.26	0.24	-0.049
	9am		0.18	0.25	0.23	-0.057
	10am		0.17	0.25	0.23	-0.064
	11am		0.16	0.22	0.20	-0.041
	12pm		0.15	0.18	0.17	-0.019
	1pm		0.14	0.14	0.14	0.0038
	2pm		0.14	0.14	0.14	-0.0048
	3pm		0.13	0.14	0.14	-0.013
	4pm		0.12	0.14	0.14	-0.022
	5pm		0.11	0.14	0.14	-0.030
	6pm		0.10	0.14	0.14	-0.039
	7pm		0.093	0.14	0.14	-0.047
	8pm		0.084	0.13	0.13	-0.045
	9pm		0.075	0.12	0.12	-0.042
Day 3	8am		0.067	0.11	0.11	-0.039
	9am		0.058	0.095	0.095	-0.036
	10am		0.050	0.083	0.083	-0.034
	11am		0.041	0.076	0.076	-0.035
	12pm		0.032	0.068	0.068	-0.035
	1pm		0.024	0.060	0.060	-0.036
	2pm		0.015	0.048	0.048	-0.033
	3pm		0.0066	0.036	0.036	-0.029
	4pm		0	0.023	0.023	0

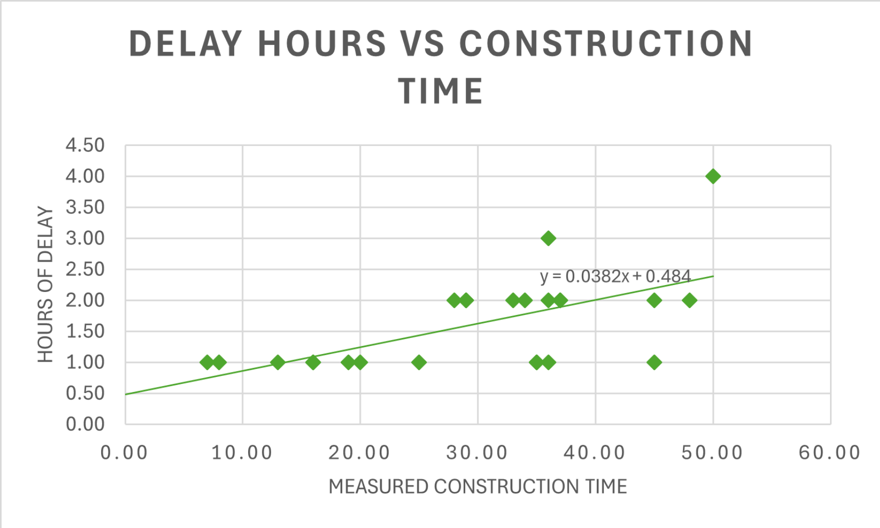

Figure 5.4: *Delay hours (measured construction duration minus ideal construction duration (D_S)) found, set off against measured construction duration. Source: author.*

5.4.2 Results

The differences found between D_s, a stand's construction time without delays, and its actual construction time (including delays) are displayed in figure 5.4. With this data, measured construction duration proved to not be a significant indicator of the delay ($R^2 = 0.14$, $F(1, 22) = 3.47$, $p = 0.076$). However, a p-value of 0.076 does suggest that there might be a relationship. Judging from the results, delays of more than one hour only occur when construction duration is longer than 25 hours.

5.5 Model performance evaluation through error metrics and explanatory power

By looking at the progressions of the ρ_s^t, and the corresponding D_s's, the differences between the calculated and measured densities can be established. By using the Mean Average Error (MAE), Root Mean Square Error (RMSE) and R^2, information is obtained about the fit of the model on the data. Boxplots of the found MAE's, RMSE's and R^2's can be found in figure 5.5. As can be seen from this figure, the MAE and RMSE are low on average. The median values are 0.035 and 0.039 respectively, with the first quartile being 0.020 and 0.027 and the third quartile 0.057 and 0.064 respectively. At the same time, the explanatory power of the model is high: the median R^2 value is 0.84, with the first quartile on 0.76 and the third quartile on 0.92. These low errors and high explanatory values validate the model.

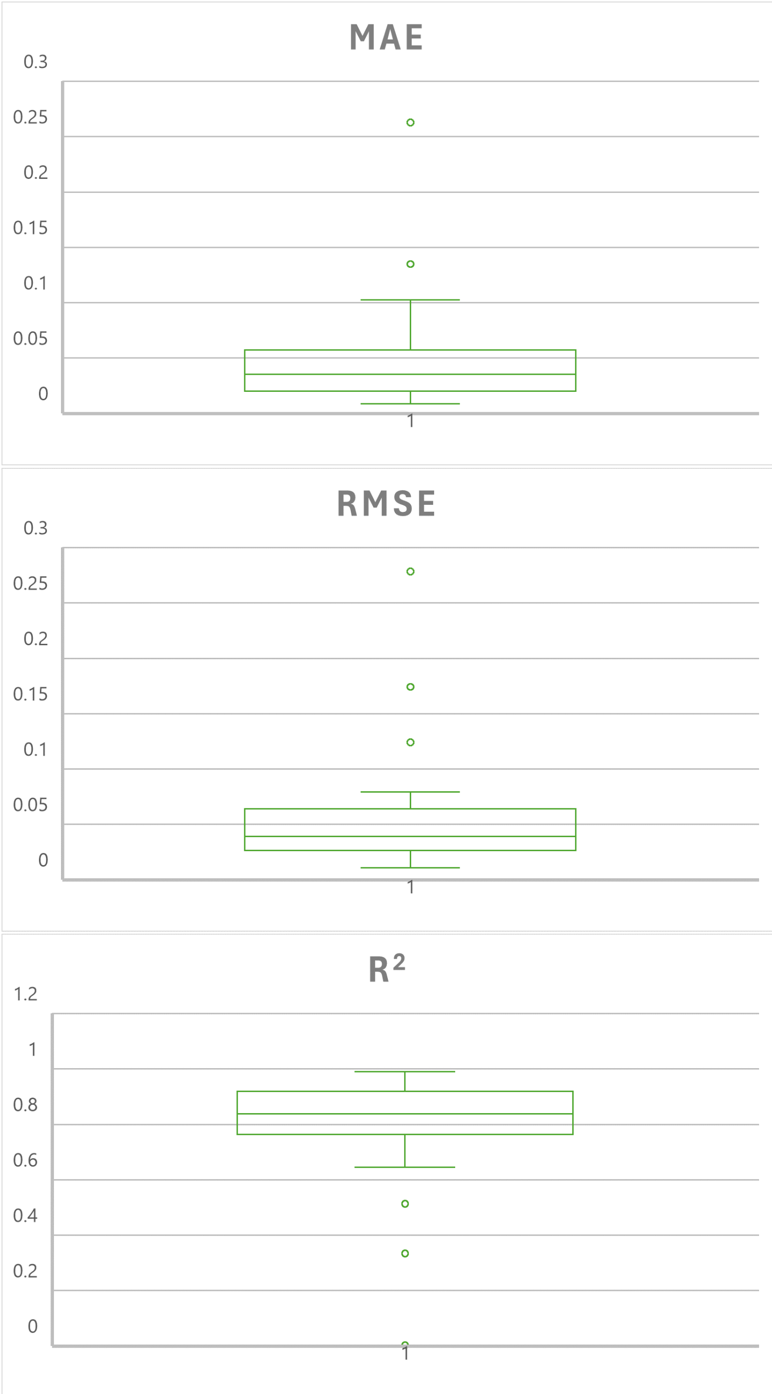

Figure 5.5: *Boxplots of the MAE, RMSE and R^2 for the calculated and measured density. Source: author.*

5.6 Conclusion

The aim of this chapter was to answer the research question *"How can the duration of construction and the volumes of materials per stand best be estimated?"*. This question was answered by using a timelapse of the construction of a fair at RAI Amsterdam, from which data regarding the construction duration and material volumes could be obtained. It was found that the area of a stand was a good predictor of the construction duration (slope $\beta_1 = 0.085$, $SE = 0.020$, $p < 0.001$; intercept $\beta_0 = 22.75$, $SE = 2.09$, $p<0.001$; $R^2 = 0.273$, $F(1, 46) = 18.64$, $p < 0.001$). and material volume (slope $\beta_1 = 0.20$, $SE = 0.026$, $p < 0.001$; intercept $\beta_0 = 7.14$, $SE = 3.06$, $p = 0.03$; $R^2 = 0.733$, $F(1, 23) = 60.4$, $p < 0.001$).

Also the impact of the delay effect on construction duration was researched. Here, construction duration proved not to be a significant indicator of the delay (R^2= 0.14, F(1, 22) = 3.47, $p = 0.076$). The delay effects were also proven to be small.

When corrected for the delay effects, the values of D_s could be estimated per stand. These values could then be used to find the progression of ρ_s^t according to the MILP model. Comparing these to the measured results from the timelapse, showed that the model had very low error values and a high explanatory power. This therefore helped to validate the model.

6

Simulation runs and analysis

6.1 Introduction

Now that the model is created and parameters are found, the model can be tested on several simulation runs to see what potential improvements can be obtained by implementing the schedule proposed by the model. The aim of this chapter is to answer the following two research questions: "*How does the performance of the scheduling model vary under different input conditions?*" and "*What strategies does the scheduling model apply under different input conditions?*".

First, the simulation run inputs are discussed in section 6.2. Each run will vary with regards to the layout, the density and the size of the stands, the number of stands that can start simultaneously and the maximum available construction time. Then, the results of this will be presented in section 6.3, in which the computational performances, as well as scores on multiple KPIs and scheduling strategies will be discussed. After this, the conclusions and managerial implications will be given in section 6.4.

6.2 Simulation runs

The variables that will be altered in these simulation runs can be categorized as scenario and configuration variables. Scenario variables describe external factors or constraints that are imposed by the environment or the situation that the system must adapt to or work with. Configuration variables are internal decision parameters that are under control of the problem owner. The variables per category are as follows:

Scenario variables:

- **Layout**: This is the floorplan of the stands in the venue. There are three types of layouts used, as shown in figure 6.1:

Type A shows a layout in which stands are located as islands in the hall. The yellow path is shaped as an L throughout the hall.

Type B shows a corridor layout, in which the stands are placed adjacent to each other. The yellow path is placed on the left. Stands have less space to place their

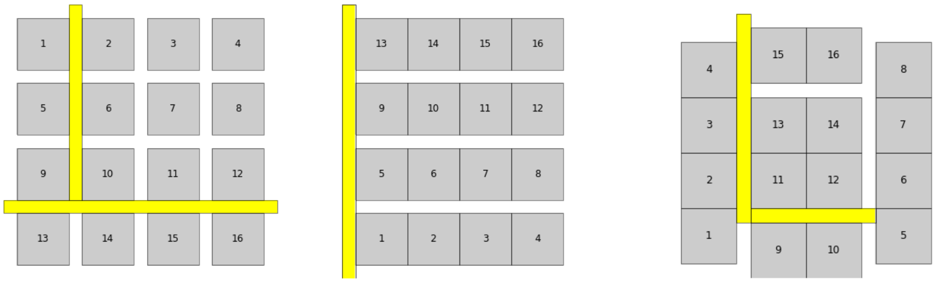

Figure 6.1: *Layout types. Left: Type A. Middle: Type B. Right: Type C*

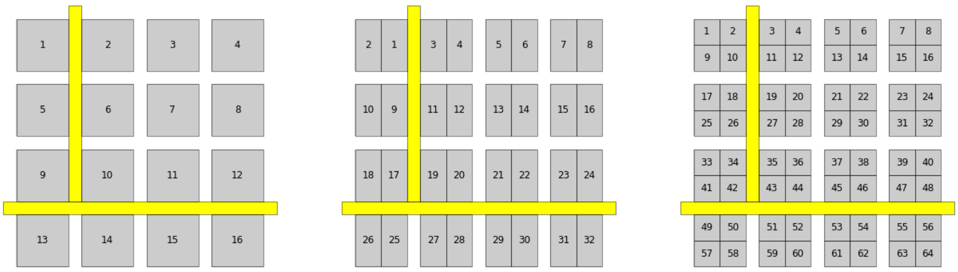

Figure 6.2: *Different densities and stand sizes for layout type A. Left: 16 large sizes stands. Middle: 32 medium sized stands. Right: 64 small sized stands. Source: author.*

materials in the aisles, that are more likely to block access to other stands than in type A.

Type C shows a combination of the two, with an island in the middle, and forming corridors on the sides. The yellow path is again L-shaped.

- **Density and stand size**: There are three levels of density and stand sizes used. In the first, 16 large stands (12×12 meters) are placed in the hall. The second contains 32 medium sized stands, half the size of the large stands (6×12 meters). And lastly, the third contains 64 small sized stands (6×6 meters). See figure 6.2 for these densities and sizes, applied to layout type A. The layouts with different stand sizes for type B and C can be found in appendix C

Configuration variables:

- τ_{max}: This indicates the number of stands that can start simultaneously. There are two τ_{max} values used: 4 and 7. 4 is the value currently found in practice. 7 was used as well in order to see the effects of increasing this capacity, and to determine whether investing in expansion would be beneficial for the venue.
- T_{max}: This is the maximum available construction time. This is varied between 36 hours (2.5 construction days), 42 hours (3 construction days) and 56 hours (4 construction days).

For the simulation runs, a full factorial design is employed, meaning that each of the layouts, densities, τ_{max} values and T_{max} are combined with each other, resulting in 54 different simulation runs. Each simulation run is numbered as displayed in table 6.1. Due to the full factorial design, no interactions or variable effects are overlooked. Therefore, a complete picture can be created of how the inputs influence the computational performance and the KPI scores. However, some combinations resulted in infeasible models. The effects of this on the KPI analysis will be discussed in section 6.3.4.

Table 6.1: *Numbering of simulation runs and computational performances. Source: author.*

Layout	Stand size	τ_{max}	T_{max}	simulation run number	Objective Value	Best Bound	Optimality Gap	Runtime (s)	Nodes Explored	Iterations
Type A	Large	4	36	1	Model Infeasible					
			42	2	0.0792	0.0783	0.0119	1.8	1	2456
			56	3	0.0592	0.0563	0.0498	28.7	1	13672
		7	36	4	Model Infeasible					
			42	5	0.0792	0.0781	0.0136	1.7	1	2192
			56	6	0.0593	0.0563	0.0499	12.9	1	7006
	Medium	4	36	7	Model Infeasible					
			42	8	0.0812	0.0791	0.0259	138.1	867	98914
			56	9	0.0605	0.0575	0.0500	411.2	1365	102427
		7	36	10	0.0947	0.0939	0.0086	31.9	452	35919
			42	11	0.0811	0.0773	0.0470	3.8	1	4954
			56	12	0.0605	0.0579	0.0432	251.9	1445	64834
	Small	4	36	13	Model Infeasible					
			42	14	No feasible solution found			2700	933	151562
			56	15	0.0728	0.0692	0.049	2214	2335	332462
		7	36	16	0.115	0.112	0.020	239	156	155989
			42	17	0.098	0.094	0.043	192.0	132	96874
			56	18	0.0733	0.0699	0.046	683.3	2746	179399
Type B	Large	4	36	19	Model Infeasible					
			42	20	0.110	0.109	0.014	0.9	1	3531
			56	21	0.082	0.079	0.045	68.6	783	48509
		7	36	22	Model Infeasible					
			42	23	0.110	0.109	0.017	0.9	1	2891
			56	24	0.082	0.079	0.036	55.5	761	37369
	Medium	4	36	25	Model Infeasible					
			42	26	0.114	0.109	0.038	3.6	1	3895
			56	27	0.085	0.081	0.049	41.6	1	33040
		7	36	28	0.132	0.130	0.015	2.0	1	6114
			42	29	0.114	0.109	0.045	2.6	1	3600
			56	30	0.084	0.081	0.046	45.0	1	30111
	Small	4	36	31	Model Infeasible					
			42	32	0.110	0.109	0.0145	0.9	1	3531
			56	33	0.0824	0.0787	0.0449	69	783	48509
		7	36	34	0.166	0.165	0.006	563.6	268	409803
			42	35	0.143	0.140	0.015	172.0	1	98717
			56	36	0.0823	0.0794	0.0365	55	761	37369
Type C	Large	4	36	37	Model Infeasible					
			42	38	0.137	0.136	0.011	0.6	1	1982
			56	39	0.103	0.098	0.048	5.1	1	4175
		7	36	40	Model Infeasible					
			42	41	0.137	0.136	0.011	0.6	1	1542
			56	42	0.103	0.098	0.048	4.7	1	3505
	Medium	4	36	43	Model Infeasible					
			42	44	0.117	0.115	0.023	11.4	1	11093
			56	45	0.087	0.083	0.050	436.4	884	106037
		7	36	46	Model Infeasible					
			42	47	0.117	0.112	0.042	2.4	1	3017
			56	48	0.087	0.083	0.049	261.6	757	56561
	Small	4	36	49	Model Infeasible					
			42	50	Model Infeasible					
			56	51	0.097	0.092	0.050	90.1	1	31908
		7	36	52	Model Infeasible					
			42	53	0.131	0.130	0.008	35.5	146	32747
			56	54	0.097	0.092	0.050	127.4	1	27111

6.3 Results

The model was run using Gurobi (a commercial solver) in python, on a HP Laptop 15-bs0xx, with 2.50 GHz Intel-Core i5 processor and 16GB RAM. The computational performance of the simulation runs will be discussed in section 6.3.1, after which the visualizations of the schedules will be introduced in section 6.3.2. Then, the KPIs and corresponding scores will be explained in sections 6.3.3 and 6.3.4, followed by a discussion of the applied scheduling strategies in 6.3.5.

6.3.1 Computational performances

The objective value, best bound, optimality gap, runtime (s), nodes explored and number of iterations for each simulation run give an indication of the computational performance of the model on each simulation run. These resulting scores can be found in table 6.1.

- **Objective value** The objective value gives the value of the objective function at the optimal solution. For each simulation run, the objective value ranges between 0.0592 and 0.166, meaning that on average between 5.9% and 16.6% of the aisles are filled with materials. Some simulation runs resulted in "Model Infeasible", meaning that the combination of input variables are unsolvable. These infeasible models are only found using $T_{max} = 36$ and occur more frequently when combined with large stands and $\tau = 4$. The infeasibility of these runs will be further discussed in section 6.3.4
- **Best bound** The best bound indicates the estimated value of the objective function at the best feasible solution. When the difference between the best bound and the optimal solution is small, the objective value is close to optimal. Here, the difference between the best bound and the objective value is the highest for simulation run 29, with a difference of 0.0052, which is an optimality gap of less than 5%. The average difference is 0.00303.
- **Optimality Gap** The optimality gap is the difference between the best bound and objective value, given as a percentage of the objective value. During the simulation runs, the acceptable optimality gap was set on 5 %, meaning that the model accepted a solution as optimal when the optimality gap van less than or equal to 5%. As can be seen from table 6.1, all feasible simulation runs have a gap of 0.05 or less.
- **Runtime (s)** The runtime indicates the time in seconds it took the model to find the solution. The runtime varies widely across simulation runs, with some solutions found in under a second while others take thousands of seconds or reach the maximum time limit without finding a solution. This is strongly correlated with the number of decision variables per simulation run, which are lowest for large stands, $T_{max} = 36$, and layout type B and C, and are highest for small stands, $T_{max} = 56$ and layout type A. This is in line with the expectation that solution time is highly sensitive to the number of decision variables.
- **Nodes Explored** The nodes explored refers to the number of nodes (subproblems) that were evaluated during the optimization process of the branch-and-bound algorithm. In simulation runs where solutions are feasible, the number of nodes explored and iterations varies widely, which again reflects the problem's complexity. High values in these columns suggest that the solver had to explore a large solution space.
- **Iterations** This indicates the number of iterations that the model went through

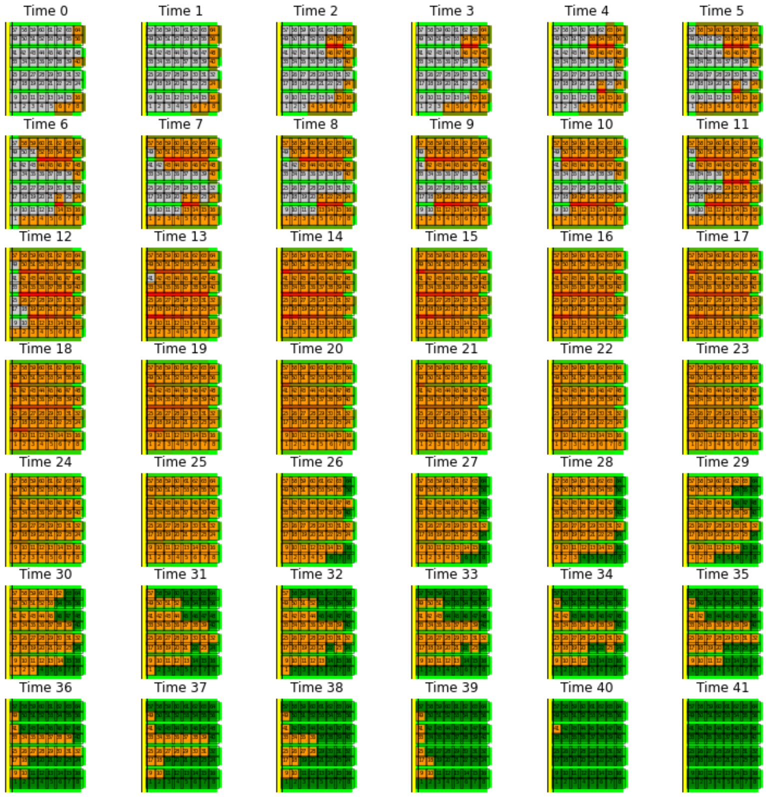

Figure 6.3: *Example of a visualization of a simulation run schedule. Displayed: simulation run 35 (Type B, Small sized stands, τ=7 and T_{max}=42). Source: author.*

before arriving at the solution. A higher number indicates a more complex problem. Some simulation runs required high iteration counts to reach a feasible solution. For instance, simulation run 18 has over 170,000 iterations and 683 seconds of runtime, indicating the solver needed to explore numerous possibilities before arriving at a feasible solution. The number of iterations is higher for simulation runs with more decision variables.

As was to expected, these results show that the computational performance depends strongly on the number of decision variables. When this number is high, the runtime and number of iterations increase significantly. For all except one simulation run, a feasible solution was found within 45 minutes, indicating that the model works fast for simulation runs up to 64 stands and $T_{max} = 56$. The performance under simulation runs with more decision variables were not tested.

6.3.2 Visualization of results

For each simulation run, an overview of the solution is created, where the construction process over time can be seen. An example of this can be seen in figure 6.3, for simulation run 35, where the layout of the hall can be seen for each time step. Stands are colored gray when they have not started construction yet, orange when they are under construction, and dark green when they have finished construction. The surrounding aisles are

Coloured on a scale from green (completely free of any materials) to red (completely filled). This way, the progress of construction and material density in the aisles can be made clear. This overview for each simulation run can be found in appendix D and is used to visualize the scheduling strategies of the model and the placement of materials in the hall.

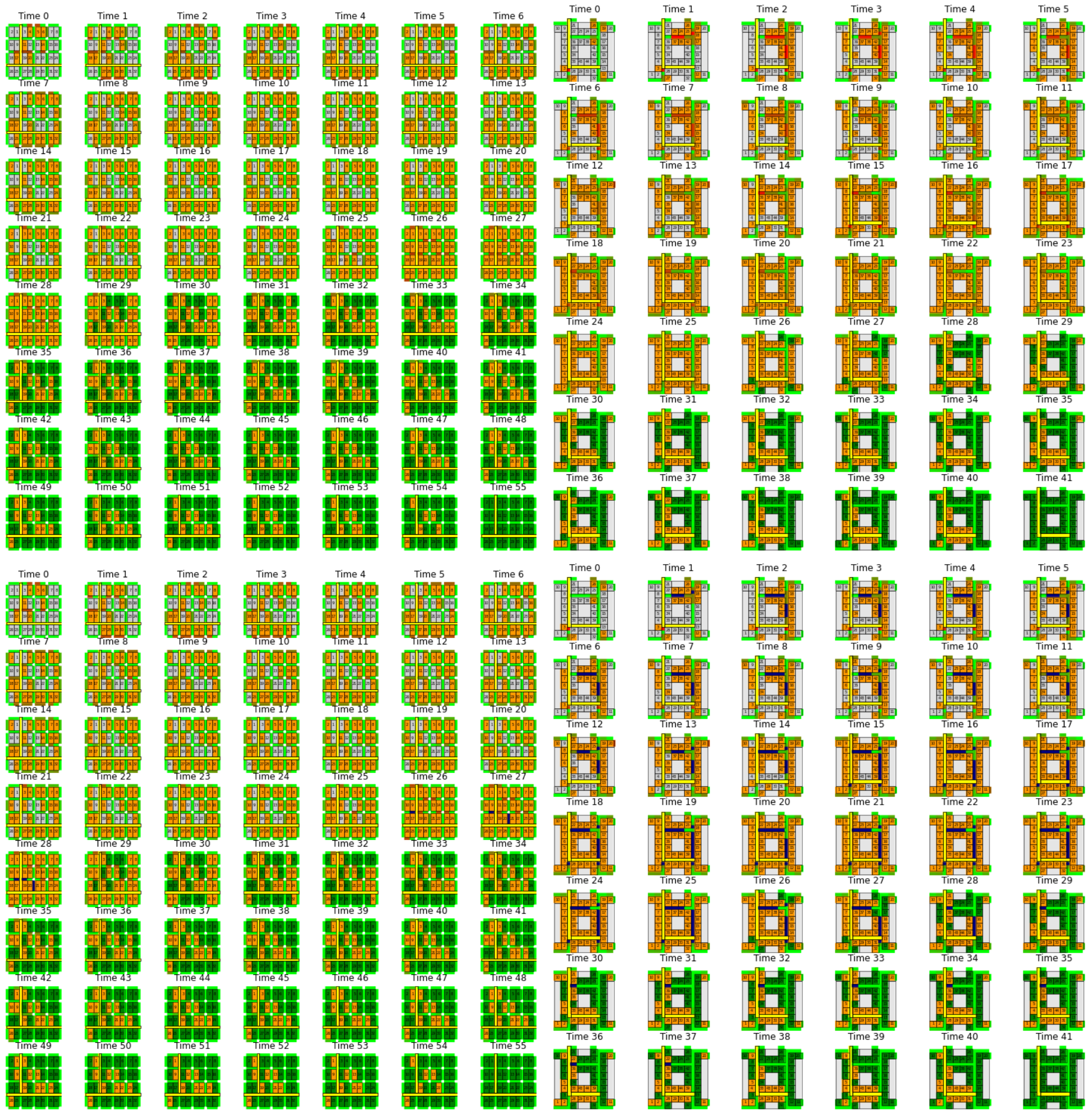

Figure 6.4: *Top: Construction overview of simulation run 12 (Type A, Medium size, τ=7 and T_{max}=56) (left) and 53 (Type C, Small size, τ=7, T_{max}=42) (right). Bottom: Construction overviews of simulation run 12 and 53, with interfering construction spaces indicated in blue. (Source: author)*

6.3.3 KPIs

The objective function for each simulation run minimizes the average density of all aisles over the full timespan. However, this is not the only performance indicator for the model. Other factors, such as the variance of the density over time, the number of interferences of stands' workspaces and the spatial spread of constructing stands also indicate the performance of the found solution. For example, a solution with a low variance in the overall material density in the hall indicates that the density remains almost unchanged over the timespan, while a high variance indicates large changes.

Simulation runs 12 (Type A, Medium size, τ=7 and T_{max}=56) and 53 (Type C, Small size, τ=7, T_{max}=42) will be used as examples to clarify and visualize the effects of each KPI. The visualizations of their schedules can be found in figure 6.4. For each KPI, the scores and the relevant data are visualized in figures 6.5, 6.6 and 6.7.

The following KPIs are used (in order of importance):

1. **Mean density:** This is the same as the objective value of the model, and is given by:

$$\frac{\sum_{s\in S}\sum_{t\in T}\rho_{s,t}\cdot v(\Omega_s)}{\sum_{s\in S}v(\Omega_s)\cdot T_{max}}$$

It indicates the average density of materials over the entire hall over all timesteps. A reduction can take place due to improved scheduling causing fewer delays. A low mean density however does not guarantee uniform density throughout the construction period: while the average congestion is reduced, there may still be moments of high density. In figure 6.5, the red line indicates the mean density. The lower mean density of simulation run 12 can also be seen in 6.4 by the aisles being more "green" on average, meaning fewer materials are stacked in the aisles overall.

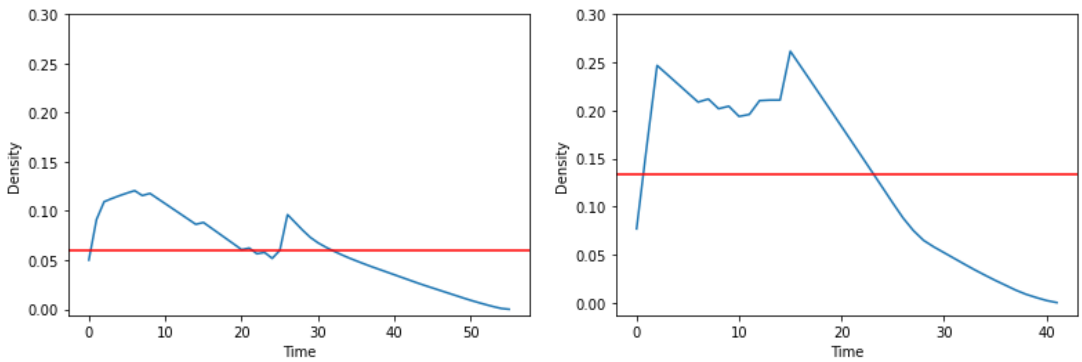

Figure 6.5: *Progression of average density of the entire hall per hour for simulation run 12 (Type A, Medium size, τ=7 and T_{max}=56) (left) and 53 (Type C, Small size, τ=7, T_{max}=42) (right). The red, horizontal line indicates the average. The mean densities are 0.061 (simulation run 12) and 0.131 (simulation run 53), and the variances in density are 0.001 (simulation run 12) and 0.007 (simulation run 53). (Source: author)*

2. **Variance of density:** This represents the spread of density across the timespan. It is calculated as:

$$(\frac{1}{T_{max}})\sum_{t'=1}^{T}\left((\sum_{s\in S}\rho_s^{t'}) - \frac{\sum_{s\in S}\sum_{t\in T}(\rho_s^t\cdot v(\Omega_s))}{\sum_{s\in S}v(\Omega_s)\cdot T_{max}}\right)^2$$

A low variance implies that materials are distributed more uniformly over the entire timespan, avoiding spikes or dips in storage density. The absence of peaks results in smoother workflows and improved accessibility of stands. In figure 6.5, it can be seen that the variance in density is lower for simulation run 12, and that the peaks in density remain closer to the average. In figure 6.4 the result of this can be seen, where the pathways in simulation run 12 remain accessible at nearly all timesteps, compared to strong blocks at time 2 in simulation run 53.

3. **(Average number of) interferences per stand:** The interferences indicate how many workspace interferences one stand experiences on average per hour, and is given by:

$$\frac{\sum_{s\in S,\sigma\in\{1,2,3,4\}}\sum_{(s',\sigma')\in I_{s,\sigma}}\kappa^t_{s,s',\sigma,\sigma'}}{|S|*T_{max}*2}$$

where:

$$\kappa^t_{s,s',\sigma,\sigma'} := \begin{cases}1 & \text{if } \rho^t_{s,\sigma}\cdot\rho^t_{s',\sigma'} > 0\\ 0 & \text{else}\end{cases}$$

The factor $\frac{1}{2}$ is introduced to make sure that interferences are not counted double. Reducing the number of simultaneous users of shared storage spaces and aisles minimizes the risk of accidents, miscommunications, or logistical challenges. It also functions as a measure of the spatial dispersion of constructing stands: when the number of interferences is high, it means that many neighboring stands are constructing simultaneously, while a low number indicates constructing stands are more spatially dispersed. See figure 6.6, where the number of interferences is lower for simulation run 12. The occurrences of these interferences and the larger spatial spread can also be seen in figure 6.4.

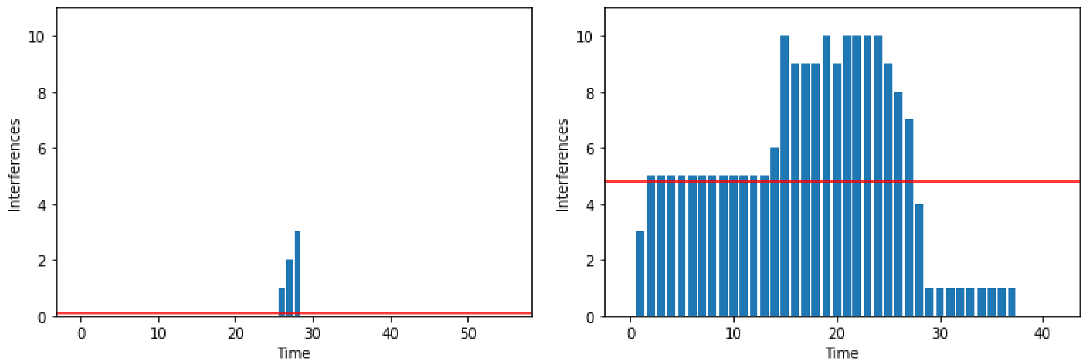

Figure 6.6: *Number of interferences for simulation run 12 (Type A, Medium size, τ=7 and T_{max}=56) (left) and 53 (Type C, Small size, τ=7, T_{max}=42) (right). The red, horizontal line indicates the average. When correcting for the number of stands, the average numbers of interferences per hour are 0.003 (simulation run 12) and 0.075 (simulation run 53). (Source: author)*

4. **Variance in starting time:** This indicates to what degree the starting times are spread over the entire timespan. The variance is given by:

$$\frac{1}{T_{max}}\sum_{t\in T}\left((\sum_{s\in S}\tau^t_s) - \frac{|S|}{T_{max}}\right)^2$$

A low variance indicates a large spread of start times. This creates more space and flexibility for trucks that are unloading at the venue. In figure 6.7, the number of stands starting per hour can be found. The variance is starting times is lower for simulation run 12, where there are less peaks in stands starting construction simultaneously.

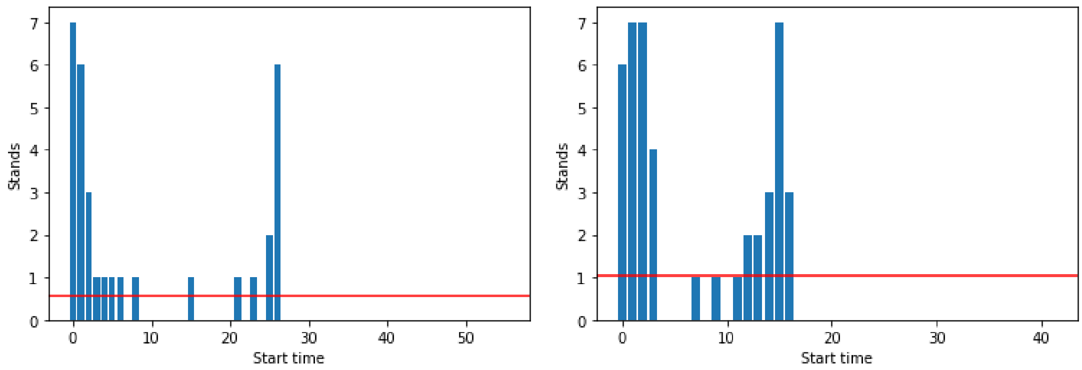

Figure 6.7: *The number of stands starting per hour for simulation run 12 (Type A, Medium size, τ=7 and T_{max}=56) (left) and 53 (Type C, Small size, τ=7, T_{max}=42) (right). The red, horizontal line indicates the average. The variances are 2.209 (simulation run 12) and 4.331 (simulation run 53). (Source: author)*

6.3.4 KPI analysis

In this section, the resulting scores of each simulation run on the KPIs will be discussed. The results can be found in table 6.2.

Simulation runs that were infeasible were left out of further analysis. Infeasibility mainly occurred when T_{max} was set to 36, which proved to be too constraining for the model to find a feasible schedule. All of the runs with large stands and $T_{max} = 36$ were infeasible, which was expected, since the large stands take 35 hours to complete. However, it was decided to keep the runs where the model was feasible under $T_{max} = 36$ in the analysis, since these show the model's behavior under more constrained conditions. They also provide insights in the strategies and the trade-offs that the model employs to achieve feasibility.

The exclusion of infeasible runs introduces minimal bias, since their infeasibility stems from overly restrictive time windows, which is an inherent aspect of the problem, and not randomness or model flaws. These cases belong to a distinct, unsolvable category, and their omission does not significantly affect the results of feasible simulations. Importantly it should be noted that the model's infeasibility does not imply that real-life construction is impossible, because adjustments such as allocating more workers, extending hours, or increasing flexibility could make it possible to still meet the construction deadline.

In order to assess the effect of each individual variable (layout, density and size, τ, and T_{max}) on the score, multiple linear regression is applied. Each KPI is modeled as a dependent variable, expressed as a function of the four independent variables:

$$Y = \beta_0 + \beta_{layout} X_{layout} + \beta_{size} X_{size} + \beta_\tau X_\tau + \beta_T X_T + \epsilon$$

Table 6.2: *KPIs for different simulation runs. Blanks indicate infeasible simulation runs, or simulation runs where no feasible solution was found. Source: author.*

Layout	**Stand size**	τ_{max}	T_{max}	**Simulation run number**	Density mean	Density variance	Interference	Variance starting time
Type A	Large	4	36	1				
			42	2	0.079	0.003	0.021	1.379
			56	3	0.059	0.001	0.008	0.883
		7	36	4				
			42	5	0.079	0.003	0.021	1.712
			56	6	0.059	0.002	0.006	0.740
	Medium	4	36	7				
			42	8	0.081	0.004	0.067	1.896
			56	9	0.061	0.001	0.006	1.566
		7	36	10	0.095	0.004	0.066	4.265
			42	11	0.081	0.004	0.024	4.324
			56	12	0.061	0.001	0.003	2.209
	Small	4	36	13				
			42	14				
			56	15	0.073	0.002	0.007	2.872
		7	36	16	0.115	0.006	0.149	8.673
			42	17	0.098	0.004	0.113	6.535
			56	18				
Type B	Large	4	36	19				
			42	20	0.110	0.006	0.003	0.776
			56	21	0.082	0.003	0.000	0.490
		7	36	22				
			42	23	0.114	0.006	0.018	1.204
			56	24	0.082	0.003	0.017	0.847
	Medium	4	36	25				
			42	26	0.114	0.006	0.182	2.324
			56	27	0.085	0.003	0.078	1.388
		7	36	28	0.132	0.007	0.194	4.765
			42	29	0.114	0.008	0.201	3.896
			56	30	0.084	0.002	0.046	2.566
	Small	4	36	31				
			42	32	0.110	0.010	0.204	3.773
			56	33				
		7	36	34	0.166	0.013	0.243	8.673
			42	35	0.143	0.010	0.208	6.964
			56	36	0.082	0.003	0.000	5.587
Type C	Large	4	36	37				
			42	38	0.137	0.009	0.000	1.379
			56	39	0.103	0.005	0.000	0.776
		7	36	40				
			42	41	0.137	0.008	0.000	1.998
			56	42	0.103	0.005	0.000	1.526
	Medium	4	36	43				
			42	44	0.117	0.007	0.016	1.943
			56	45	0.087	0.002	0.014	1.495
		7	36	46				
			42	47	0.117	0.006	0.013	4.324
			56	48	0.087	0.003	0.002	3.031
	Small	4	36	49				
			42	50				
			56	51	0.097	0.003	0.020	1.918
		7	36	52				
			42	53	0.131	0.007	0.075	4.331
			56	54	0.097	0.003	0.015	2.954

Here, $\beta_{layout}, \beta_{size}$ and β_τ are the regression coefficients, showing the effects of each variable. While T_{max} and τ are numeric discrete variables, size and type are ordinal and nominal categorical variables respectively. Therefore, dummy variables are introduced, that serve as indicators for each category. Using layout type C and stand size $Large$ as references, the dummy variables become X_A, X_B, X_{small}, X_{medium}, (where e.g. layout type A is indicated by $X_A = 1$, type B by $X_B = 1$ and C by $X_A = X_B = 0$). The function now becomes:

$$Y = \beta_0 + \beta_A X_A + \beta_B X_B + \beta_{small} X_{small} + \beta_{medium} X_{medium} + \beta_\tau X_\tau + \beta_T X_T + \epsilon$$

This can be solved using the Ordinary Least Squares method. The results can be found in table 6.3, with the overall statistics of the overall multilinear regression model in 6.4. All models are statistically significant (p-value = 0.000), indicating that the independent variables have a meaningful relationship with the dependent variable.

Table 6.3: *Multilinear regression results for different dependent variables. Source: author.*

Dependent Variable	Independent Variable	Coefficient	Standard Error	t-Statistic	p-Value
Mean Density	Constant	0.2275	0.014	16.448	0
	Type A	-0.0433	0.004	-10.756	0
	Type B	-0.0114	0.004	-2.888	0.007
	Tau	0	0.001	0.052	0.959
	Time	-0.0023	0	-10.809	0
	Size Small	0.0139	0.004	3.347	0.002
	Size Medium	-0.0037	0.004	-0.986	0.332
Density Variance	Constant	0.0187	0.002	9.611	0
	Type A	-0.0031	0.001	-5.517	0
	Type B	-0.0002	0.001	-0.298	0.768
	Tau	0	0	0.038	0.97
	Time	-0.0003	0	-8.932	0
	Size Small	0.0008	0.001	1.345	0.189
	Size Medium	-0.0007	0.001	-1.301	0.204
Interferences	Constant	1.6796	0.102	16.498	0
	Type A	0.2854	0.03	9.641	0
	Type B	0.2403	0.029	8.243	0
	Tau	-0.0028	0.008	-0.342	0.735
	Time	-0.0253	0.002	-16.097	0
	Size Small	-0.1402	0.031	-4.583	0
	Size Medium	-0.0935	0.028	-3.367	0.002
Starting Time Variance	Constant	3.1414	1.363	2.305	0.029
	Type A	0.4267	0.396	1.077	0.29
	Type B	0.4251	0.39	1.089	0.285
	Tau	0.4719	0.109	4.322	0
	Time	-0.0996	0.021	-4.733	0
	Size Small	3.5297	0.409	8.622	0
	Size Medium	1.4081	0.372	3.789	0.001

Table 6.4: *Overall statistics of the multilinear regression models*

Independent variable	R^2	Probability (F-statistic)	Log-Likelihood
Mean density	0.900	0.000	120.34
Density variance	0.817	0.000	190.91
Interferences	0.939	0.000	48.483
Starting time variances	0.846	0.000	-44.906

Concluding from table 6.3, the effects of the independent variables are as follows:

- **Layout:** Type A scores best on mean density and density variance, with an increase of -19.0% and -16.6% respectively compared to type B, and -5.0%, -1.1% compared to type C. On the other hand, type C scores best on interferences (-14.5% and -12.5% compared to type A and B respectively). For starting time variance, there is no significant difference between the three layouts. These effects found from the layout can be explained by the following:
  - Layout A (followed by layout B) has more space available per stand for the same amount of materials. This results in a lower mean density
  - These layouts have an increased space, providing more flexibility in the placement of materials. As a result, materials are distributed more evenly around the stand rather than concentrated in a single location, leading to a lower variance in density.
  - These layouts also present more sides that are susceptible to interferences with adjacent stands, leading to more interferences.
- **Size:** The medium and large stands score -5.76% lower on mean density than small stands, but no difference is found in density variance. Small stands score best on interferences (-8.38%), followed by medium sized stands (-5.57%). Large stands score best on starting time variance (-52.9% compared to small sized stands, and -31.0% compared to medium). The effects found on mean density and density variance can be explained as follows:
  - The mean density in a hall is lower when it contains larger stands than smaller ones, despite larger stands bring in more materials per stand, because smaller stands are greater in number, leading to a higher overall material density.
  - Fewer stands (as is the case with large sized stands) also allow for more uniformity in material storage density.
  - However, scheduling larger stands in a in a limited space without interfering workspaces is more challenging than for smaller stands, which results in more workspace interferences.
- **Tau:** The value of τ does not have a significant influence on the mean density, density variance and interferences. It does increase the starting time variance by 1.42 on average when increasing τ from 4 to 7. However, since it has no effect on the other three KPIs that are more important to the simulation run's performance,

it can be concluded that τ does not significantly impact the overall performance of a simulation run.

- **Time:** Additional available constructing time has been shown to significantly improve all four of the KPIs. The increases per additional hour per KPI are -1.0%, -1.6%, -1.5% and -3.2% respectively.

6.3.5 Strategy

In this section, the different scheduling strategies for the simulation runs will be explored. In Appendix D, visualizations of all schedules of the simulation runs can be found.

- **Layout:** From the solutions of the simulation runs, the following patterns in starting times were found (see figure 6.8):
  - Both layouts B and C incorporate corridor elements in their designs, and both prioritize starting construction with stands located at the back of the corridors. In layout B, construction progresses corridor by corridor, with one corridor starting after another. In layout C, construction begins with stands furthest from the yellow path and moves progressively closer. In both cases, start times are arranged to ensure accessibility is maintained throughout the process.
  - In contrast, layout type A has more open space between stands, resulting in stands at the back remaining accessible. This layout type therefore has the liberty to let stands close to the yellow path start early. It employs this strategy for large stands, while medium or small sized stands begin with construction furthest away from the yellow path.

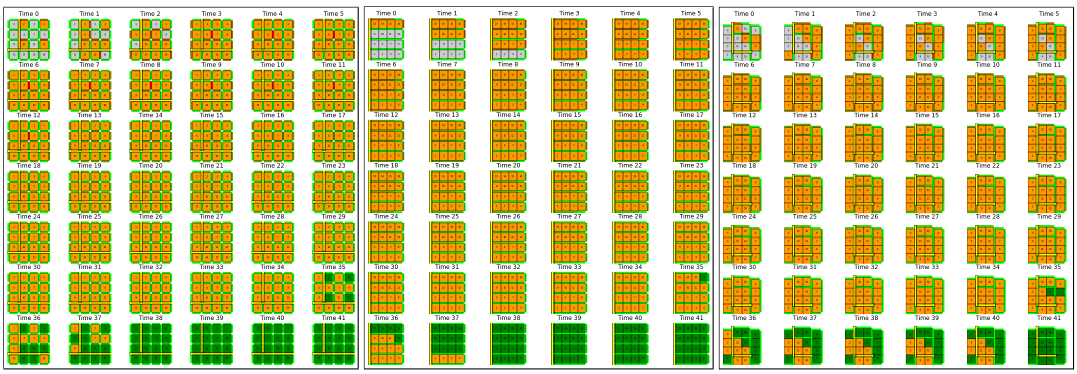

Figure 6.8: *Visualisations of simulation runs 2 (Layout type A) (left), 20 (layout type B) (middle) and 38 (layout type C) (right). Source: author*

- **Density and size:** The density or the size of the stands does not change the scheduling tactics significantly. Stands start constructing gradually over the first half of the timespan and are spatially apart. However, no structural scheduling differences between the different stand sizes (see figure 6.9).

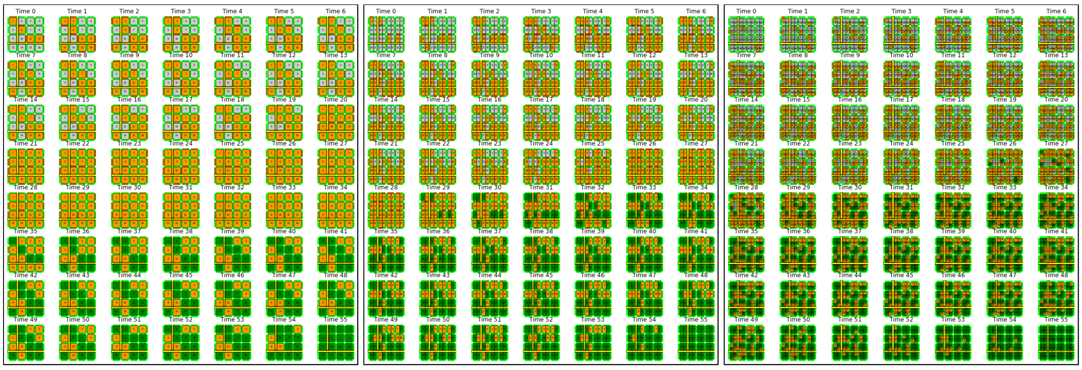

Figure 6.9: *Visualizations of simulation runs 3 (large) (left), 9 (medium) (middle) and 15 (small) (right). Source: author*

- τ_{max}: Despite τ_{max} not having an effect on the KPIs, it does change the strategy. In the first two to three construction hours, more stands would start constructing. After hour 4, little to no changes were found in starting order. An example of this effect can be seen in figure 6.10.

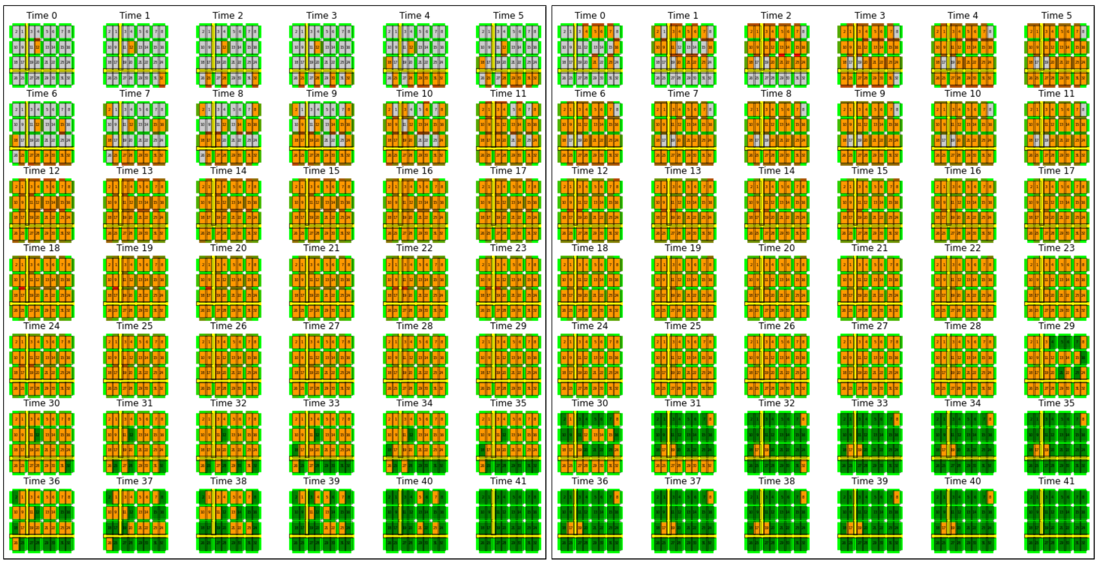

Figure 6.10: *Visualizations of simulation runs 8 (τ_{max} = 4) (left) and 11 (τ_{max} = 7) (right). Source: author.*

- T_{max}: The change from T_{max} = 36 to T_{max} = 42, as well as from T_{max} = 42 to T_{max} = 56, resulted in a bigger spread of starting times across the entire timespan. As a result, the higher T_{max}, the more the more the stands under construction are spatially spread as well. Examples of the effect of changing T_{max} can be seen in figure 6.11.

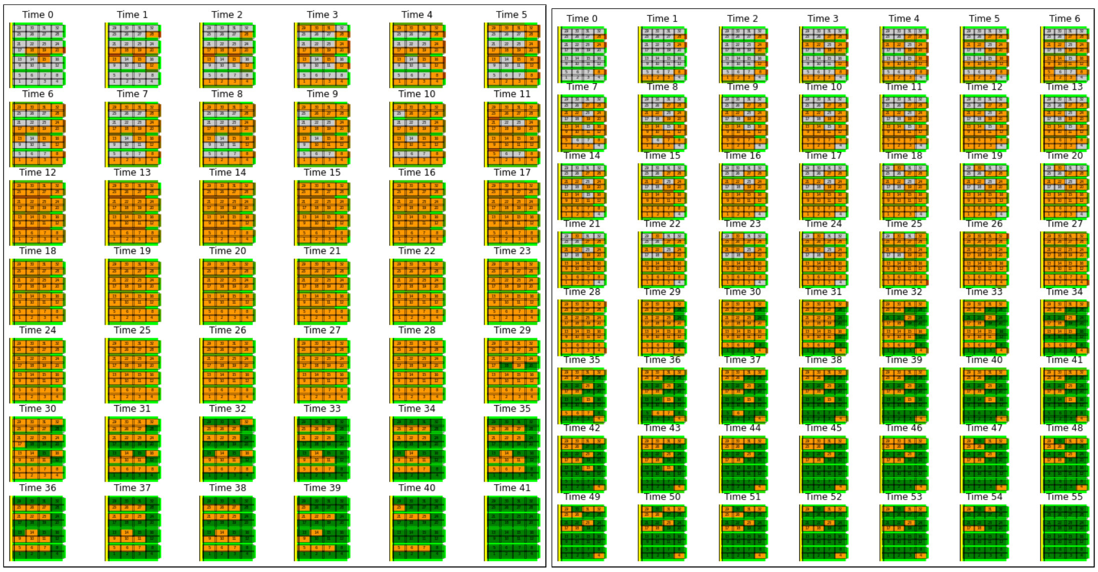

Figure 6.11: *Visualizations of simulation runs 26 (T_{max} = 42) (left) and 27 (T_{max} = 56) (right). Source: author.*

6.4 Conclusion and managerial implications

This chapter aimed to answer the research questions: *"How does the performance of the scheduling model vary under different input conditions?"*, and *"What strategies does the scheduling model apply under different input conditions?"*. 54 Simulation runs were created with different venue layouts, densities and stand sizes, τ_{max} values and different construction durations (T_{max}). Gurobi was used as a solver. It was found that a significant proportion of the simulation runs with T_{max} = 36 resulted in infeasible models, suggesting that this timespan, combined with the other input variables, limited the solution space too strongly. However, in case these simulation runs were to take place in real life, construction could still be feasible due to real world flexibilities that are not captured in the model.

For nearly all the remaining simulation runs a feasible solution was found within 45 minutes. Runtime varied across simulation runs, and was highly sensitive to the number of decision variables. A similar result was found for the number of nodes explored and iterations, showing that the computational performance decreases significantly with extra decision variables. The computational performances of more complex simulation runs were not tested.

The results of each simulation run were then analyzed using the following KPIs: mean density, variance of density, interferences and variance in starting time. By using the OLS method, the effects of each input variable on the KPIs could be determined. It was found that:

- Layout type A scored better on mean density and density variance, with an increase of -19.0% and -16.6% respectively compared to type B, and -5.0%, -1.1% compared to type C. This effect can be explained by layout type A having more

space available per stand, resulting in a lower mean density, and more flexibility in the placement of material, leading to a lower variance in density. This also leads to more possibilities for interferences. It was found that layout types B and C, with corridor elements in their designs, prioritize stands at the back of the corridor, and progressively move closer to the yellow path. A layout like type A with more open space between the stands lets large stands close to the yellow path start first, while medium or small sized stands begin furthest away from the yellow path.
- The effects of stand sizes were mixed. While medium and large stands score best on mean density (-5.76% compared to small stands), small and medium stands scored better on interferences (-8.38% and -5.57% respectively). These effects can be attributed to fewer large stands bringing fewer materials than more smaller stands. Fewer stands also allow for a more uniform material storage distribution. However, the larger size of the stands also creates more interferences. Density and size appeared to not significantly change starting tactics.
- τ_{max} had no significant influence on any KPI other than starting time variance. Since this is the least important KPI, the influence of τ_{max} is minimal. However, despite τ_{max} not influencing the KPIs, a higher τ_{max} resulted in more stands starting construction within the first two to three hours.
- Additional construction time proved to significantly improve all four KPIs (-1.0%, -1.6%, -1.5% and -3.2% respectively). An increase in available construction time T_{max} resulted in a scheduling strategy with a larger temporal spread of the starting times.

From this, it can be concluded that differences in layout, stand sizes, stand density and available construction time can significantly impact the model's performance, affecting the construction's outcomes across several KPIs.

6.4.1 Managerial implications

To put these results into practice, the venue can influence several adjustments to improve construction outcomes. During the construction of a trade fair, the venue has the most influence on the configuration variables τ_{max} and T_{max}. This chapter showed that adjusting τ_{max}, whether to increase or decrease unloading capacity, does not significantly increase the potential for optimizing schedules. Therefore, it is advised to find a suitable τ_{max} that allows for a feasible construction and that works within all the practical limitations that were not captured within this model. However, investing heavily in improving unloading capacity is not necessary, since it has minimal impact on construction outcomes. In contrast, increasing the total available construction time, T_{max}, significantly improved performance across all KPIs. Therefore, in order to enhance the construction phase, the venue is advised to prioritize increasing the available construction time.

The layout of the venue also influences scheduling strategies. For layouts with corridor elements, it is recommended to schedule stands at the back of the corridor first and progressively schedule stands closer to the yellow path. More open layouts, with more space between stands, are more flexible in this regard, although starting furthest away from the yellow path is still advisable. While these recommendations may seem straightforward, their simplicity allows for practical and easily implementable solutions.

While scenario variables such as layout and stand size are not considered to be within the venue's first interest to alter in order to improve construction logistics, these variables can affect the outcomes of the construction performance. However, in case the venue is open for changing these aspects, it is advised to go for fewer, larger stands rather than more, smaller ones, and to select layouts with non-adjacent stands over those with closely neighboring ones. These changes can lead to significant reductions in the density of materials in the halls, and allow for better construction performances.

7

Case Study

7.1 Introduction

To evaluate the potential improvements the model offers compared to the current situation, it is tested on a case study. This case study will help to answer the last two research questions: "*To what extent can the scheduling model improve the overall storage of materials at a trade fair?*" and " *What strategies does the scheduling model apply under different input conditions?*". For this case study, the same fair is used as for the data collection. The start times of the 77 stands were obtained using photos from the timelapse, and data from the delivery appointment system.

In figure 7.1, the layouts for the three halls used in this case study can be found. First, a baseline scenario is created in section 7.2 with the actual start times of the stands, which will function as a reference. This scenario is compared to real life data collected in the timelapse, to validate the model. Then, the model's suggested schedules will be compared to the baseline scenario in section 7.3 to see what improvements the model makes. This is first done by applying the delay policy, and then the accessibility policy, to gain insight in the performances of different policies, and gain an understanding of the trade-offs made by the model. Lastly, a sensitivity analysis will be done in section 7.4, to see how the model responds to changes in construction durations and material volume.

7.2 Baseline scenario

For the baseline scenario, the actual start times, construction durations and estimated m^3 of materials are used to run the model. In appendix E, the start time and finish time of each stand's construction are given. By using the actual starting and finish time for each stand, the model creates a scenario that is as close to the actual scenario as possible. This is used as a reference later. The KPI scores of the baseline scenario, as well as the scores of the delay and the accessibility policy can be found in table 7.1. Visualizations of the construction schedules can be seen in Appendix F.1.

The calculated baseline scenario was compared to the pictures taken at the timelapse

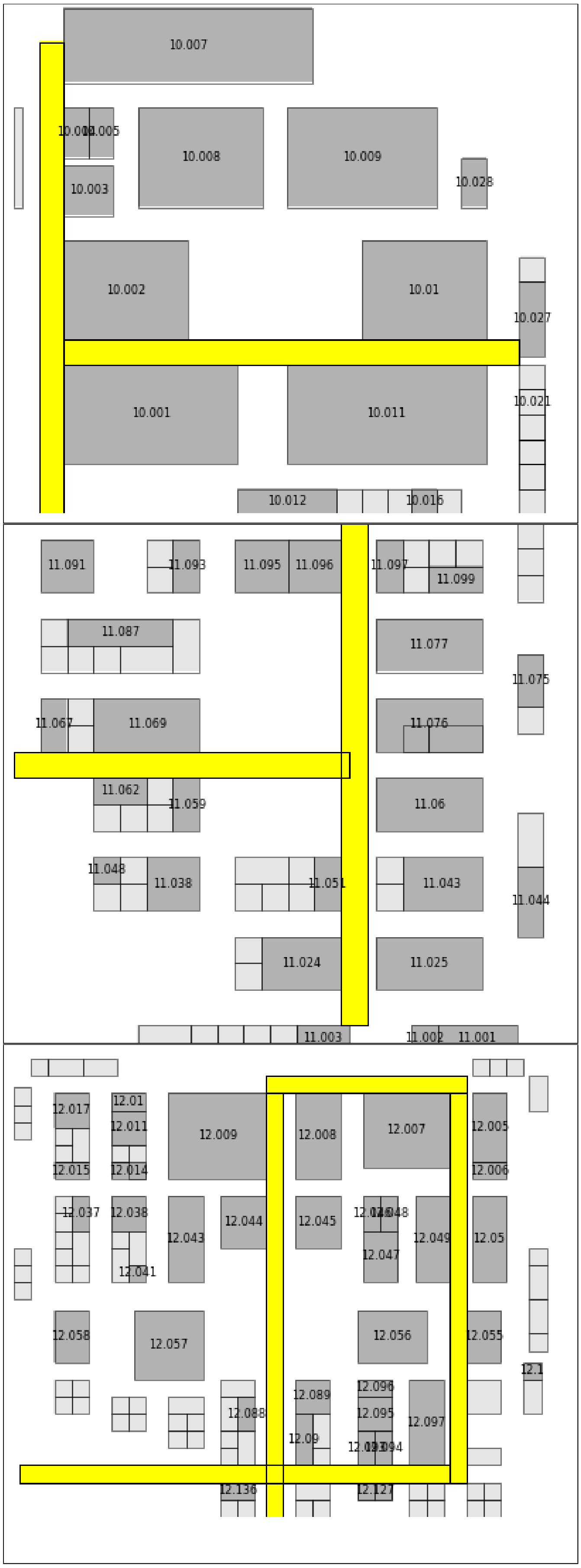

Figure 7.1: *Three hall layouts for the case study. To be constructed stands are displayed in dark gray, and labelled with a stand number. Already constructed UB and MSD stands are displayed in light gray. Top: hall 10, middle: hall 11, bottom: hall 12. Source: author.*

Table 7.1: *Simulation results comparing the original and optimized scenarios for Halls 10, 11, and 12. Source: author.*

Hall	Scenario	Average start time (h)	Mean Density	Difference to baseline (%)	Density Variance	Difference to baseline (%)	Interferences	Difference to baseline (%)	Starting Time Variance	Difference to baseline (%)
10	Baseline	14.1	0.0751	n.a.	0.0025	n.a.	0.67	n.a.	0.45	n.a.
	Delay Policy	9.1	0.0749	-0.266%	0.0017	-32.0 %	0.58	-13.4%	0.46	+2.22%
	Accessibility Policy	9.5	0.0754	+0.40%	0.0016	-36.0%	0.60	-10.4%	0.48	+6.67%
11	Baseline	19.0	0.0476	n.a.	0.00097	n.a.	0.26	n.a.	1.18	n.a.
	Delay Policy	15.0	0.0441	-7.35%	0.00039	-59.8%	0.18	-30.8%	0.71	-39.8%
	Accessibility Policy	13.0	0.0444	-6.72%	0.00068	-29.9%	0.20	-23.1%	0.75	-36.4%
12	Baseline	17.2	0.0546	n.a.	0.0015	n.a.	0.49	n.a.	1.28	n.a.
	Delay Policy	13.6	0.0529	-3.11%	0.00082	-45.3%	0.39	-20.4%	1.14	-10.9%
	Accessibility Policy	16.1	0.0530	-2.9%	0.00074	-50.7%	0.39	-20.4%	1.03	-19.5%

in chapter 5, in order to validate the model. It was found that the placement of materials by the model was similar to that in real life, and the overall progression of the construction period was found to be equivalent. However, the amount of materials per stand seemed to be somewhat lower in the baseline scenario than in the collected data. Reasons for this will be discussed in chapter 9.2.2.

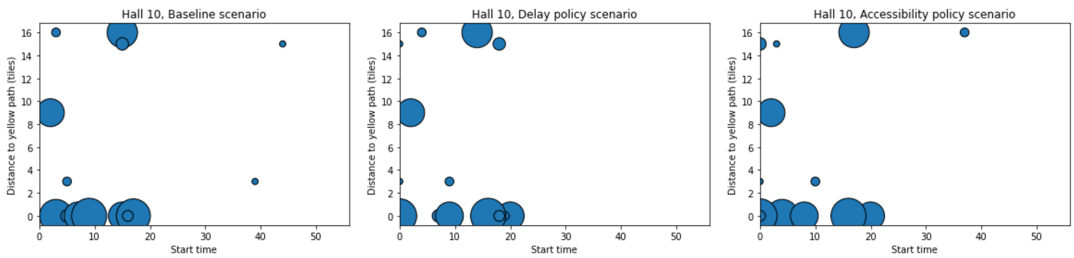

Figure 7.2: *Differences in starting times for baseline (left), delay policy (middle) and accessibility (right) policy scenario in hall 10. Size of the plot points indicates the size of the stand. Both stand size and distance to yellow path are fixed per stand, but start times change between policies. Source: author.*

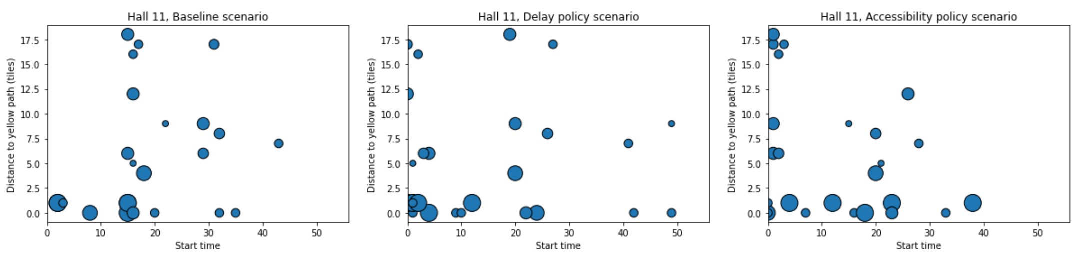

Figure 7.3: *Differences in starting times for baseline (left), delay policy (middle) and accessibility (right) policy scenario in hall 11. Size of the plot points indicates the size of the stand. Both stand size and distance to yellow path are fixed per stand, but start times change between policies. Source: author.*

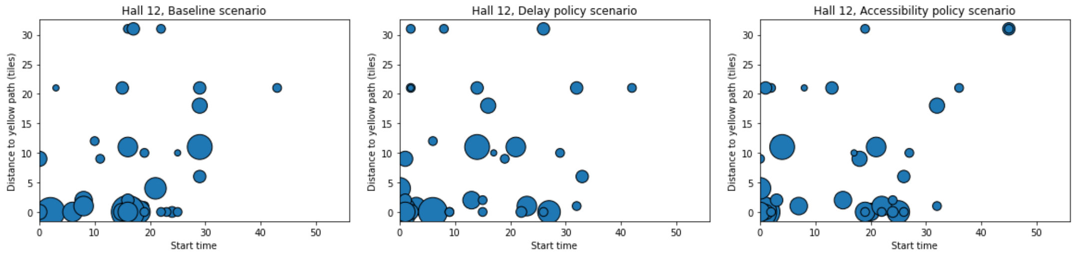

Figure 7.4: *Differences in starting times for baseline (left), delay policy (middle) and accessibility (right) policy scenario in hall 12. Size of the plot points indicates the size of the stand. Both stand size and distance to yellow path are fixed per stand, but start times change between policies. Source: author.*

7.3 Optimal schedules

Now that the baseline scenarios are established, the optimal schedules can be determined, by letting go of the predetermined starting times of stands' constructions. It is important to note that, since the baseline scenario did not consider broad accessibility routes to the stands, the constraints for the accessibility policy are not considered at first (so only the delay policy). After this, the accessibility policy is added to see the trade-off that the model makes between accessibility and efficient material storage.

The resulting changes in objective value, KPI scores and average start time can be found in table 7.1. The differences in starting times for the baseline, delay policy and accessibility policy can be found in figures 7.2, 7.3 and 7.4. Here, the size of the plot points indicate the size of the stand. Both the stand size and distance to the yellow path are fixed per stand, so only the start time changes, so these figures only show the changes in start times (x-axis). The progression of the average density of the baseline, delay policy and accessibility policy scenario over the full construction timespan can be found in figure 7.5. Here it can be seen how the density changes between the different scenarios, and how it progresses per hall over time. For a total overview that includes the construction duration and the occupation of the aisles, see the visualizations in appendix F.2 and F.3.

7.3.1 Delay policy

Using only the delay policy, and not the accessibility policy, the model optimizes the start times while not considering accessibility constraints. The objective values for hall 10, 11 and 12 are now 0.0749, 0.0441 and 0.0529 respectively. This means that the objective values were reduced by 0.27%, 7.4% and 3.1% (see table 7.1). This might seem like a very small reduction. However, notice that the model can only improve the value of the objective function by reducing storage space interferences, since this is the only way extra delays are caused, which increase the overall average material density. The variance in density has reduced greatly, with 32.0%, 29.9% and 45.3% respectively. Also, interferences are reduced by 13.4%, 30.8% and 20.4% respectively. As a result, materials are more uniformly distributed over the entire timespan, and spikes or dips in storage density are reduced (see figure 7.5). This results in an improved usage of space and

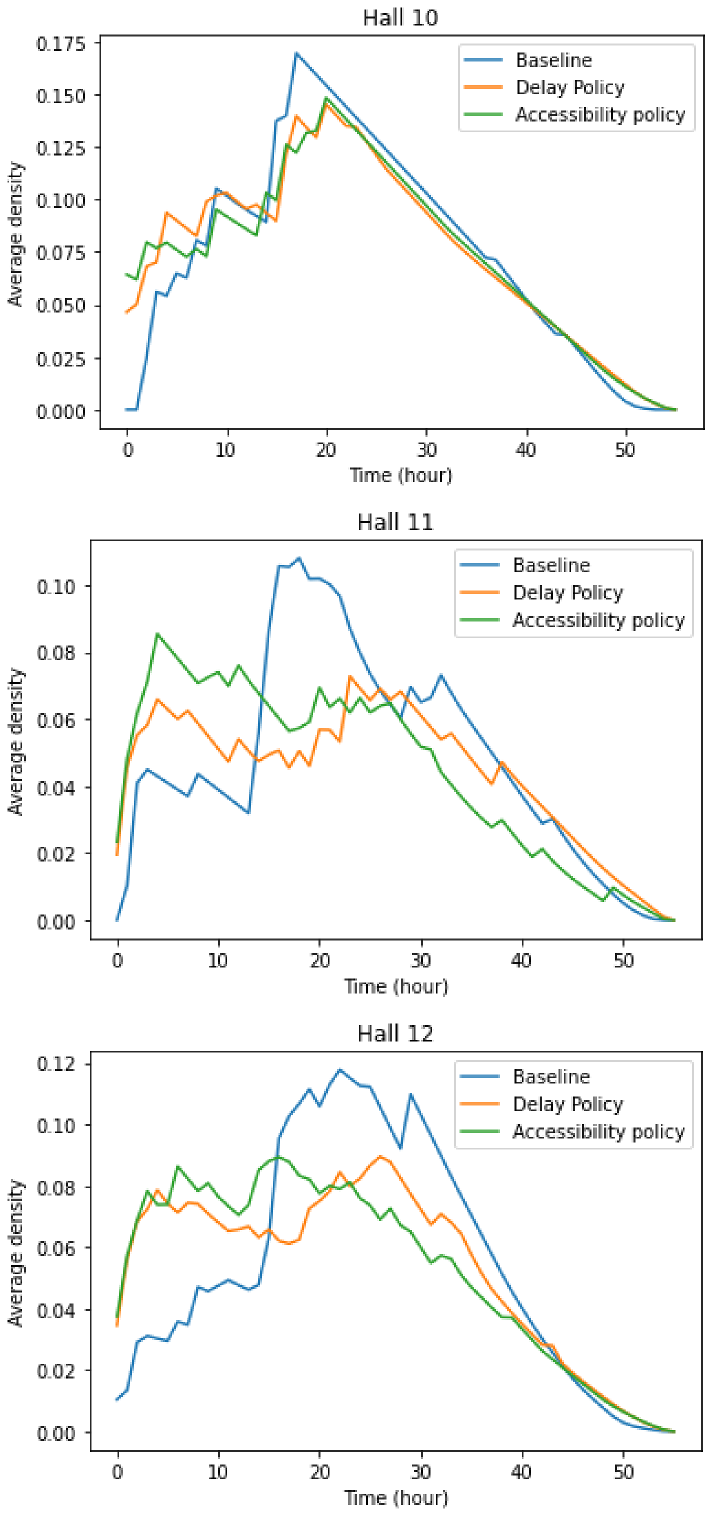

Figure 7.5: *Progression of the average density in hall 10 (top), 11 (middle) and 12 (bottom) under the baseline, delay and accessibility scenario. Source: author.*

smoother workflows. Also, the reduction in interferences results in less space being shared with multiple users, which reduces the risk of accidents and logistical challenges. It can also be noted that the mean start time of the stands dropped significantly per hall, meaning that stands started construction earlier on average.

More specifically, the changes per hall are as follows (see appendix F for full visualizations of the baseline scenarios and delay policy schedules):

Hall 10: In the delay policy scenario, an overall larger spread of constructing stands over the full timespan can be seen: four stands start construction within the first three hours, compared to only one in the baseline (see figure 7.2), and in the last hour of the delay policy scenario, three stands complete construction, compared to the last stand being finished two hours earlier in the baseline scenario. The selection of which stands should start early, and which later, was not related to stand size or the distance to the yellow path.

Hall 11: Large stands were clearly favored to start earlier. Overall, stands started earlier than the baseline scenario (see table 7.1): at the end of the sixth hour, 12 stands have started construction, compared to 5 in the baseline scenario (see figure 7.3). This also diminished the density peak in figure 7.5.

Hall 12: For this hall, an overall larger spread of constructing stands over the full timespan was found as well. More stands start constructing in the first few hours (see figure 7.4), causing a significant drop in density variance and number of interferences. The decision of which stands to start early and which to delay was not influenced by stand size or proximity to the yellow path.

So, while the delay policy performs better on the KPIs compared to the baseline scenario, it still lacks a clear and defined scheduling strategy. Compared to the simulation runs in chapter 6, this case study introduces varying stand sizes, construction durations and materials within one layout. However, despite these variations, no clear connection could be found between these factors and specific scheduling strategies, indicating that the model's solutions are more complex and depend on additional considerations that make it difficult to reproduce consistently.

7.3.2 Accessibility policy

Putting the accessibility constraints on the model, will ensure that the model takes the accessibility of stands from the yellow path into account when assigning start times to stands. In appendix F.3, the visualizations for the accessibility policies on hall 10, 11 and 12 can be found. The objective values are now 0.0754, 0.0444 and 0.0530 respectively, meaning an increase of +0.4%, −6.72% and −2.9% compared to the baseline. Also the number of interferences went down (-10.4%, -23.1% and -20.4%). However, compared to the delay policy the objective values for this policy will be greater than or equal to the delay policy. Both the objective values and the number of interferences went up. This shows that when adding accessibility constraints, the model makes a trade-off between accessibility on the one hand, and interferences and optimal storage space scheduling on the other. In order for stands to remain accessible, the model has less freedom of choice in placing materials and choosing start times. This leads to higher overlap in workspaces, and and increased number of interferences and density. While this approach reduces congestion, it will require resolving more workspace conflicts in real-time.

The differences in strategy between the delay and accessibility policy were found to be as follows:

Hall 10: For hall 10, it was found that stands that could potentially be blocked by other stands started construction earlier. For the other stands, the model applied nearly the same strategy as for the delay policy, leading to a similar schedule.

Hall 11: Many changes were made to the starting order of hall 11. Clearly, stands that were furthest away from the yellow path started construction earlier than those closer to the path (see figure 7.3). This result is in line with the changes that are expected with the accessibility constraints. As a result of these changes, the overall density in the hall peaks in the first half of the construction period.

Hall 12: Figure 7.4 seems to suggest an inverted effect, where stands furthest away started last. However, these stands are 12.010, 12.015, 12.017, 12.037 and 12.058. These stands are at the sidelines on the hall, so that their access routes from the yellow path can hardly be blocked by any stand. The model uses this to schedule them later. When correcting for this notion, a similar effect as in hall 10 and 11 can be found, where stands that are further away from the yellow path, and can easily be blocked by other stands, start construction earlier than stands that are close to the yellow path. Also for hall 12, a peak in the average density can be found in the first half of the construction period.

So despite the accessibility policy performing less optimal on the KPIs than the delay policy, it protects the accessibility of stands at the start of construction. As a result, it also introduces a more tangible and practical scheduling strategy, namely prioritizing stands that are furthest away from the yellow path. This approach is quite straightforward, and therefore also easy to implement. This clarity and ease of execution offer a practical balance between feasibility and performance.

7.4 Sensitivity Analysis

For this sensitivity analysis, the amount of materials and construction duration were altered per stand. Values were set on 75%, 125%, and 150% of their original value. In table 7.2, the results can be found (see appendix G for the full visualizations).

For both construction duration and materials, changes in values led to a nearly proportional changes in objective value. An increase in construction duration led to a slightly lower change of objective value. This can be explained by the fact that a correction was made for stands whose construction durations were going to exceed the given 56 hours. For these stands, construction duration was set to 54 hours, in order to

Table 7.2: *Sensitivity analysis results. Source: author.*

Hall name	Changed input	Value	Objective value	Comparison to baseline	Strategy changes
Hall 10	Construction duration	75%	0.0585	-22.1%	Start order changes significantly, but with no clear pattern. Overall, there are fewer stands constructing simultaneously.
	Construction duration	125 %	0.0895	+ 19.1%	More stands start construction early. Overall, more stands are constructing simultaneously throughout the available Construction duration
	Construction duration	150%	0.0961	+ 28.0%	More stands start construction in the first three hours. At 42 of the 56 hours available, all stands are under construction, compared to only 13 hours in the baseline scenario.
	Materials	75%	0.0564	-24.9%	Large stands, close to the yellow path get preferenced to start earlier than smaller stands that are further away.
	Materials	125%	0.0951	+ 26.6%	Stands that are not adjacent to the yellow path are more often put first, compared to adjacent stands
	Materials	150%	0.114	+ 51.8%	All stands away from the yellow path start first.
Hall 11	Construction duration	75%	0.0362	-24.0%	No significant changes in starting policy
	Construction duration	125%	0.0573	+ 20.0%	No significant changes in starting policy.
	Construction duration	150%	0.0651	+ 36.8 %	More stands start early. Due to the longer duration of construction, on average more stands are under construction at any given time.
	Materials	75%	0.0344	-27.7%	No significant changes in starting order
	Materials	125%	0.0581	+ 22.1 %	Most of the stands further away from the yellow path start earlier
	Materials	150%	0.0696	+ 46.2 %	All stands further away from the yellow path are prioritized and start within the first five hours.
Hall 12	Construction duration	75 %	0.0392	-28.2%	No significant changes in starting order
	Construction duration	125%	0.0641	+ 17.4%	No significant changes in starting order
	Construction duration	150%	0.0738	+35.2%	Surprisingly, little to no change in starting order. Stands do not start earlier.
	Materials	75%	0.0392	-28.2%	No significant changes in starting order found
	Materials	125%	0.0662	+ 21.2%	No significant changes in starting order found
	Materials	150%	0.0799	+46.3%	Surprisingly, little to no changes are made to the starting order. No preference seems to be given to stands further away from the yellow path

avoid infeasible models. Because of this, the effect of increased duration is lower than expected. This is especially the case for hall 10, which contained the largest stands of all three halls.

Changes in material volume led to slightly higher changes in objective values. This is due to the delay effect in the model. The more materials are stored around stands, the higher this delay effect is, and the longer construction takes. This increase in construction duration is likely to cause the increase of objective value.

By observing these consistent and predictable changes in the outputs when inputs were varied, it can be confirmed that the model behaves as expected and functions in line with the theoretical structure. This sensitivity analysis thereby increased confidence in the model's accuracy and reliability.

Strategy changes due to construction duration and material volume changes were inconsistent. For hall 10, clear changes were found, while no changes were found in hall 12. This effect can not easily be explained, since the increases had a higher effect on the objective value in hall 12 than in hall 10.

7.5 Conclusion

This chapter aimed to answer the research questions: "*To what extent can the scheduling model improve the overall storage of materials at a trade fair?*" and " *What strategies does the scheduling model apply under different input conditions?*". A case study was performed for a fair, in which 77 stands were constructed in three halls, over the course of four days. The actual start and finish times of the construction of each stand was used in order to establish a baseline scenario. After this, the model was run again without the predetermined start times. This way, the optimal schedules could be established, first using only the delay policy, and later also using the accessibility policy.

The delay policy managed to get clear improvements on the objective value (-0.27 %, -7.35% and -3.11% per hall) as well as the variance in density (-32.0%, -29.9% and -45.3%) and number of interferences (-13.4%, -30.8% and -20.4%). This was done by letting stands start construction earlier in such a way that construction was more spread over the entire timespan than in the baseline scenario. However, while the delay policy outperforms the baseline scenario on KPIs, it lacks a clear scheduling strategy. This case study incorporates varying stand sizes, construction durations, and materials. Yet, no clear link was found between these factors and specific scheduling strategies, suggesting the model's solutions for the delay policy are more complex, which make them difficult to replicate.

The accessibility policy introduced a trade-off between accessibility of stands, and the number of interferences and density of materials. Therefore, the objective value and number of interferences were higher for the accessibility policy compared to the delay policy. However, the accessibility policy still performed significantly better compared to the baseline scenario, with significant decreases in density variance (-36.0%, -29.9% and -50.7%) and number of interferences (-10.4%, -23.1% and -20.4%). This introduced a trade-off between accessibility on the one hand, and interferences and optimal storage space planning on the other. However, the scheduling strategy was clearer: stands located farther from the yellow path and at risk of being blocked by other stands started construction earlier. This offers a simple and easy to implement approach, with a practical balance between feasibility and performance.

The sensitivity analysis showed that changing the material volume or construction duration of stands does not influence the objective value disproportionately. This helped to verify the model. Increases in construction duration lead to slightly lower increases of objective value, likely due to more stands passing the maximum possible construction duration, and being corrected to a shorter construction duration.

Overall, this case study demonstrated that by adjusting start times using the delay and accessibility policies, significant reductions in density variance and interferences can be achieved. These findings suggest that scheduling adjustments can significantly improve space usage.

8 Conclusion

8.1 Answers to the sub research questions

This study aimed to contribute to the scheduling of construction start times of stands at trade fairs. Within this goal lies the question of whether a scheduling model can be created that reduces the overall density of stored materials in the aisles, and improves accessibility of stands. The main research question to this research was:

> In what way can a scheduling model for the start times of stand constructions improve the overall storage of materials in aisles and minimise workspace interferences during the construction of trade fairs?

Several subquestions were proposed to support this main question. These are repeated and answered below:

1: How does the construction of trade fairs currently work?

In chapter 2, the current structure of a trade fair construction was explained. There are four parties involved in the organisation of a trade fair: the venue, the organiser, the exhibitor and the stand builder. The exhibitor chooses the stand design, and either rents a stand at the venue, or hires a third party to create a custom design. The venue takes care of the rented stands, and hires specific parties for each component of the stand. These teams bring little materials with them into the halls, and often do their construction before the regular buildup days. For these reasons, they often do not contribute to the material storage problems in the aisles.

In case a custom design is selected, a standbuilder team is assembled to construct the stand for the exhibitor. The team first books a truck unloading slot, at which the materials can be unloaded at the work terrace. Then, the materials are brought into the hall, and stored around the stand, in the aisles. During construction, materials are picked from the piles in the aisles, and placed on the stand, until construction is completed. The scheduling of the truck unloading slots (and therefore the start times of stands' construction) influences how many materials are stored in the aisles at each time.

Storing materials in the aisles leads to several issues: stands become inaccessible due to blocked aisles, construction work faces delays from limited working space, and safety risks increase. Implementing a scheduling method for stand start times could help optimize material storage in the aisles.

2: What models found in literature are most suitable for solving the scheduling problem at trade fairs?

In chapter 3, a literature review was given on the current literature on event logistics, construction logistics, workspace planning and unloading slot scheduling. No existing studies were found that used mathematical models or formal frameworks to address scheduling problems at trade fairs or similar events. Studies on workspace interferences mainly focused on removing all interferences rather than optimizing a schedule with allowable interferences. Studies that did allow for some interferences, such as Chua et al. (2010), Roofigari-Esfahan et al. (2017) and Tao et al. (2020), did not link the intensity of these workspace limitation to workspace dependent delays. The scheduling of unloading slots can be seen as both a time and a sequence dependent PJSSP. However, no study has yet covered the combination of the two. This research aimed to address the gap in scheduling models for trade fairs by building on prior studies and including the connection between workspace interferences and the severity of delays, and by integrating this relationship into more effective workspace planning.

3: How can the scheduling problem be represented in a mathematical model?

For this research, a MILP model was used to create improved start time schedules for the construction of trade fair stands. Three policies were introduced. First, an intuitive, no delay policy was created, in which the construction productivity and decrease in materials in the aisles were kept constant. This served as a first setup that was then expanded upon in the delay policy, in which the productivity was reduced when depending on the amount materials stored in the aisles and the amount of workspace available. Lastly, an accessibility policy was introduced, in which the accessibility of stands at the start of their construction was taken into account, to make sure that materials could be brought to a stand at the start of its construction.

The model was verified by solving simple test cases, checking constraints by temporarily isolating them, and performing a sensitivity analysis. The model was validated by comparing calculated density progressions to collected data, and comparing a calculated baseline scenario to data from the case study. Also the progression of density reduction by the model was compared to real life data. It was found that the errors of the model were low, and that the explanatory power was high. The median scores on the MAE, RMSE and R^2 0.035, 0.039 and 0.84 respectively. This also validated the model.

4: How can the duration of construction and the volumes of materials per stand best be estimated?

To answer this question, a timelapse of the construction of a fair at RAI Amsterdam was used to gather data. It was found that stand area was a significant predictor for construction duration (slope $\beta_1 = 0.085$, $SE = 0.020$, $p < 0.001$; intercept $\beta_0 = 22.75$, $SE = 2.09$, $p<0.001$; $R^2 = 0.273$, $F(1,46) = 18.64$, $p < 0.001$). and material volume (slope $\beta_1 = 0.20$, $SE = 0.026$, $p < 0.001$; intercept $\beta_0 = 7.14$, $SE = 3.06$, $p = 0.03$; $R^2 = 0.733$, $F(1,23) = 60.4$, $p < 0.001$). The delay effect could not be predicted from the measured construction duration (R^2= 0.14, F(1,22) = 3.47, p= 0.076).

5: How does the performance of the scheduling model vary under different input conditions?

54 simulation runs, with different layouts, stand densities and stand sizes, different numbers of stands starting simultaneously, and available construction time were tested. The computational performance of all the tested simulation runs were acceptable.

It was found that the layout with the island design (and the most aisle space) had the lowest objective value of the three with an increase of -19.0% and -16.6% in mean density and density variance respectively compared to a corridor design, and -5.0% and -1.1% compared to a mixed design. Fewer and larger stands caused lower material densities in the aisles than more and smaller stands. The maximum of stands that could start simultaneously was not found to have an influence on the objective value. However, the maximum available construction time had an effect on all KPIs, with improvements of -1.0%, -1.6%, -1.5% and -3.2% respectively per additional hour.

To improve construction outcomes, a venue could focus on increasing construction time (T_{max}), which significantly improves performance across all KPIs, further investments in unloading capacity (τ_{max}) is unnecessary, as its impact is limited. Thus, a practical τ_{max} that functions within operational limits is sufficient. Additionally, if adjustments to layouts and stand sizes are possible, prioritizing fewer, larger stands and non-adjacent layouts can reduce material density and improve efficiency in the construction process.

In short, variations in layout, stand sizes, stand density, and available construction time can affect the model's performance, and thereby impact the construction's outcomes across multiple KPIs. Recognizing these relationships and the opportunities they present to a venue is important in improving overall efficiency in the construction process.

6: To what extent can the scheduling model improve the overall storage of materials at a trade fair?

A case study was performed in chapter 7, in which a trade fair across three halls with 77 stands was analyzed. A baseline scenario was established, using the original starting times of each stand. After this, an improved schedule was found by running the delay model. This resulted in clear improvements in the objective value (-0.27%, -7.35% and -3.11% per hall) as well as the variance in density (-32.0%, -29.9% and -45.3%) and number of interferences (-13.4%, -30.8% and -20.4%).

By introducing the accessibility policy, a trade-off was made between the accessibility of stands, and the number of interferences and density of materials. The objective value and number of interferences were therefore higher compared to the delay, but were still significantly better than the baseline scenario, (density variance reduced by -36.0%, -29.9% and -50.7% respectively and number of interferences by -10.4%, -23.1% and -20.4%).

This case study showed that adjusting start times through the delay and accessibility policies can lead to significant reductions in density variance and interferences. These results indicate that scheduling adjustments can greatly improve storage space usage.

7: What strategies does the scheduling model apply under different input conditions?

Using the accessibility policy, the model identified similar strategies across both the analysis of the simulation runs and the case study. In the scenario runs it was found that layouts with corridor elements in their designs, prioritize stands at the back of the corridor, and progressively move closer to the main path—the "yellow path". A layout with more open space between the stands lets large stands close to the yellow path start first, while medium or small sized stands begin furthest away from the yellow path.

Using the accessibility policy, similar approaches were found, where stands farther from the yellow path, particularly those at risk of being blocked by other stands, were scheduled to start earlier. Interestingly, variations in stand sizes, construction durations, and materials did not seem to influence the scheduling strategy.

Additionally, the case study revealed another strategy: construction was distributed more evenly across the available time span, improving the use of storage space and reducing congestion.

While these strategies may appear straightforward, the simplicity of these strategies can be valuable in a complex operational environment. These methods are practical and accessible, making them easy to understand, implement, and communicate to clients, exhibitors, and stand builders alike, facilitating their implementation of in practice.

8.2 Answer to the main research question

The MILP model developed in this research effectively reduced both material storage in aisles and workspace interferences during stand construction at trade fairs. In the case study, the model decreased the overall average of materials stored in aisles by 3.1%, reduced the variance in material density by 38.9%, and lowered the number of workspace interferences by 18.0% on average. These improvements were primarily achieved by prioritizing earlier start times for stands located farther from the yellow path, to better distribute the materials storage over the available construction period.

When accessibility constraints were removed, allowing the model greater flexibility in scheduling, even higher reductions were found: a 10.7% decrease in aisle material storage, a 45.7% reduction in density variance, and a 64.6% drop in interferences. This creates a trade-off between maintaining accessibility and minimizing interferences while optimizing storage space planning.

Simulation runs with differing input variables showed that the degree of improvement largely depends on hall layout, stand density, stand size, and available construction time. Among the layouts, the island design produced the most favorable results, achieving reductions of 19.0% in mean density and 16.6% in density variance compared to the corridor design, and 5.0% and 1.1% compared to the mixed design. Additional available construction time also proved beneficial, improving each key performance indicator: for every extra hour, mean density, density variance, number of interferences, and variance in start time improved by 1.0%, 1.6%, 1.5%, and 3.2%, respectively.

In conclusion, this study demonstrated that a scheduling model, that prioritizes distant stands and stands are scheduled to be evenly distributed across the entire available timespan, can significantly reduce aisle storage usage and reduce workspace interferences in trade fair constructions. While the model performs best when given full flexibility, practical application may require the additional accessibility constraints. These insights can offer a guideline for trade fair organizers to improve construction schedules.

9

Discussion

This discussion is divided into four sections. First, the contributions of this research and the practical implications will be discussed in 9.1. After this, the limitations in the model and data collection will be discussed in 9.2. This is followed by specific recommendations for the RAI in section 9.3. After this, section 9.4 concludes with the recommendations for future research.

9.1 Research contributions and practical implications

As concluded in the literature review in chapter 3, there is a notable lack of quantifiable or scientifically rigorous research on event logistics, particularly in the area of construction logistics. No existing studies have used mathematical models or formal frameworks to address this issue. This research takes the first step in filling this gap by developing a scheduling model specifically for trade fair construction logistics. A MILP model is introduced that effectively reduces material density in shared aisles and minimizes workspace interferences. This contributed to the current body of knowledge on construction scheduling by incorporating the predicted impact of scheduled workspace availability on delays as a factor in scheduling decisions. The model and insights that were obtained in this research are not only relevant for trade fairs, but can also be applied in similar event setups or complex construction environments.

However, effectively applying these scheduling strategies may be challenging as it requires coordination and communication among multiple stakeholders, from event organizers to stand builders and exhibitors. This has proven to be difficult in the past, due to communication barriers between exhibitors and standbuilders, and language barriers with foreign standbuilders. Therefore, a flexible approach that allows for partial implementation or adjustment of these strategies may be necessary to address these challenges in the future.

9.2 Limitations

9.2.1 Model simplifications

The MILP model is based on several assumptions and simplifications.

The model assumes that each stand is built by a dedicated team working independently from others. In reality, however, this is not always the case, as larger stand-building companies often construct multiple stands at a single fair (see the interview in Appendix H.2). While each stand may have its own assigned team, teams of the same company frequently collaborate. This distribution of teams and companies is often unknown to the venue, making it difficult to incorporate this factor into the model. Consequently, it was not considered in this model.

The model also presumes that a single delivery is made per stand at the start of construction. Although this is the case for most stands, large stands sometimes require multiple deliveries. This can be due to not all materials fit in one vehicle, or due to these stands being built by companies constructing multiple stands at the same fair, who combine materials for different stands across multiple vehicles (see Appendix H.2). This distribution of materials is however unknown to the venue.

The model also does not have a flexible delivery cap for different vehicle types, while these are frequently used in real life: a working terrace can contain more passenger cars than large trucks for example. Since it was not possible to predict or analyze what vehicle type would be employed by what stand, the model did not distinguish between different vehicle types.

9.2.2 Data collection limitations

In chapter 5, data was collected regarding construction duration and volume of material. This was done using a timelapse of the venue halls. Although the pictures were very insightful, and could easily be analysed, there were several biases in the method.

First of all, it was hard to see from the static pictures when teams were working on the stands. For large teams, it can be assumed that they work at all the available hours (see Appendix H.2), while smaller teams of 1, 2 or 3 people, who work on smaller stands, might go home earlier, and come back the next day. This could not be captured in the pictures, possibly leading to an overestimation of construction durations for smaller stands. Also, some information due to pictures not being taken at the start and end of each construction day.

While the middle of the aisles often not being covered with materials and thus indicating a clear division between the two sides, this was not always the case. Therefore, it was not always clear from the pictures to which stand materials belonged. Estimations had to therefore be made based on previous pictures, packaging clues, or color matches with the stand or crew logos.

Empty packages were also put in the aisles. Although these were sometimes visibly empty, this was not always the case on the pictures. This may have created a bias for in material volumes.

However, material volumes likely also suffered from a bias towards lower volumes. Some stands packed their surrounding aisles so fully, that it was impossible to get close to take clear pictures. Some of these aisles were inaccessible for over a day. Therefore, a lot of data was missing on these densely packed aisles and their surrounding stands, resulting in several of them being left out of consideration in the data collection chapter. This very likely created a bias towards stands that stored less materials in their aisles.

9.3 Recommendations for RAI Amsterdam

During this research, the insights gained at the RAI were very useful for a better understanding of the workings of the construction of a trade fair, and the available data was highly useful for the results of this research. The managerial implications presented in section 6.4.1 can be use for practical improvements to the scheduling of construction. In case the RAI is interested in further researching the construction of their trade fairs, there are several recommendations regarding future directions and improvements for more accurate data:

- Understanding which companies construct which stands, and gaining more information on the individual plannings per stand, in order to form a better understanding of the constructions in the halls. Here, individual plannings refer to the number of people working on a stand, the deliveries, the materials brought per delivery, the working hours, etc.
- Gaining a higher accuracy of the delivery appointment system. Estimating the number of deliveries per stand from the delivery appointment was not possible since there was a lot of missing or strange data. Some stands had no scheduled delivery, some had their first delivery after construction had already begun, and other very small stands had multiple big deliveries over several days.
- It was also not possible to see from the appointment system whether appointments were made to deliver new materials, or pick up empty packagings. Adding an extra feature, that indicates whether a vehicle arrives to delivery materials, or pick up empty packaging, will give more insight in the traffic movements per stand.

9.4 Recommendations for future research

There are several suggestions for future researches to expand upon the model presented in this work.

First of all, a research that dives deeper into the details of the construction of a stand can be of help to provide more insight in the differences between stands, as well as obtain a deeper understanding of the construction of a stand. These details can relate to the number of people working on a stand, the productivity per team, the complexity of stands, the delivery schedules and plans of a team, and structural differences between different standbuilding companies. Knowledge of this can help further improve and finetune the scheduling of constructions and can create new directions for the model presented in this research.

Other directions could be further refining the model by incorporating multiple deliveries, providing a more detailed representation of material quantities and construction times based on team sizes and specific design details. Further researching the different phases of construction, such as the rigging, placing of floors, etc. and their impacts on materials in aisles will give a more accurate insight in when materials are stored in the aisles. Another direction for future research would be to investigate the possibilities for a Just-In-Time (JIT) delivery system, in which materials are sorted outside the venue, and are brought into the halls, at the time they are needed by the stand builders.

Testing the model in a wider range of scenarios can provide insights into additional scheduling rules and strategies, which allows for a deeper understanding of the applicability of the model in different contexts. Additionally, the model can be applied to different types of events in order to evaluate how well it works in different situations. This would allow the model to be adapted for similar events, such as conferences, exhibitions, or large-scale festivals, where similar logistical challenges and scheduling complexities occur.

Additionally, implementing the recommendations outlined in this work in a real-world setting would offer valuable insights into their practical application. As the model simplifies real-world conditions, unforeseen factors may arise that could either enhance or constrain its applicability, highlighting areas for further improvement. Understanding these factors and applying the recommendations in practice can lead to better and more effective scheduling solutions for trade fair construction.

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Appendices

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A

Scientific paper

Building beyond the booth: improving logistics for the construction of trade fairs

R.J.M. Tjeerdsma

Abstract Trade fairs bring together suppliers from specific industries or fields, offering them a valuable platform to showcase their products, gather information on competitors, and find potential partners. During construction, materials that are not yet in use are often stored in pathways. When multiple stands are under construction simultaneously, pathways can get increasingly congested, resulting in stands becoming inaccessible, safety risks and delays. Despite the importance of managing these issues, no scheduling method has been developed to address these challenges to date. To fill this gap, this research introduces a Mixed Integer Linear Programming (MILP) model designed to improve the construction scheduling process at trade fairs by incorporating the predicted impact of scheduled workspace availability on delays as a factor in scheduling decisions. A case study at RAI Amsterdam was performed to collect data and validate the model. The improved schedules proposed by the MILP model are estimated to reduce average aisle material storage by 3.1%, variance in material storage density by 38.9%, and workspace interferences by 18.0%. When accessibility constraints were relaxed, even greater gains were achieved, with reductions up to 10.7% in material storage and 64.6% in interferences. Simulation runs with varying input variables showed that the degree improvement varied by hall layout, stand density, and available construction time, with island layouts and additional setup time yielding the best results. The most recurring and clear scheduling strategy applied by the model was letting stands furthest away from the accessible safety paths start first, followed sequentially by closer stands. Overall, the model provides a practical scheduling approach to reduce congestion and enhance safety, offering a useful tool for trade fair organizers.

Keywords

Mixed Integer Linear Programming (MILP), scheduling optimization, trade fairs, construction logistics, workspace management, event logistics

Introduction

Trade fairs are events that bring together suppliers from specific industries or fields, offering them the opportunity to showcase their products, present their innovations, learn about user needs, gather information on competitors, and find potential partners [1], [2], [3]. [3]. Trade fairs have a long history, dating back to biblical times, yet they continue to play a significant role in today's business landscape [4].

Before the fair opens, the exhibitors' stands need to be constructed in the venue hall. The construction conditions at trade fairs are different from those of regular construction project and can be characterized by the following:

- Stands are constructed simultaneously, and can therefore be seen as multiple construction projects being undertaken at the same time, instead of one project.
- There is a strict deadline for completion. Each stand must be finished by the opening of the fair
- The layout of the fair is determined beforehand. Although the layout has an effect on the construction logistics, it is not created with construction logistics in mind, but rather by the sizes of the stands and by the proximity/distance that exhibitors want from their competitors.
- A team of standbuilders can start construction of a stand once its materials are delivered and unloaded at the venue.
- Only a limited amount of trucks can be unloaded at the venue at the same time, and therefore a limited number of stands start construction simultaneously.
- Stand builders only use the assigned stand location and its surrounding pathways as workspace
- Materials that are not used yet, are stored in the pathways. In case other stands are adjacent to the same pathways, the storage space of the pathways is shared.

Due to the limited time and space, materials get densely stored in the aisles. As a result, three things happen:

1. Stands become inaccessible and materials can not be brought to the stand
2. Too densely stacked materials create safety risks
3. Construction work is done in too limited spaces, which causes delays.

The effects of limited or congested workspaces on productivity and safety have long been recognised as a problem in construction logistics [5], [6], [7]. In a case study on a £6 million construction site, it was found that about 30% of time on site was unproductive due to the lack of a detailed planning of space [8]. Others found an even higher effect, up to a 65% productivity loss [9]. Thomas and Smith [10] suggested that 19m^2 per person is needed on a construction site and when this is declined to 10.4 m^2, 50% more man-hours are required. The minimum of workspace was found to be 9.4 m^2. Maximum productivity was reached at 30.2 m^2.

Yet, no research has been done to date on how to improve the workspace conditions at trade fairs, or on how to effectively schedule the construction start times of stands, in order to minimize these effects. This research will therefore develop a scheduling method for trade fairs that incorporates the predicted impact of scheduled workspace availability on delays as a factor in scheduling decisions, such that:

- The excess stored material density caused by stands using the same pathways for storage is reduced, by letting neighbouring stands start construction earlier or later
- Stands are accessible when their materials are delivered.
- Stands are provided sufficient time to finish construction before the opening of the fair.

1 Literature review

Events, such as sport events, music events, theaters or festivals, or congresses, share similarities with trade fairs regarding preparations, venues and size. However, most papers on their logistcs focus on the general management of events, and write little details on the on-site construction logistics or preparations for these events (e.g. [11]; [12]; [13]; [14]; [15]; [16]; [17]; [18]).

Literature on trade fairs mostly focuses on the optimal layout of a fair [19], how to design a stand [20]; [21], how the experience for visitors can be improved [22]; [23] or on how companies can create business opportunities at trade fairs [24]; [3]; [25].

To the author's knowledge, only one research has been performed on formally analysing bottlenecks at trade fair constructions. Sad[26] simulated the arrival of delivery trucks using queuing theory and focused on the supply logistics at a trade fair. The complexities of the internal logistics were not considered. The unique logistical challenges at the organisation of events have therefore not yet been researched in the event logistics research field [27].

When focusing on construction logistics, more literature can be found on workspace planning. Space can be seen as a renewable resource, that is released again after an activity is completed. Task execution space on a construction site is therefore dynamic. In case the same workspace is occupied by two or more activities simultaneously, a workspace conflict occurs [28]. The scheduling problem can be optimized by minimizing workspace conflicts rather than by eliminating them. Despite studies with this approach being sparse [28], there are still several valuable studies in this area: Dang and Bargstädt [29] for example solved a multi-objective space scheduling problem by using an evolutionary algorithm; Rohani et al. [30] combined reactive and proactive methods in a 5D CAD model (3D model, including a time and costs dimension), by first optimizing the schedule using a Genetic Algorithm, and then solving detected workspace clashes using heuristics; Chua et al. [31] quantified the spatio-temporal congestion in workspace interferences by introducing the dynamic space interference (DSI) variable and a congestion penalty indicator (CPI). Although the CPI was a good quantification of a linear penalty costs of workspace congestion, the congestion was not translated to an actual delay of the activities. Roofigari-Esfahan and Razavi [32] also looked at costs in the form of linear productivity losses due to time and space constraints. However, the end time of activities was fixed in their model, so that a lower productivity did not result in a longer activity execution time. Tao et al. [28], on the other hand, introduced a nonlinear delay factor. Productivity loss and delays occurred during work space interferences, but were taken at random and were not linked to the severity or duration of the interference.

So while Chua et al. [31] and Roofigari-Esfahan and Razavi [32] introduced linear productivity rates, and Tao et al. [28] addressed delays, the impact of shared workspace intensity on delays has not yet been linked or considered in scheduling processes. This creates a gap in the literature regarding scheduling methods that account for the complex dynamics of workspace interferences and associated delays. Consequently, current scheduling practices are often suboptimal, failing to consider the workspace dynamics that occur on the work floor. By incorporating these dynamics into scheduling models, more realistic and effective approaches to planning in high-density, shared work environments can be achieved.

2 Model formulation

2.1 Venue layout analysis

Similar to the works of Moon et al. [33], the layout of the venue is given as a 2D-space. Instead of seeing this space as the continuous Euclidean plane, it can be discretised in a grid $X \times Y$, where $X := \{0, 1, \dots, X_{max}\}$ and $Y := \{0, 1, \dots, Y_{max}\}$. Each stand has two types of spaces. The first is the construction space, which indicates the area where that the stand will occupy once it is fully constructed. The second is the storage space, which is the space around a stand that is used for the storage of construction materials. Let S be the set of stands, then the binary indicator $c_{s,(x,y)}$ indicates if (x, y) belongs to the construction space of stand $s \in S$, then the total construction space of s is given by:

$$\Phi_s := \{(x, y) | c_{s,x,y} = 1\} \quad (1)$$

Let binary $\delta_{s,(x,y)}$ indicate if (x, y) belongs to the storage space of s. Let Ω_s be the total storage space of stand s, such that:

$$\Omega_s := \{(x, y) | \delta_{s,(x,y)} = 1\} \quad (2)$$

For each side $\sigma \in \{1, 2, 3, 4\}$ (where 1 indicates the top, 2:right, 3: bottom and 4: left), the storage space of stand s can be defined by:

$$\Omega_{s,\sigma} := \{(x, y) | \delta_{s,(x,y)} = 1 \land (x, y) \text{ on side } \sigma \text{ of } s\} \quad (3)$$

Storage spaces of stands may overlap (see figure 1). The set of stands s' that have overlapping storage space with stand s, can be defined as:

$$I_s := \{s' \in S | \Omega_s \cap \Omega_{s'} \neq 0\} \quad (4)$$

Now for each side $\sigma \in \{1, 2, 3, 4\}$, the overlap with other stands is given in:

$$I_{s,\sigma} := \{(s', \sigma') | s' \in S \setminus s, \; \sigma' \in \{1, 2, 3, 4\}, \Omega_{s,\sigma} \cap \Omega_{s',\sigma'} \neq 0\} \quad (5)$$

2.2 Constraint definition

The first step of creating a MILP for the problem is to define the objective function. Let ρ_s^t be the density of materials around stand s and time t, where $\rho_s^t \in [0, 1]$. Instead of seeing time as continuous, it is discretised into timesteps of 1 hour, where $T := \{1, \dots, T_{max}\}$ is the set of timesteps. The objective is to minimize the average density of all aisles at all times $t \in T$. Let $v(\Omega) := |\Omega|$ be the volume of space Ω, then the objective function can be formulated as:

$$\text{Minimize } Z = \frac{\sum_{t \in T} \sum_{s \in S} \rho_s^t \cdot v(\Omega_s)}{(\sum_{s \in S} v(\Omega_s)) * T_{max}} \quad (6)$$

Let binary variable τ_s^t indicate whether stand s starts construction at time t ($\tau_s^t = 1$) or not ($\tau_s^t = 0$). Since each stand must

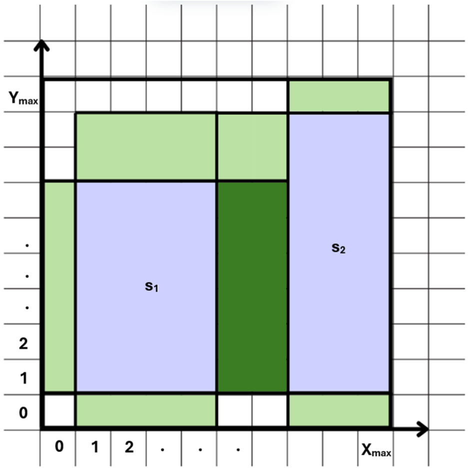

Figure 1. Construction spaces (blue) and storage spaces (green) of two stands. Storage spaces overlap in the middle (dark green). Source: author

have exactly one starting time, the following constraint is introduced:

$$\sum_{t \in T} \tau_s^t = 1 \qquad \forall s \in S \tag{7}$$

Let τ_{max} be the maximum number of stands that can start construction per timeslot. Then:

$$\sum_{s \in S} \tau_s^t \leq \tau_{max} \qquad \forall t \in T \tag{8}$$

Let m_s be the total amount of materials for stand s in m^3, and let h be the maximum allowed height for storage of materials per m^2, given in m. Then:

$$\mu_s := \frac{m_s}{h * v(\Omega_s)} \qquad \forall s \in S \tag{9}$$

This is a constant per stand, and indicates the starting density of stand s. Let D_s be the duration of construction of stand s. Then, the linear reduction of ρ_s^t can be given by:

$$\rho_s^t = \sum_{t'=t-D_s}^{t} \left(\mu_s \cdot \tau_s^{t'} - \frac{1}{D_s} \cdot \mu_s \cdot \tau_s^{t'} (t - t') \right) \qquad \forall s \in S, t \in T \tag{10}$$

Which can be reformulated to:

$$\rho_s^t = \tau_s^t \cdot \mu_s + \rho_s^{t-1} - \left(\sum_{t'=1}^{t-1} \tau_s^{t'} \right) \frac{\mu_s}{D_s} \tag{11}$$

$$\forall t \in \{2, \dots, T_{max}\}$$

$$\rho_s^1 = \tau_s^1 \cdot \mu_s \tag{12}$$

$$\forall s \in S$$

However, since the amount of materials stored in the aisles causes a delay, a delay factor needs to be added such that the productivity reduces and ρ_s^t reduces less. In this case, some penalty should be given to the $-\left(\sum_{t'=1}^{t-1} \tau_s^{t'}\right) \frac{\mu_s}{D_s}$ factor. The delay can be measured by the density should depend on all the materials stored around (i.e. $\rho_s^t + \sum_{\sigma \in \{1,2,3,4\}} \sum_{(s',\sigma') \in I_{s,\sigma}} \rho_{s',\sigma'}^t \cdot \frac{v(\Omega_{s,s'})}{v(\Omega_s)}$, so the total sum of a stands own materials and the materials of others placed around it), multiplied with some weight factor w_s. ρ_s^t can now be reformulated as:

$$\begin{aligned} \rho_s^t \geq & \tau_s^t \cdot \mu_s + (1 + w_s) \rho_s^{t-1} \\ & - \left(\sum_{t'=1}^{t-1} \tau_s^{t'} \right) \frac{\mu_s}{D_s} + w_s \\ & \cdot \left(\sum_{\sigma \in \{1,2,3,4\}} \sum_{(s',\sigma') \in I_{s,\sigma}} \sum_{t'=1}^{t-1} \rho_{s',\sigma'}^{t-1} \cdot \tau_s^{t'} \cdot \frac{v(\Omega_{ss'})}{v(\Omega_s)} \right) \\ & \forall s \in S, t \in \{2, \dots, T\} \end{aligned} \tag{13}$$

From the works of Thomas and Smith [10], it was found that when workspace is reduced by 50%, productivity should also be reduced by 50%, so:

$$w_s := \frac{|\Omega_s|}{|\Omega_s| + |\Phi_s|} \cdot \frac{\mu_s}{D_s} \tag{14}$$

As mentioned before, materials can not be brought to stands that have become inaccessible due to the blockage of pathways. For safety reasons, trade fairs have pathways marked on the floor that serve as emergency path (here called "yellow paths"). Because these paths are connected to the entrances, stands do not have to be accessible from the entrance specifically, but could also be accessible from the yellow path. The layout can first be analysed as a graph $G^t = (N^t, E)$. Each pathway section is seen as a node, and edges represent the adjacency of pathway sections. Let K_s be the total number of paths from stand s to the yellow path and let $p_s^{t,k}$ be a path from stand s to the yellow path at time t, and let ρ_i be an edge in $p_s^{t,k}$, and let binary variable $\alpha_s^k = 1$ when path $p_s^{t,k}$ is accessible at time t, and 0 otherwise. For a safe and convenient pass through each aisle, it is estimated that 3/4th of the aisle should be passable, and materials should not be stacked higher than 1 meter. With a maximum height of $h = 2$ meters, material density should therefore not exceed 12.5%. Then, the following constraints need to be added to the model:

$$(1 - 0.875 \cdot \tau_s^t) \geq \rho_i \cdot \alpha_s^k \quad \forall s \in S, t \in T, k \in \{1, \dots, K\}, \; \rho_i \in p_s^{t,k} \tag{15}$$

$$\sum_{k \in K} \alpha_s^k \geq 1 \quad \forall s \in S \tag{16}$$

$$\alpha_s^k \in \{0, 1\} \quad \forall s \in S, k \in K \tag{17}$$

For the full MILP model, see Appendix A

Model verification was done by checking that each constraint in the model behaved correctly and consistently. Also, a sensitivity analysis was done to check that the model was not overly sensitive to minor changes in the input parameters.

To validate the model, first the progression of ρ_s^t in the model was compared to collected data. It was found that the model's errors were small (median scores on the MAE, RMSE and R^2 0.035, 0.039 and 0.84 respectively). The model was also run using a baseline scenario that closely mirrored real-world conditions, which ensured that its outputs matched actual results. Also, discussions and interviews with employees at a trade fair venue, as well as experiencing construction periods first hand, provided insight in the workings of trade fair constructions, which established a framework for defining the model's constraints.

3 Applications of the model

3.1 Simulation runs and analysis

The model can be tested on several sets of different input variables. Each simulation run varied on one of the following variables:

- **Layout**: The floorplan of the stands in the venue. There are three types of layouts used, as shown in figure 2:

  Type A shows an island type layout

  Type B shows a corridor layout

  Type C shows a combination of the two

- **Density and stand size**: There are three levels of density and stand sizes used: 16 large stands (12 × 12 meters); 32 medium sized stands, (6 × 12 meters); 64 small sized stands (6 × 6 meters) (see figure 3)

- τ_{max}: This indicates the number of stands that can start simultaneously. There are two τ_{max} values used: 4 and 7.

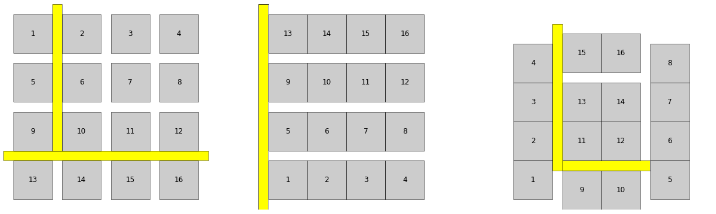

Figure 2. Layout types. Left: Type A. Middle: Type B. Right: Type C

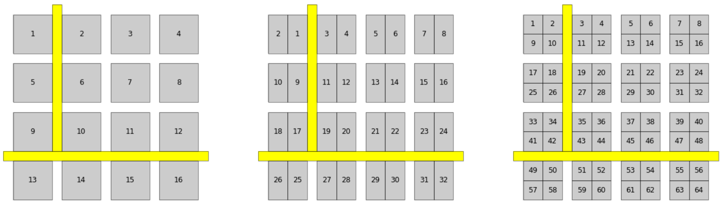

Figure 3. Different densities and stand sizes for layout type A. Left: 16 large sizes stands. Middle: 32 medium sized stands. Right: 64 small sized stands. Source: author.

- T_{max}: This is the maximum available construction time. This is varied between 36 hours (2.5 construction days), 42 hours (3 construction days) and 56 hours (4 construction days).

Each of the layouts, densities, τ_{max} values and T_{max} are combined with each other, resulting in 54 different scenarios.

3.2 Case study

Now that the model is created, it can be applied on a case study. Data for this case study was collected from a fair at RAI Amsterdam. During this fair, three halls were in use, with a total of 218 stands of which 77 stands were included. Construction took place over the course of four days.
First a baseline scenario is created, with the actual start times of stands' construction. After this, the model is run and predetermined starting times of stands' construction are let go of. The model takes the accessibility of the stands into account (named the "accessibility policy"). The model is also run without these constraints in order to see the trade-off the model makes (this model only uses the delay aspects in its optimization and is therefore called the "delay policy").

4 Results

The model was run using Gurobi (a commercial solver) in python, on a HP Laptop 15-bs0xx, with 2.50 GHz Intel-Core i5 processor and 16GB RAM. All simulation run results were scored on four KPIs:

1. **Mean density:** This is the same as the objective value of the model

2. **Variance of density:** A lower variance

indicates that density is distributed more evenly over time, avoiding peaks of high density.

3. **(Average number of) interferences per stand:** The interferences indicate how many constructing stands share their workspace with others.

4. **Variance in starting time:** This indicates to what degree the starting times are spread over the entire timespan.

4.1 Simulation run results

Using the ordinary least squares method, the following effects can be found per variable (see table 1):

- Layout type A scored better on mean density and density variance, with an increase of -19.0% and -16.6% respectively compared to type B, and -5.0%, -1.1% compared to type C. Layout type A, with more space per stand, results in lower mean density and greater flexibility in material placement, leading to reduced density variance but more potential for interferences. Layouts B and C, with corridors, prioritize stands at the back, progressively moving closer to the yellow path, while layout A lets large stands near the yellow path begin first, but begins with the furthest away stands when stands are smaller.

- τ_{max} had no significant influence on any KPI other than starting time variance. Since this is the least important KPI, the influence of τ_{max} is minimal. However, despite τ_{max} not influencing the KPIs, a higher τ_{max} resulted in more stands starting construction within the first two to three hours.

- Additional construction time proved to significantly improve all four KPIs (-1.0%, -1.6%, -1.5% and -3.2% respectively). An increase in available construction time T_{max} resulted in a scheduling strategy with a larger temporal spread of the starting times.

- The effects of stand sizes were mixed. While medium and large stands score best on mean density (-5.76& compared to small stands), small and medium stands score better on interferences (-8.38% and -5.57% respectively). These effects can be attributed to fewer large stands bringing fewer materials than more smaller stands. Fewer stands also allow for a more uniform material storage distribution. However, the larger size of the stands also creates more interferences. Density and size appeared to not significantly change starting tactics.

4.2 Case study results

The resulting changes in objective value, KPI scores and average start time for the case study can be found in table 2. The progression of the average density of the baseline, delay policy and accessibility policy scenario over the full construction timespan can be found in figure 4.

The delay policy managed to get clear improvements on the objective value (-0.27 %, -7.35% and -3.11% per hall) as well as the variance in density (-32.0%, -29.9% and -45.3%) and number of interferences (-13.4%, -30.8% and -20.4%). This was done by letting stands start construction earlier in such a way that construction was more spread over the entire timespan than in the baseline scenario. High peaks in density that were found in the baseline scenario were absent in the proposed delay policy schedule.

The accessibility policy introduced a trade-off between accessibility of stands, and the

Dependent Variable	Independent Variable	Coefficient	Standard Error	t-Statistic	p-Value
Mean Density	Constant	0.2275	0.014	16.448	0
	Type A	-0.0433	0.004	-10.756	0
	Type B	-0.0114	0.004	-2.888	0.007
	Tau	0	0.001	0.052	0.959
	Time	-0.0023	0	-10.809	0
	Size Small	0.0139	0.004	3.347	0.002
	Size Medium	-0.0037	0.004	-0.986	0.332
Density Variance	Constant	0.0187	0.002	9.611	0
	Type A	-0.0031	0.001	-5.517	0
	Type B	-0.0002	0.001	-0.298	0.768
	Tau	0	0	0.038	0.97
	Time	-0.0003	0	-8.932	0
	Size Small	0.0008	0.001	1.345	0.189
	Size Medium	-0.0007	0.001	-1.301	0.204
Interferences	Constant	1.6796	0.102	16.498	0
	Type A	0.2854	0.03	9.641	0
	Type B	0.2403	0.029	8.243	0
	Tau	-0.0028	0.008	-0.342	0.735
	Time	-0.0253	0.002	-16.097	0
	Size Small	-0.1402	0.031	-4.583	0
	Size Medium	-0.0935	0.028	-3.367	0.002
Starting Time Variance	Constant	3.1414	1.363	2.305	0.029
	Type A	0.4267	0.396	1.077	0.29
	Type B	0.4251	0.39	1.089	0.285
	Tau	0.4719	0.109	4.322	0
	Time	-0.0996	0.021	-4.733	0
	Size Small	3.5297	0.409	8.622	0
	Size Medium	1.4081	0.372	3.789	0.001

Table 1. **Multilinear regression results for different dependent variables. Source: author.**

number of interferences and density of materials. Therefore, the objective value and number of interferences were higher for the accessibility policy compared to the delay policy. However, the accessibility policy still performed significantly better compared to the baseline scenario, with significant decreases in density variance (-36.0%, -29.9% and -50.7%) and number of interferences (-10.4%, -23.1% and -20.4%). There was a distinct preference for starting construction earlier for stands located farther from the yellow path and at risk of being blocked by other stands. Consequently, this led to a peak in material density during the first half of the construction period.

5 Conclusion and discussion

This research developed a first scheduling method for trade fairs. This research takes the first step in filling the literature gap on event logistics, by developing a scheduling method specifically for trade fair construction logistics. It introduced a MILP model that effectively reduces both material storage in aisles and workspace interferences during stand construction at trade fairs. In the case study, the model decreased the overall average of materials stored in aisles by 3.1%, reduced the variance in material density by 38.9%, and lowered the number of workspace interferences by 18.0% on average. These improvements were pri-

Hall	Scenario	Average start time (h)	Mean Density	Difference to baseline (%)	Density Variance	Difference to baseline (%)	Interferences	Difference to baseline (%)	Starting Time Variance	Difference to baseline (%)
10	Baseline	14.1	0.0751	n.a.	0.0025	n.a.	0.67	n.a.	0.45	n.a.
	Delay Policy	9.1	0.0749	-0.266%	0.0017	-32.0 %	0.58	-13.4%	0.46	+2.22%
	Accessibility Policy	9.5	0.0754	+0.40%	0.0016	-36.0%	0.60	-10.4%	0.48	+6.67%
11	Baseline	19	0.0476	n.a.	0.00097	n.a.	0.26	n.a.	1.18	n.a.
	Delay Policy	15.0	0.0441	-7.35%	0.00039	-59.8%	0.18	-30.8%	0.71	-39.8%
	Accessibility Policy	13	0.0444	-6.72%	0.00068	-29.9%	0.20	-23.1%	0.75	-36.4%
12	Baseline	17.2	0.0546	n.a.	0.0015	n.a.	0.49	n.a.	1.28	n.a.
	Delay Policy	13.6	0.0529	-3.11%	0.00082	-45.3%	0.39	-20.4%	1.14	-10.9%
	Accessibility Policy	16.1	0.0530	-2.9%	0.00074	-50.7%	0.39	-20.4%	1.03	-19.5%

Table 2. Simulation results comparing the original and optimized scenarios for Halls 10, 11, and 12. Source: author.

marily achieved by prioritizing earlier start times for stands located farther from the main path ("yellow path"), to better distribute the materials storage over the available construction period.

When accessibility constraints were removed, allowing the model greater flexibility in scheduling, even higher reductions were found: a 10.7% decrease in aisle material storage, a 45.7% reduction in density variance, and a 64.6% drop in interferences. This trade-off suggests that reducing logistical constraints allows for more efficient scheduling, but may come at the cost of practicality or feasibility in real-world applications, where these accessibility rules are often necessary. So, while allowing the model unrestricted freedom yields optimal results, implementing this strategy requires balancing with practical constraints.

The analysis of different simulation runs showed that the degree of improvement largely depends on hall layout, stand density, stand size, and available construction time. Among the layouts, the island design produced the most favorable results, achieving reductions of 19.0% in mean density and 16.6% in density variance compared to the corridor design, and 5.0% and 1.1% compared to the mixed design. Additional available construction time also proved beneficial, improving each key performance indicator: for every extra hour, mean density, density variance, number of interferences, and variance in start time improved by 1.0%, 1.6%, 1.5%, and 3.2%, respectively.

The takeaway messages that could be implemented in real-life trade fair management are as follows:

1. Prioritize early start times for distant stands: By allowing stands that are farther from main access paths to begin construction earlier, overall material density in shared spaces can be reduced.

2. Spread start times to distribute construction density: Spreading start times across all stands, rather than clustering them around the same period, allows for a more balanced use of workspace. This approach not only reduces peaks in material density but also decreases the chance of workspace interferences.

In future research, the current MILP model could be expanded by including the multiple deliveries and construction teams into the model. Another recommended direction for future research, is to investigate

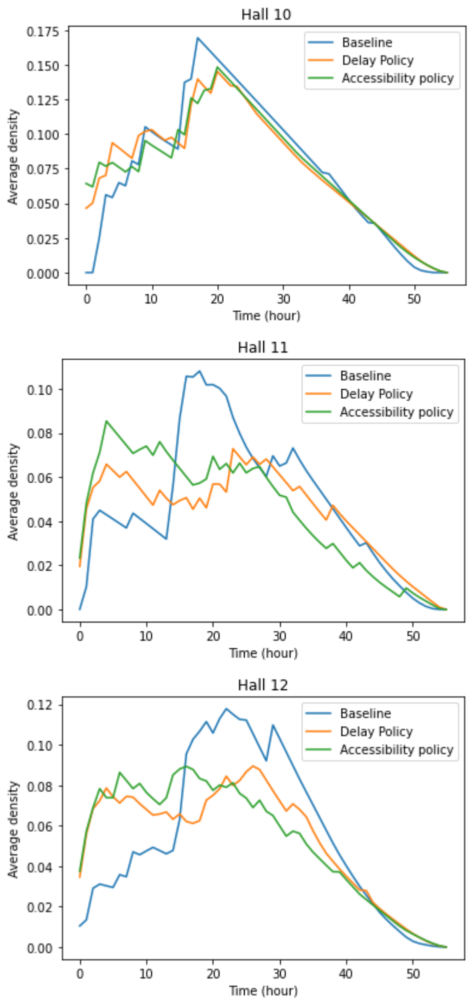

Figure 4. Progression of the average density in hall 10 (top), 11 (middle) and 12 (bottom) under the baseline, delay and accessibility scenario. Source: author.

how each standbuilder precisely plans the construction of a stand. This approach will not only differ per stand, but also per company. Researching this, will give a better insight in the traffic movements and construction flow of stands.

In conclusion, this study demonstrated that a scheduling method, particularly one that prioritizes distant stands and lets stands start earlier, can significantly reduce aisle storage usage and reduce workspace interferences in trade fair constructions. While the model performs best when given full flexibility, practical application may require the additional accessibility constraints. These insights can offer a guideline for trade fair organizers to improve construction schedules.

Appendix A

$$\text{Minimize } Z = \frac{\sum_{t\in T}\sum_{s\in S}\rho_s^t \cdot \nu(\Omega_s)}{(\sum_{s\in S}\nu(\Omega_s)) * T_{max}}$$

s.t.

$$\sum_{t=1}^{T_{max}-D_s} \tau_s^t = 1 \qquad \forall s \in S$$

$$\sum_{t=T_{max}-D_s+1}^{T_{max}} \tau_s^t = 0 \qquad \forall s \in S$$

$$\sum_{s\in S} \tau_s^t \leq \tau_{max} \qquad \forall t \in T$$

$$\rho_s^t = \sum_{\sigma\in\{1,2,3,4\}} \rho_{s,\sigma}^t \frac{\nu(\Omega_{s,\sigma})}{\nu(\Omega_s)} \qquad \forall s \in S, t \in T$$

$$\rho_{s,\sigma}^t + \rho_{s',\sigma'}^t \leq 1 \qquad \forall s \in S, \sigma \in \{1,2,3,4\}, (s',\sigma') \in I_{s,'}, t \in T$$

$$\rho_s^t \geq \tau_s^t \cdot \mu_s + (1+w_s)\rho_s^{t-1} - (\sum_{t'=1}^{t-1} \tau_s^{t'})\frac{\mu_s}{D_s}$$

$$+ w_s \cdot \left(\sum_{\sigma\in\{1,2,3,4\}} \sum_{(s',\sigma')\in I_{s,\sigma}} \sum_{t'=1}^{t-1} \psi_{(s,\sigma),(s',\sigma')}^{t',t} \cdot \frac{\nu(\Omega_{ss'})}{\nu(\Omega_s)} \right) \qquad \forall s \in S, t \in \{2,\dots,T\}$$

$$\rho_s^1 = \tau_s^1 \cdot \mu_s \qquad \forall s \in S$$

$$\rho_s^{T_{max}} = 0 \qquad \forall s \in S$$

$$\psi_{(s,\sigma),(s',\sigma')}^{t',t} \leq \cdot \tau_s^{t'} \qquad \forall s \in S, t \in T, \sigma \in \{1,2,3,4\}, (s',\sigma') \in I_{s,\sigma}, t' \in \{1,\dots,t-1\}$$

$$\psi_{(s,\sigma),(s',\sigma')}^{t',t} \leq \rho_{s',\sigma'}^t \qquad \forall s \in S, t \in T, \sigma \in \{1,2,3,4\}, (s',\sigma') \in I_{s,\sigma}, t' \in \{1,\dots,t-1\}$$

$$\psi_{(s,\sigma),(s',\sigma')}^{t',t} \geq \rho_{ss'}^t - (1-\tau_s^{t'}) \qquad \forall s \in S, t \in T, \sigma \in \{1,2,3,4\}, (s',\sigma') \in I_{s,\sigma}, t' \in \{1,\dots,t-1\}$$

$$\boldsymbol{(1-0.875\cdot\tau_s^t) \geq \rho_i^t \cdot \alpha_s^k} \qquad \boldsymbol{\forall s \in S, t \in T, k \in \{1,\dots,K\}, \rho_i^t \in p_s^{t,k}}$$

$$\boldsymbol{\sum_{k\in K} \alpha_s^k \geq 1} \qquad \boldsymbol{\forall s \in S}$$

$$\boldsymbol{\alpha_s^k}, \tau_s^t \in \{0,1\} \qquad \forall s \in S, t \in T, k \in K$$

$$\rho_{s,0}^t, \rho_{s,s'}^t \in [0,1] \qquad \forall s \in S, s' \in I_s, t \in T$$

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B

Definition of $\delta_{s,(x,y)}$

A stand has 4 areas that it could use for storage (see figure 4.1). For each of these areas, a different set of statements need to be true, indicated by A_s^1, A_s^2, A_s^3 and A_s^4 respectively:

Area 1 : For $\delta_{s,(x,y)}$ to be 1 in area 1, the following should hold: the x value should fall within the boundaries of the stand, and the y value should be between than y_s^u, and $y_s^u + L$. Also, $\delta_{s,(x,y)} = 0$ if (x, y) is used for construction by another stand. $A^1_{s,(x,y)}$ can be defined as follows:

$$A^1_{s,(x,y)} := (x_s^l \leq x < x_s^r) \wedge (y_s^u \leq y < y_s^u + L) \wedge \left(\sum_{s' \in S \setminus \{s\}} c_{s',(x,y)} = 0 \right)$$

Area 2 : In a similar fashion $A^2_{s,(x,y)}$ can be defined as:

$$A^2_{s,(x,y)} := (x_s^r \leq x < x_s^r + L) \wedge (y_s^l \leq y < y_s^u) \wedge \left(\sum_{s' \in S \setminus \{s\}} c_{s',(x,y)} = 0 \right)$$

Area 3:

$$A^3_{s,(x,y)} := (x_s^l \leq x < x_s^r) \wedge (y_s^l - L \leq y < y_s^l) \wedge \left(\sum_{s' \in S \setminus \{s\}} c_{s',(x,y)} = 0 \right)$$

Area 4:

$$A^4_{s,(x,y)} := (x_s^l - L \leq x < x_s^l) \wedge (y_s^l \leq y < y_s^u) \wedge \left(\sum_{s' \in S \setminus \{s\}} c_{s',(x,y)} = 0 \right)$$

Now, $\delta_{s,(x,y)}$ can be defined as:

$$\delta_{s,(x,y)} := \begin{cases} 1 & \text{if } A^1_{s,(x,y)} \vee A^2_{s,(x,y)} \vee A^3_{s,(x,y)} \vee A^4_{s,(x,y)} \\ 0 & \text{else} \end{cases}$$

C

Layouts, with different densities and stand sizes

C.0.1 Type A

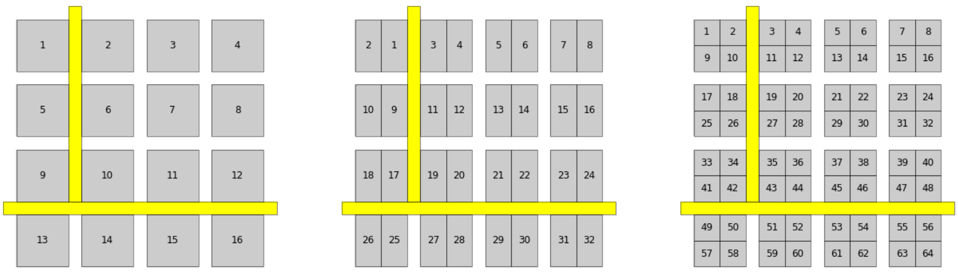

Figure C.1: *Different densities and stand sizes for layout type A. Left: 16 large sizes stands. Middle: 32 medium sized stands. Right: 64 small sized stands. Source: author.*

C.0.2 Type B

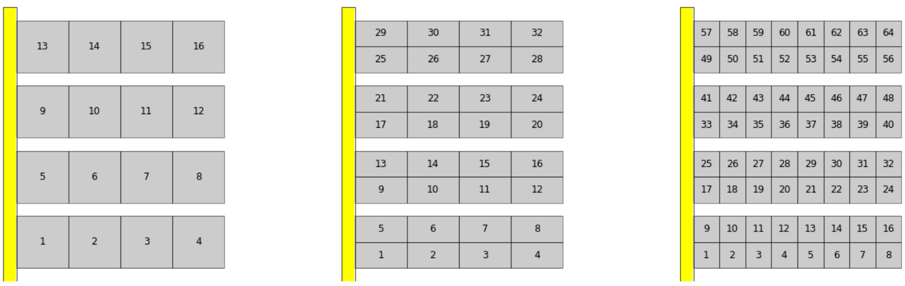

Figure C.2: *Different densities and stand sizes for layout type B. Left: 16 large sizes stands. Middle: 32 medium sized stands. Right: 64 small sized stands. Source: author.*

C.0.3 Type C

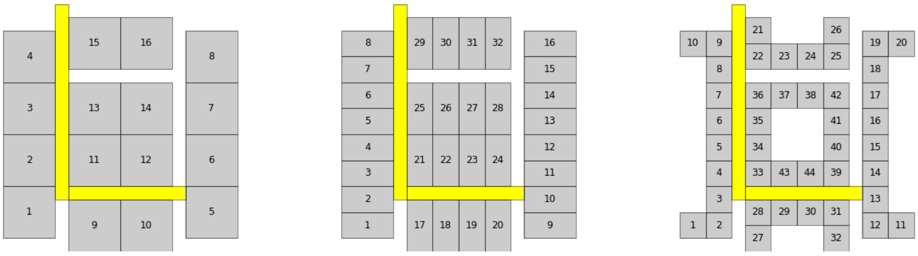

Figure C.3: *Different densities and stand sizes for layout type C. Left: 16 large sizes stands. Middle: 32 medium sized stands. Right: 64 small sized stands. Source: author.*

D

Results of the simulation runs

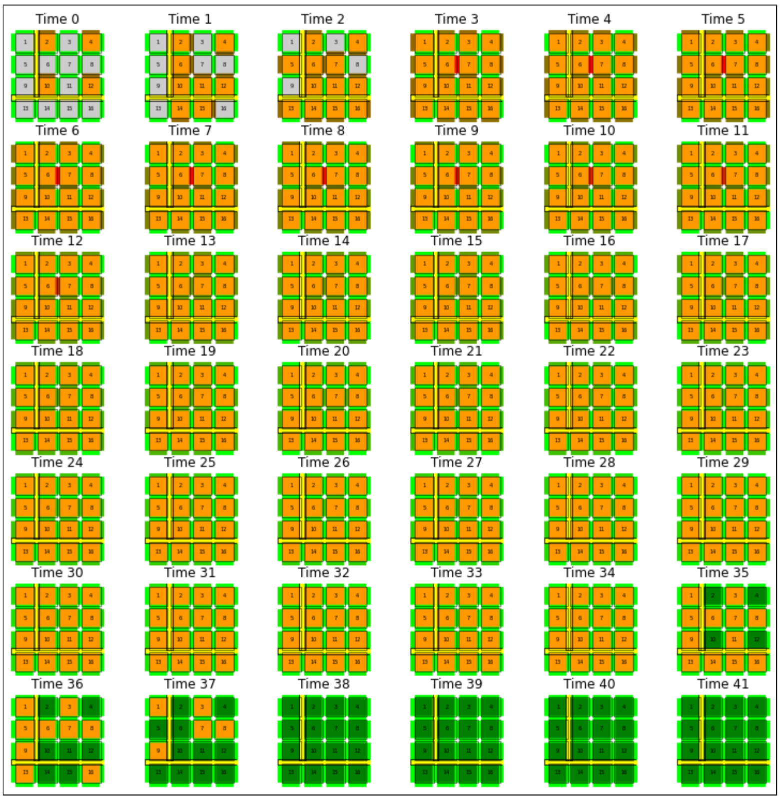

Figure D.1: *Scenario 2. Source: author.*

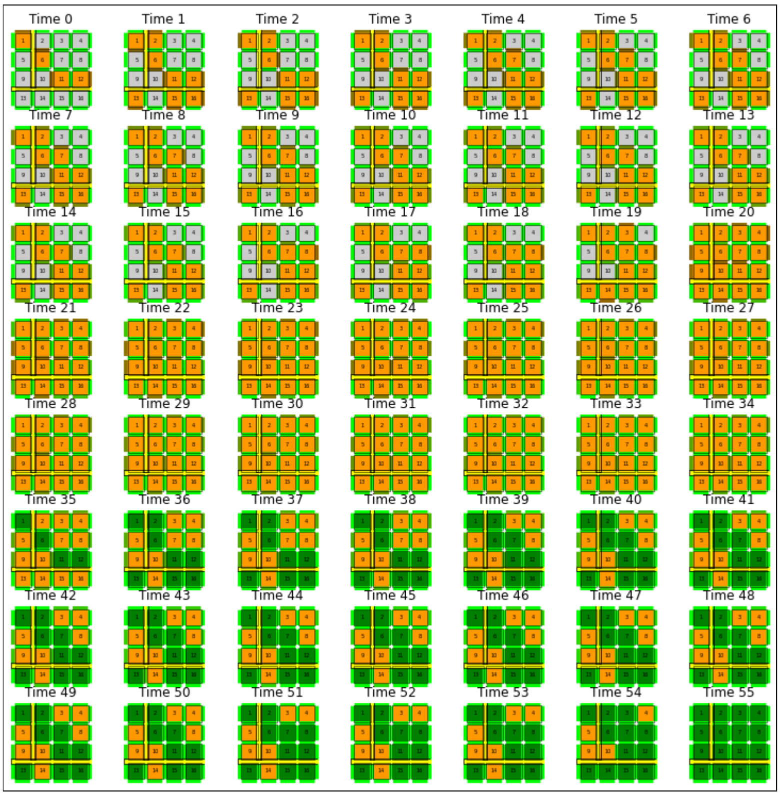

Figure D.2: *Scenario 3. Source: author.*

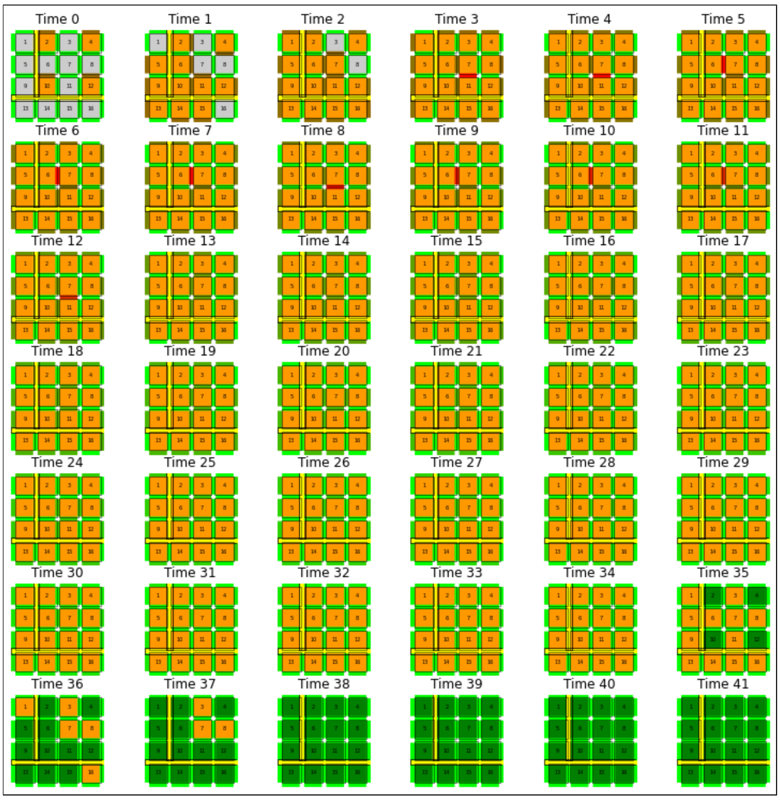

Figure D.3: *Scenario 5. Source: author.*

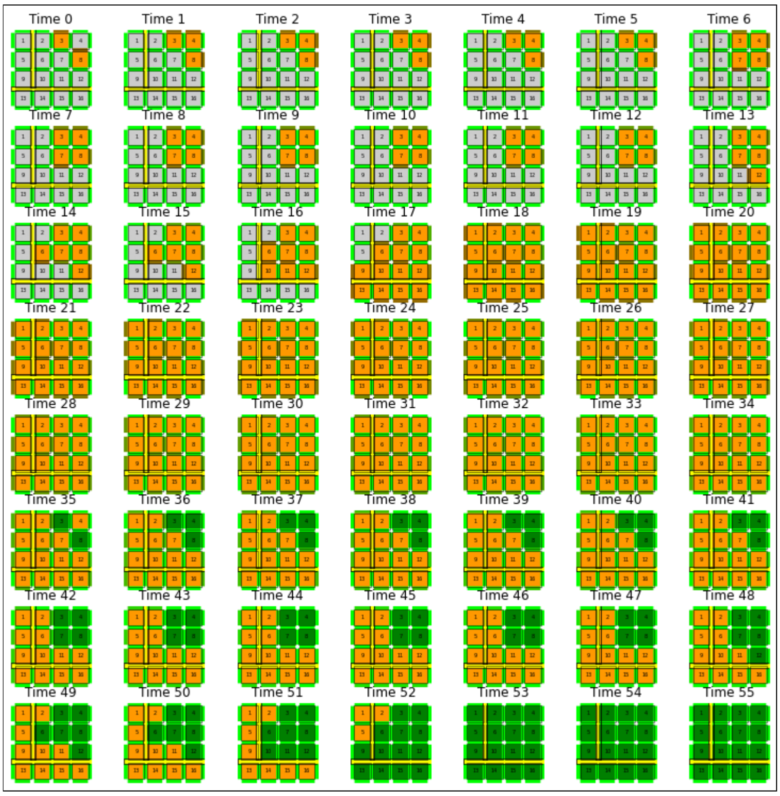

Figure D.4: *Scenario 6. Source: author.*

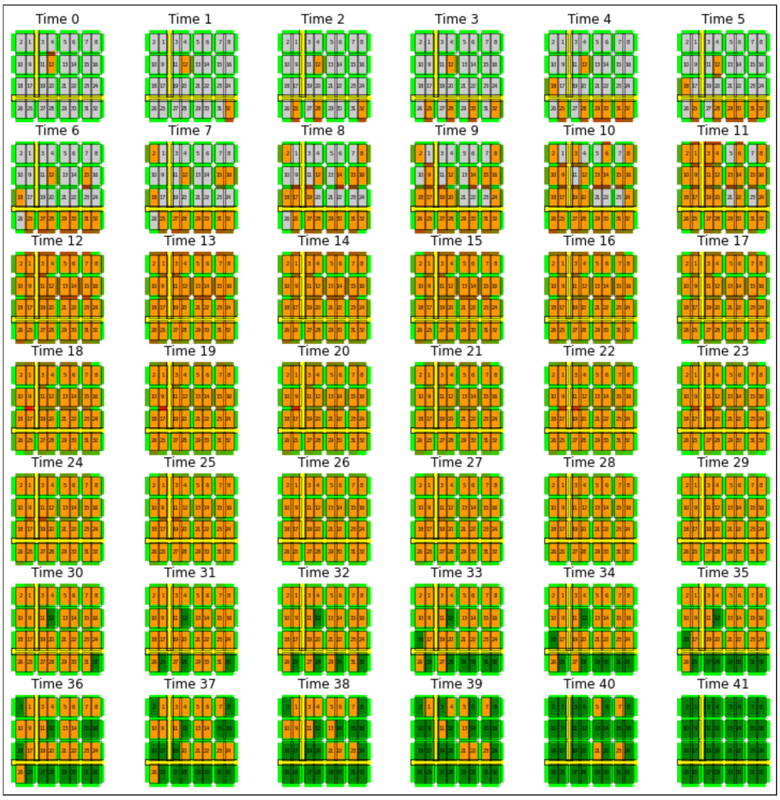

Figure D.5: *Scenario 8. Source: author.*

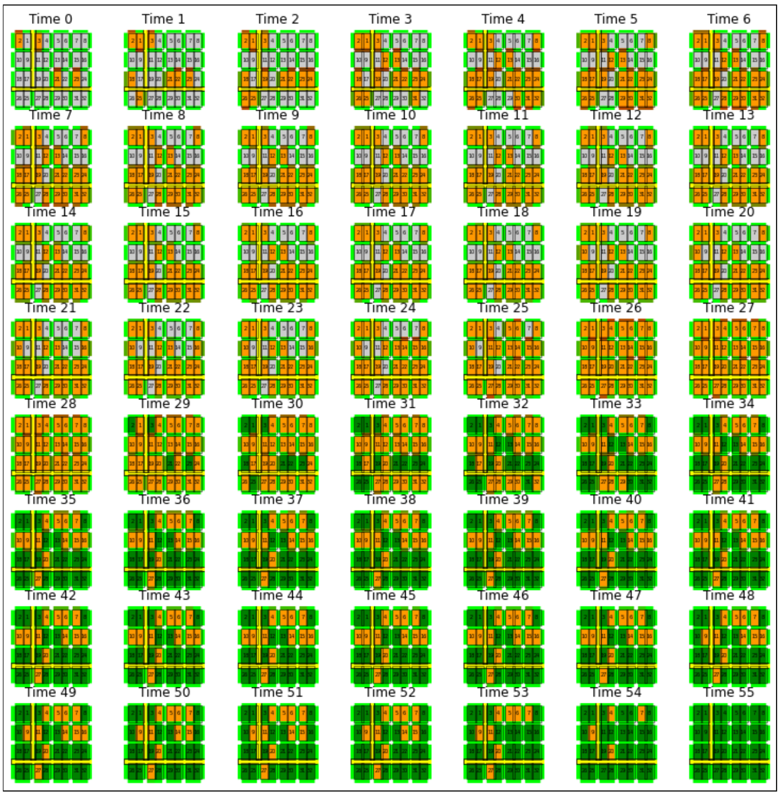

Figure D.6: *Scenario 9. Source: author.*

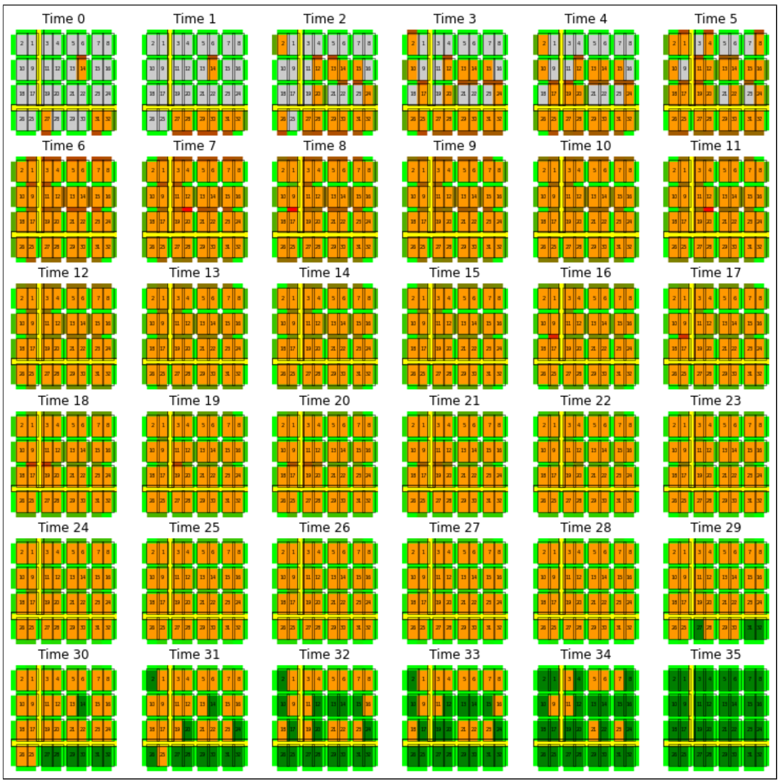

Figure D.7: *Scenario 10. Source: author.*

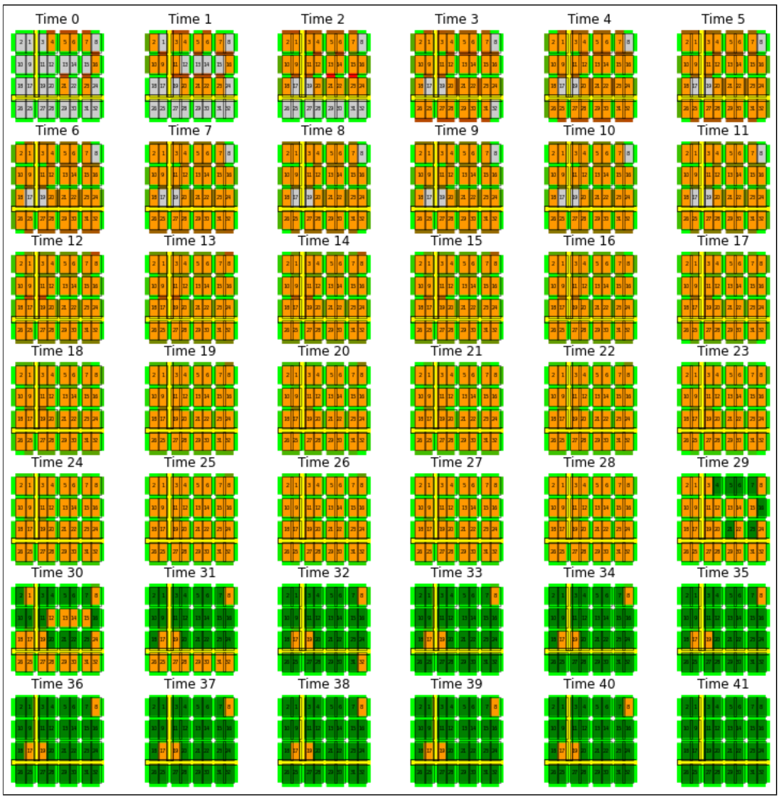

Figure D.8: *Scenario 11. Source: author.*

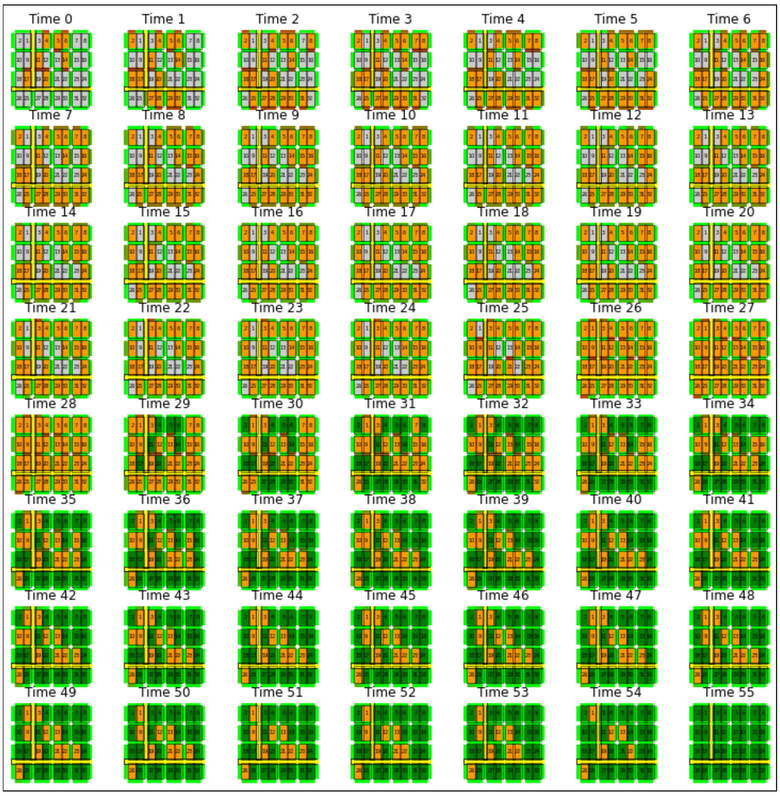

Figure D.9: *Scenario 12. Source: author.*

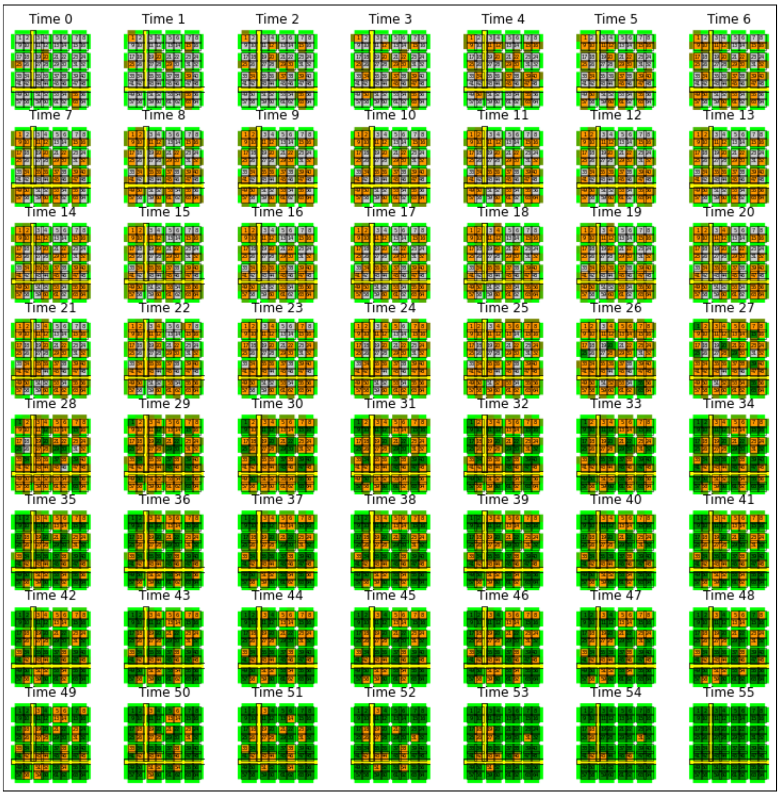

Figure D.10: *Scenario 15. Source: author.*

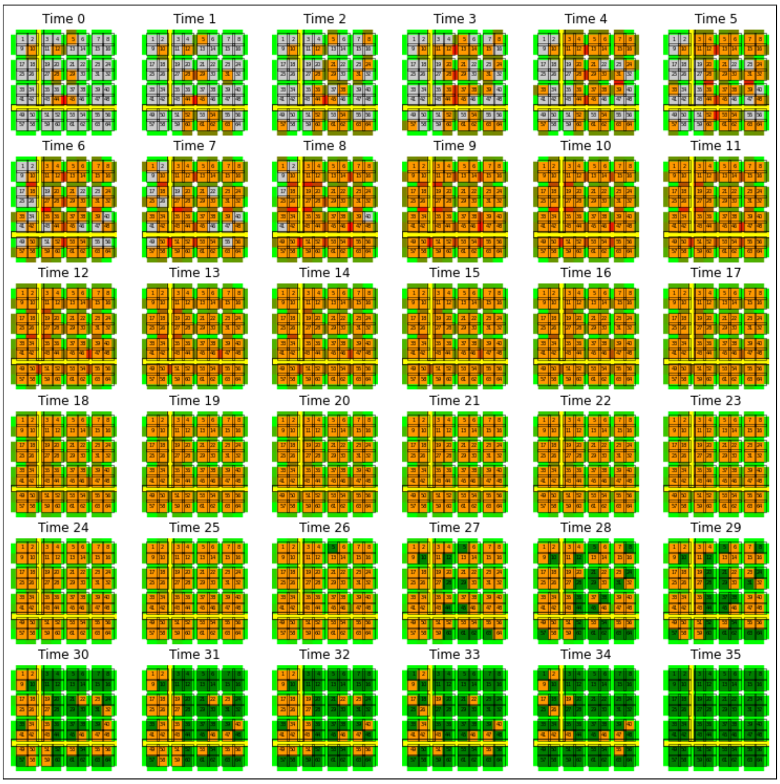

Figure D.11: *Scenario 16. Source: author.*

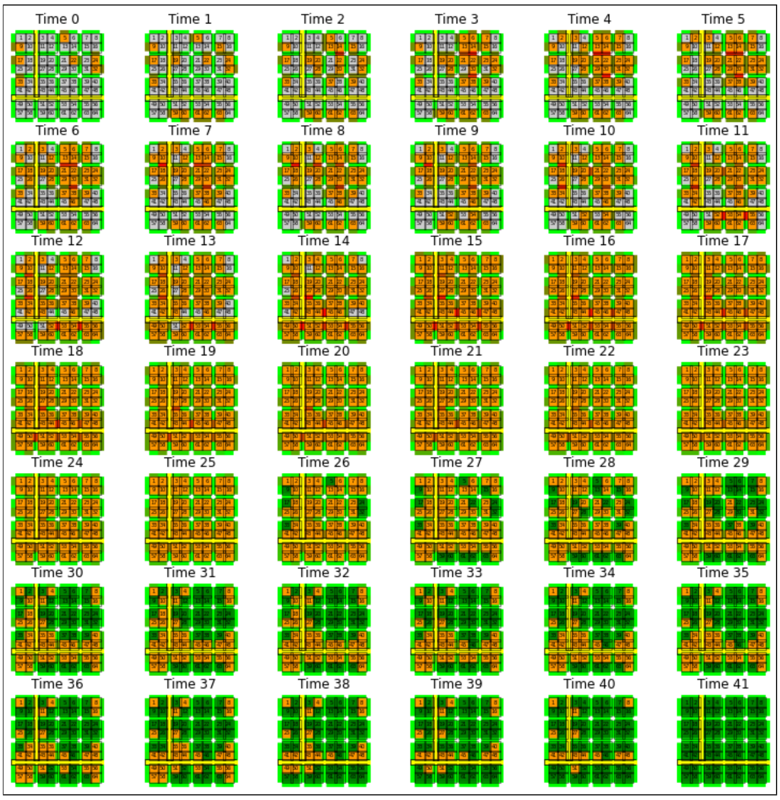

Figure D.12: *Scenario 17. Source: author.*

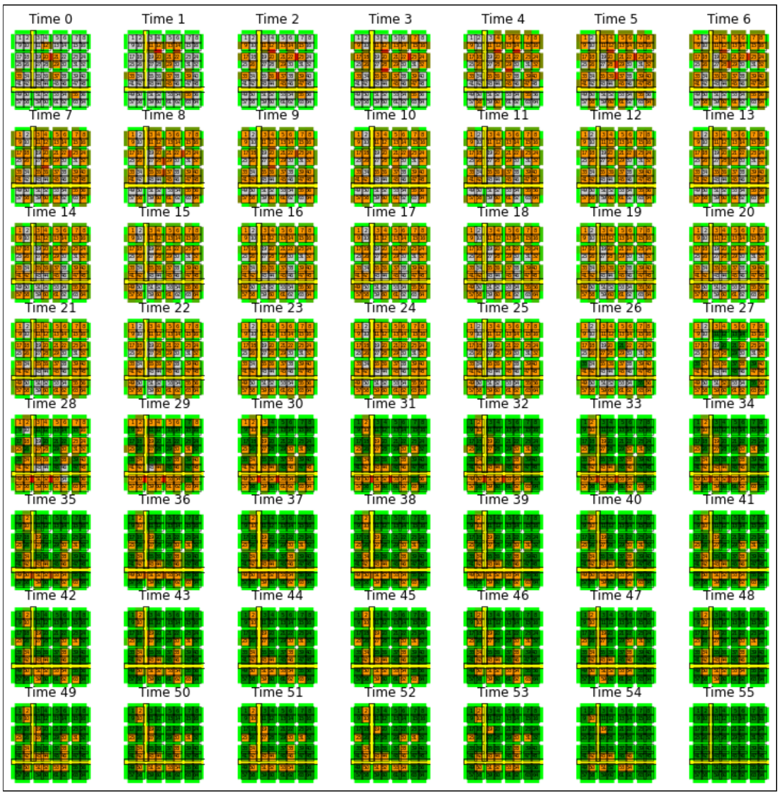

Figure D.13: *Scenario 18. Source: author.*

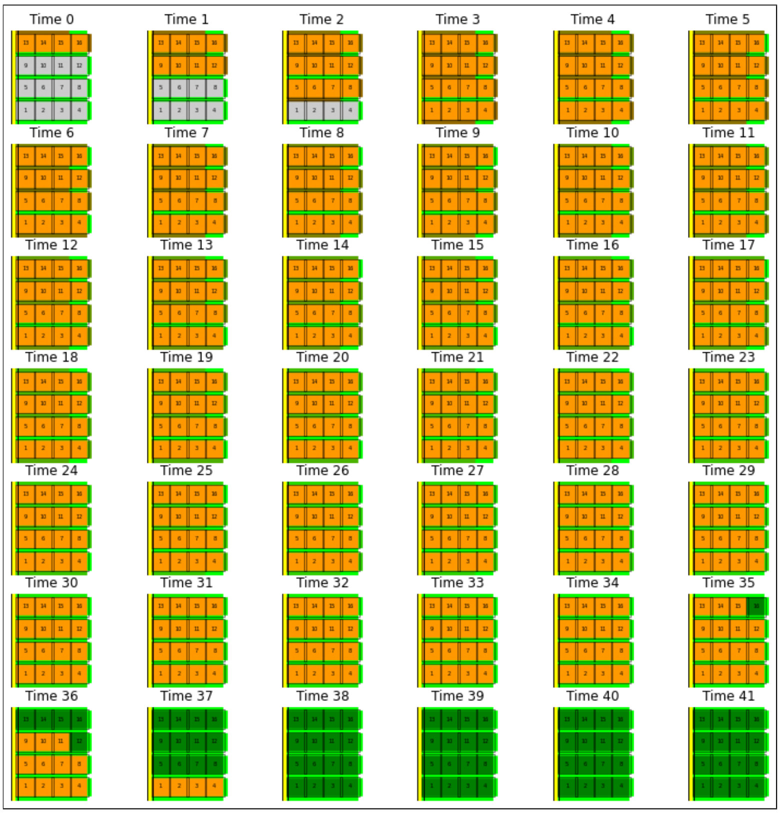

Figure D.14: *Scenario 20. Source: author.*

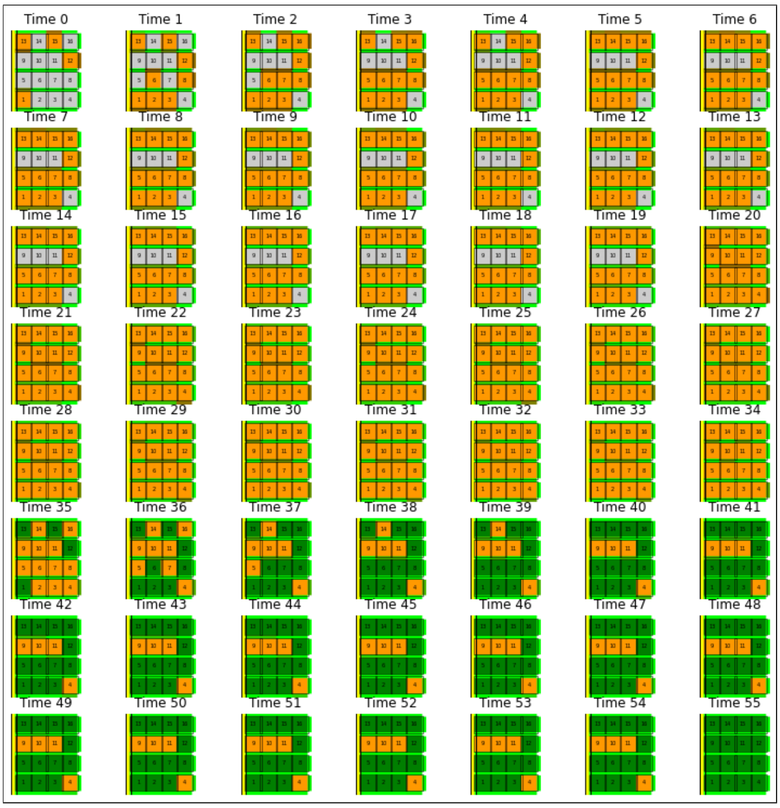

Figure D.15: *Scenario 21. Source: author.*

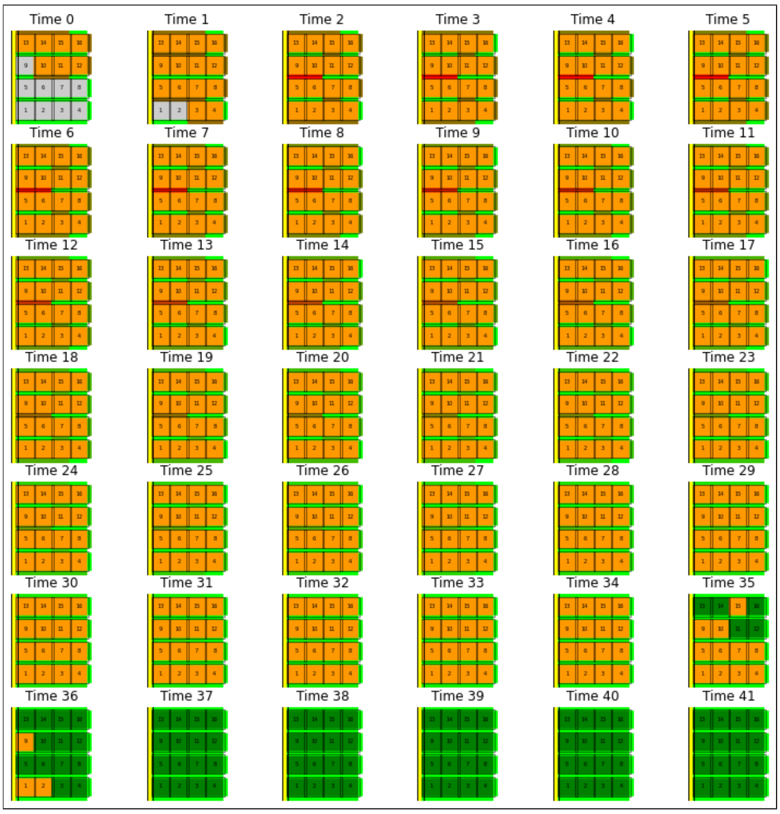

Figure D.16: *Scenario 23. Source: author.*

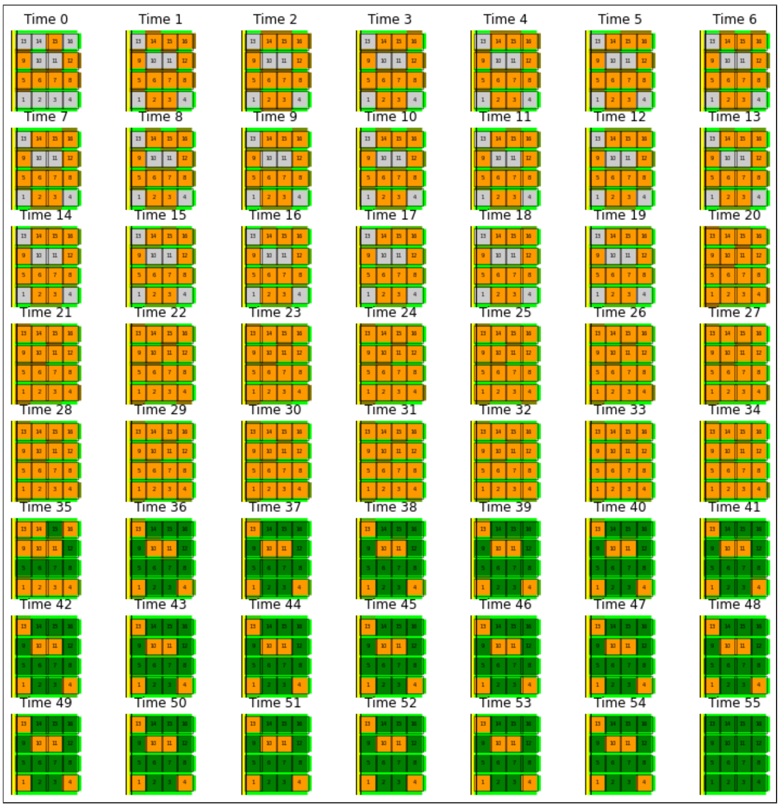

Figure D.17: *Scenario 24. Source: author.*

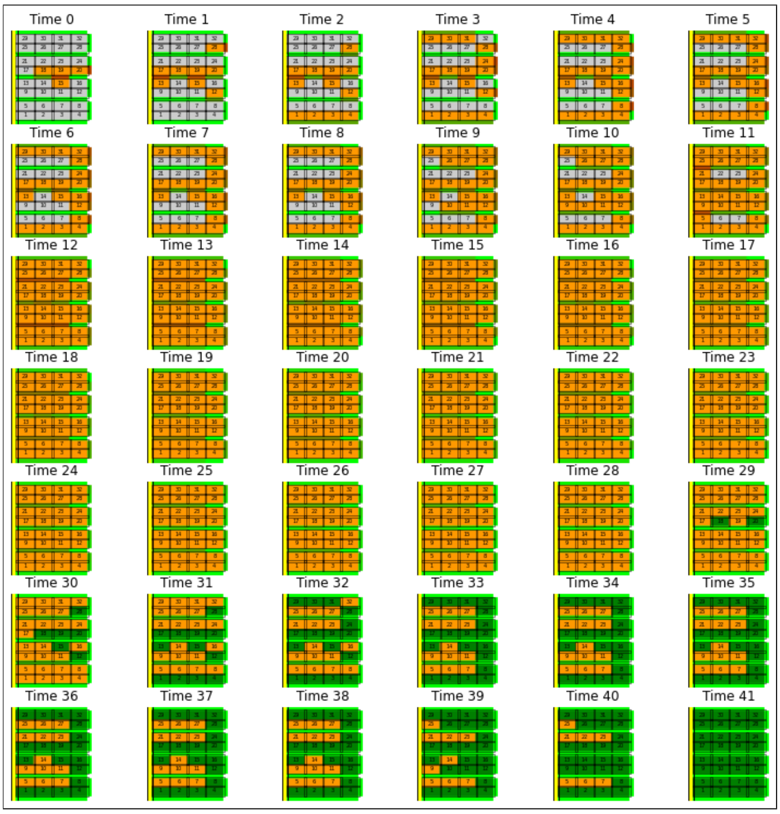

Figure D.18: *Scenario 26. Source: author.*

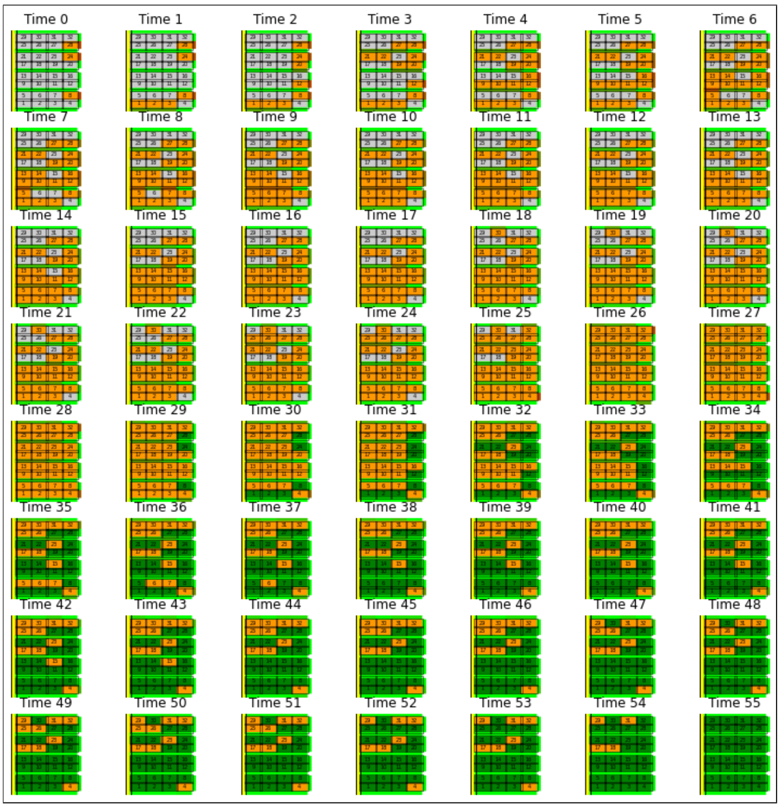

Figure D.19: *Scenario 27. Source: author.*

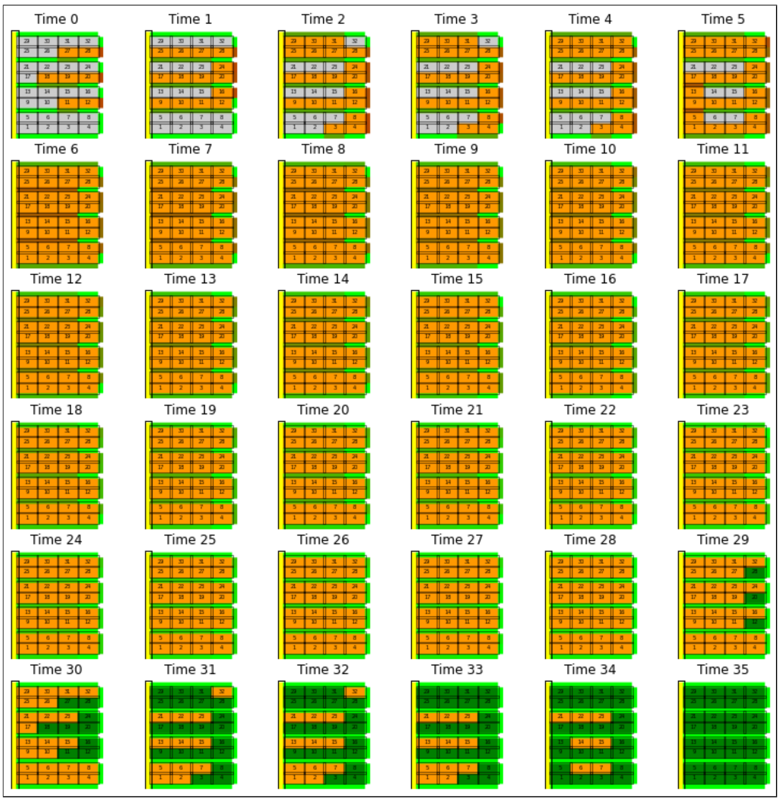

Figure D.20: *Scenario 28. Source: author.*

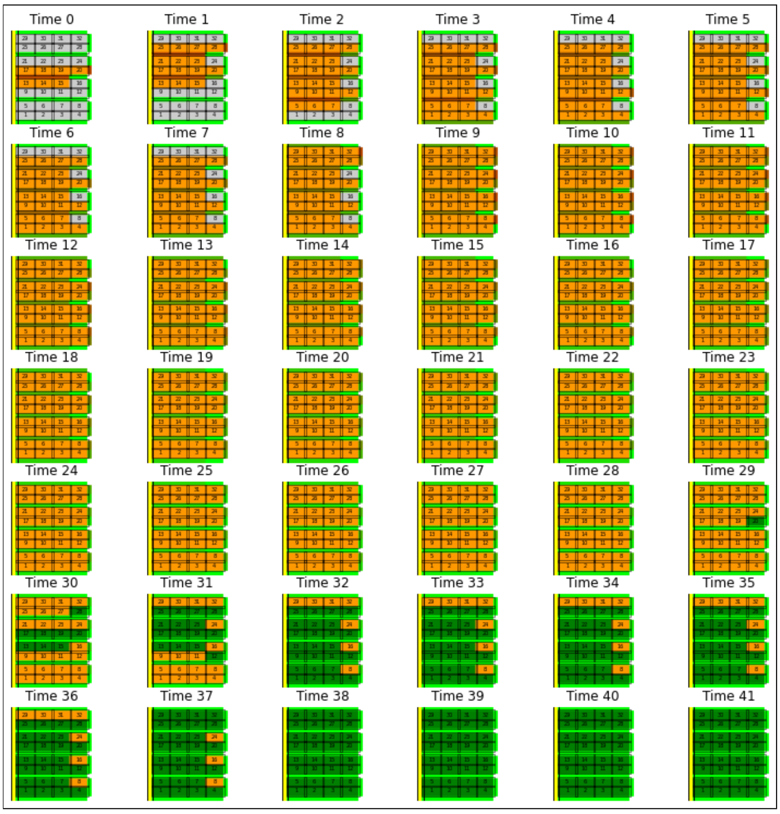

Figure D.21: *Scenario 29. Source: author.*

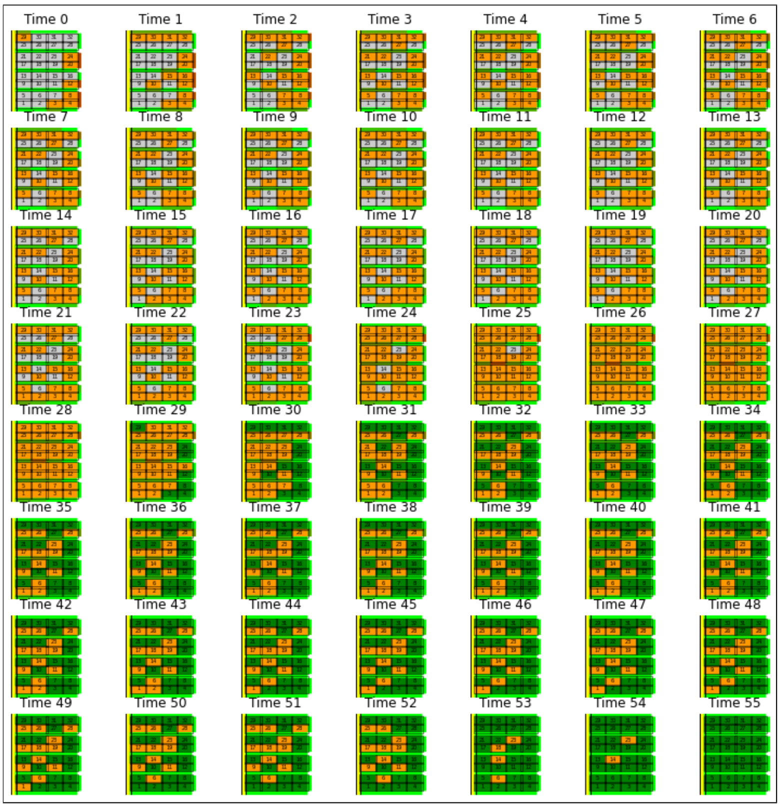

Figure D.22: *Scenario 30. Source: author.*

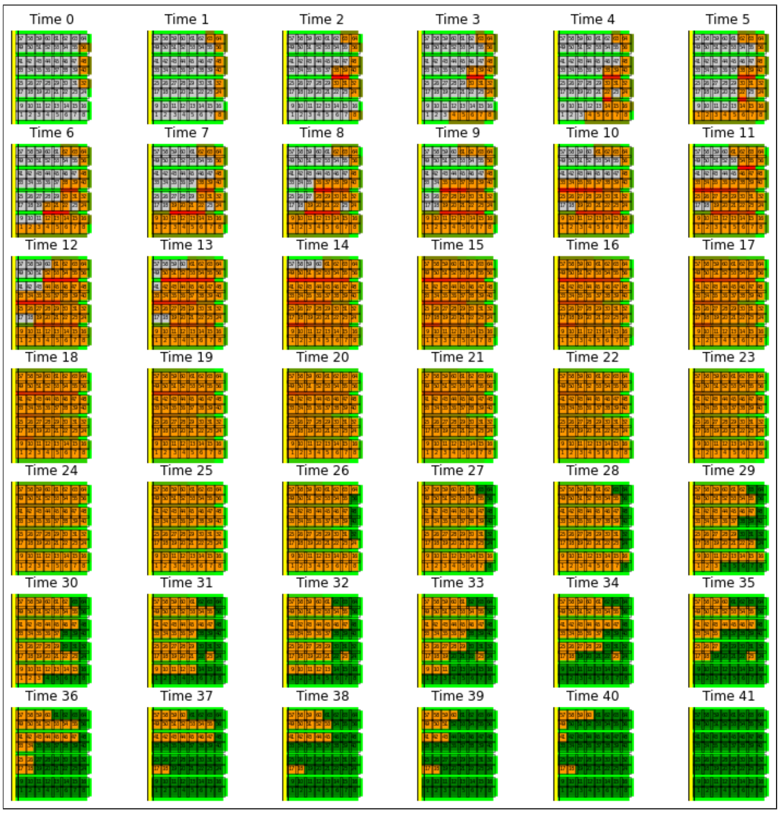

Figure D.23: *Scenario 32. Source: author.*

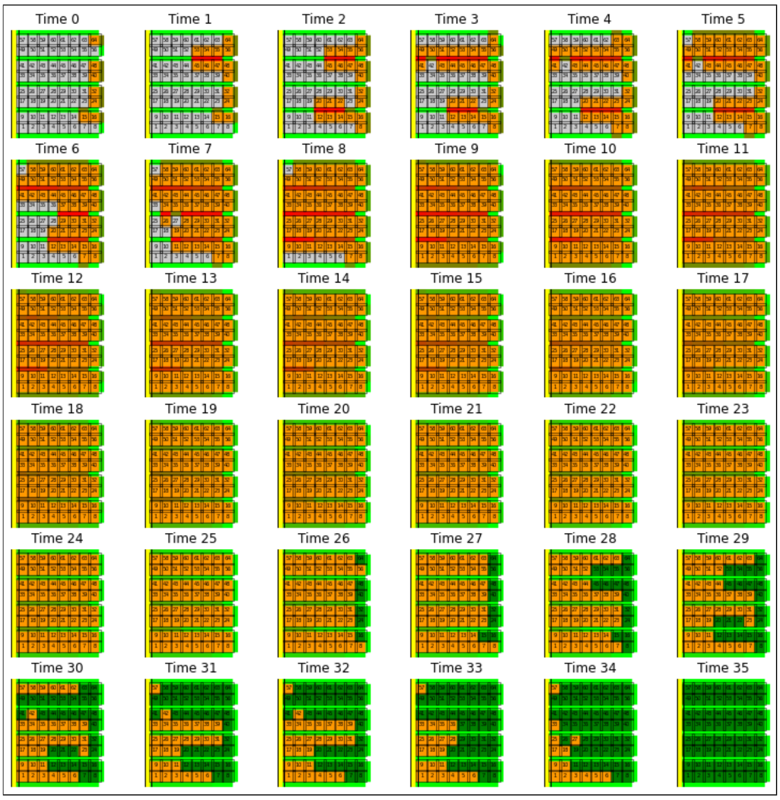

Figure D.24: *Scenario 34. Source: author.*

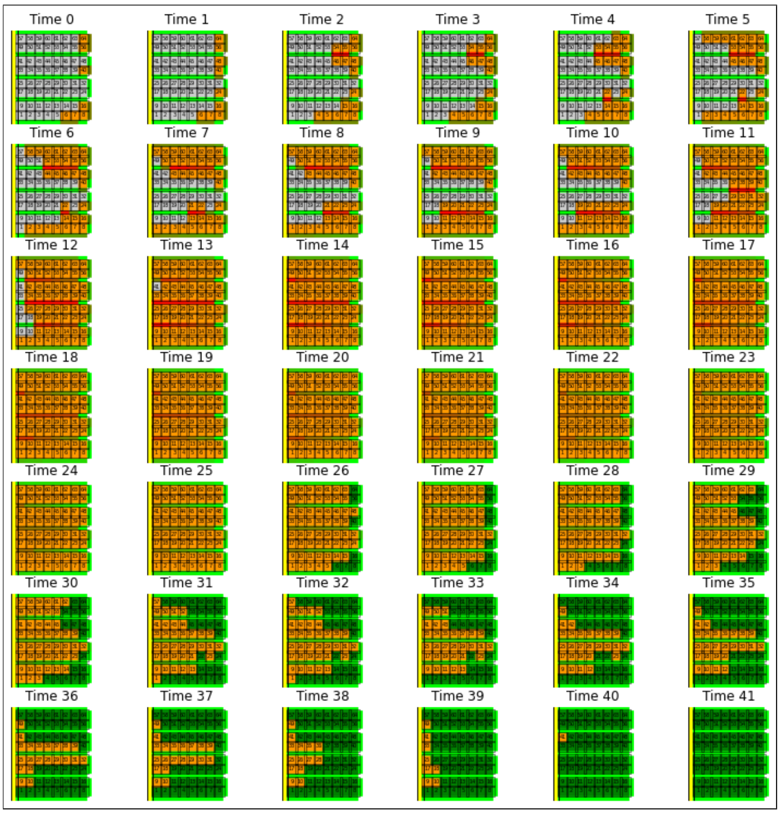

Figure D.25: *Scenario 35. Source: author.*

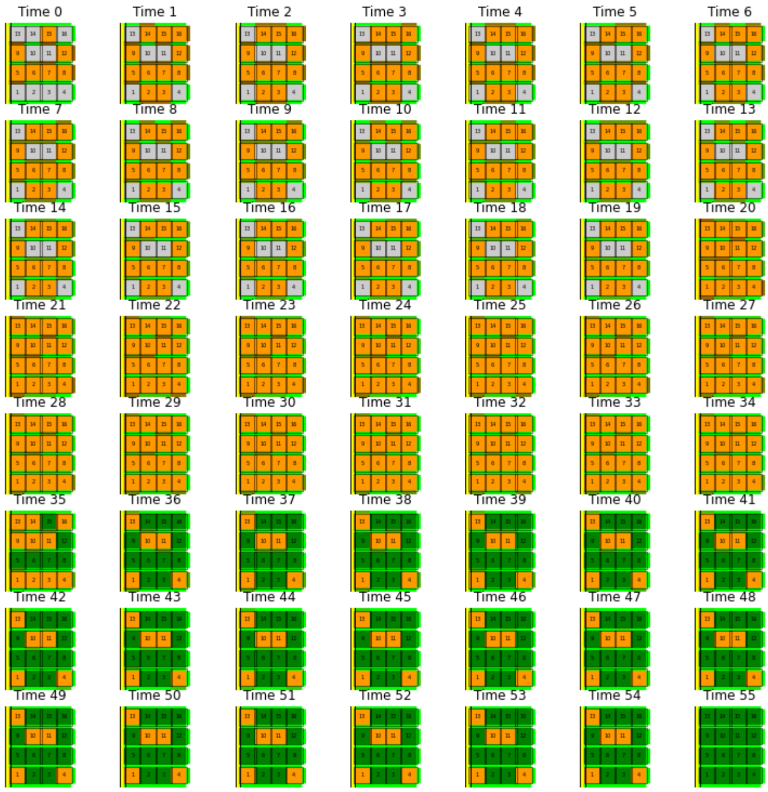

Figure D.26: *Scenario 36. Source: author.*

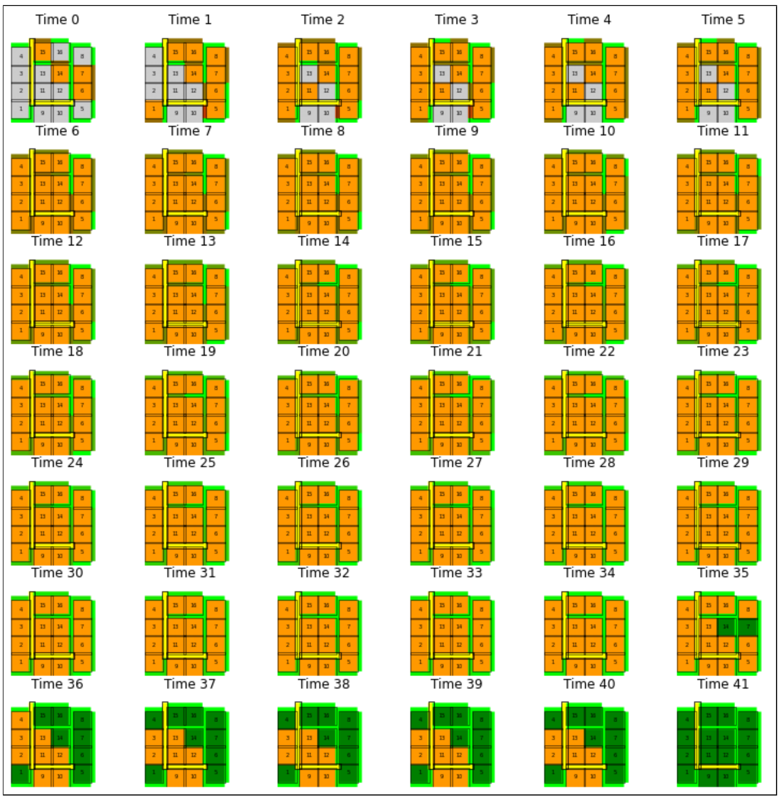

Figure D.27: *Scenario 38. Source: author.*

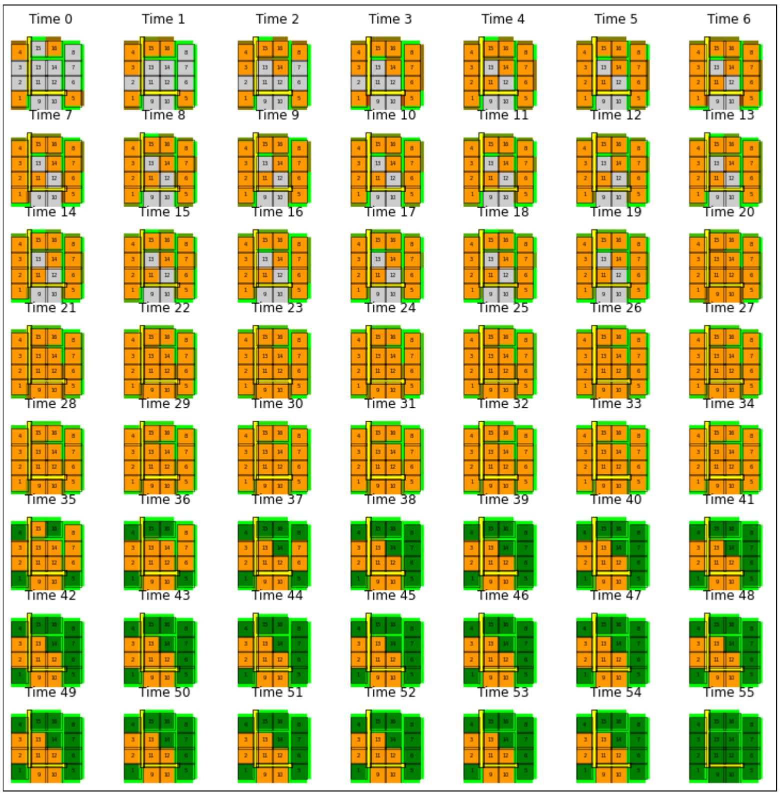

Figure D.28: *Scenario 39. Source: author.*

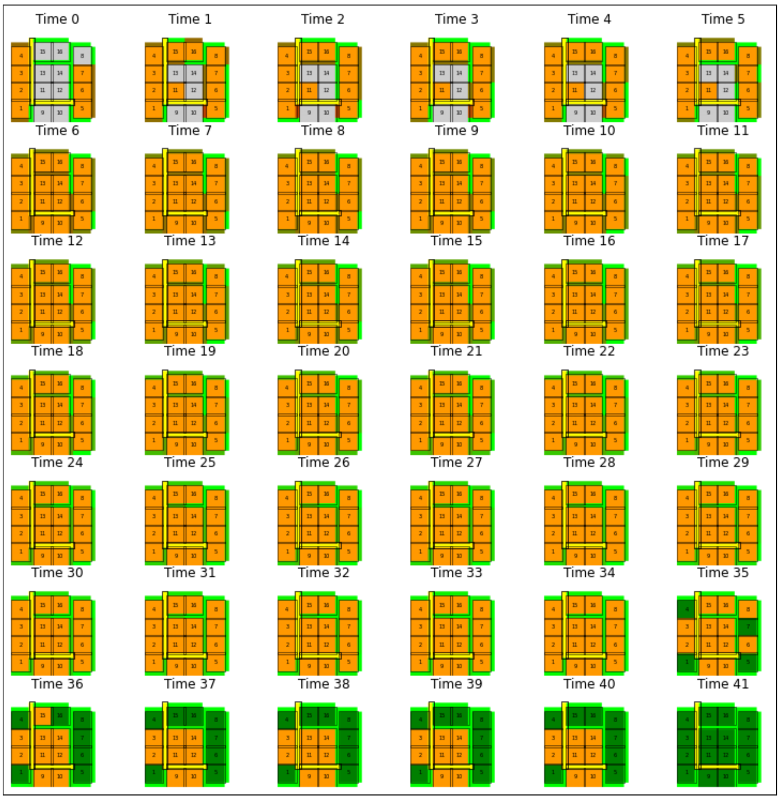

Figure D.29: *Scenario 41. Source: author.*

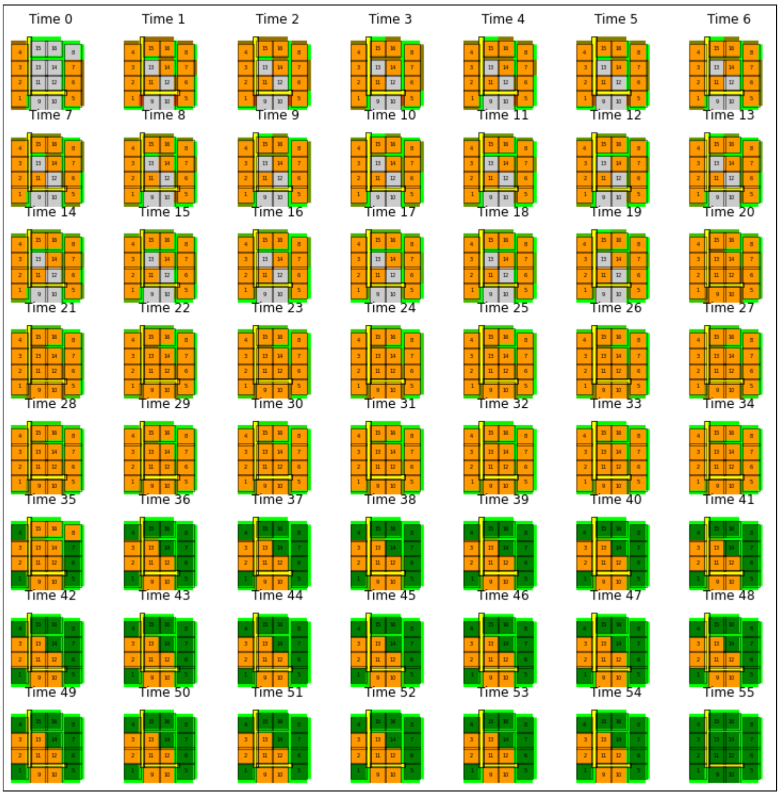

Figure D.30: *Scenario 42. Source: author.*

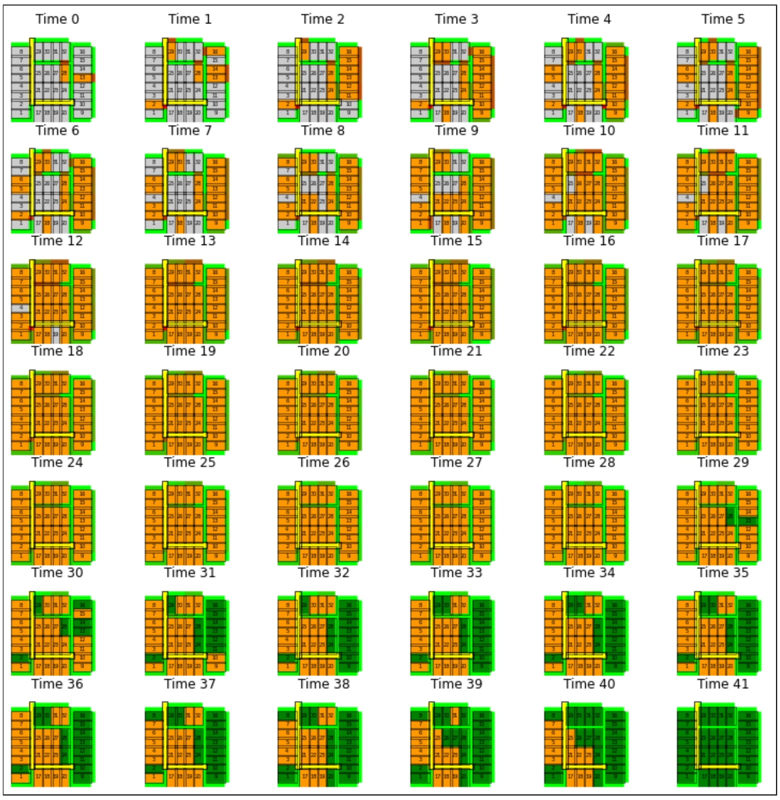

Figure D.31: *Scenario 44. Source: author.*

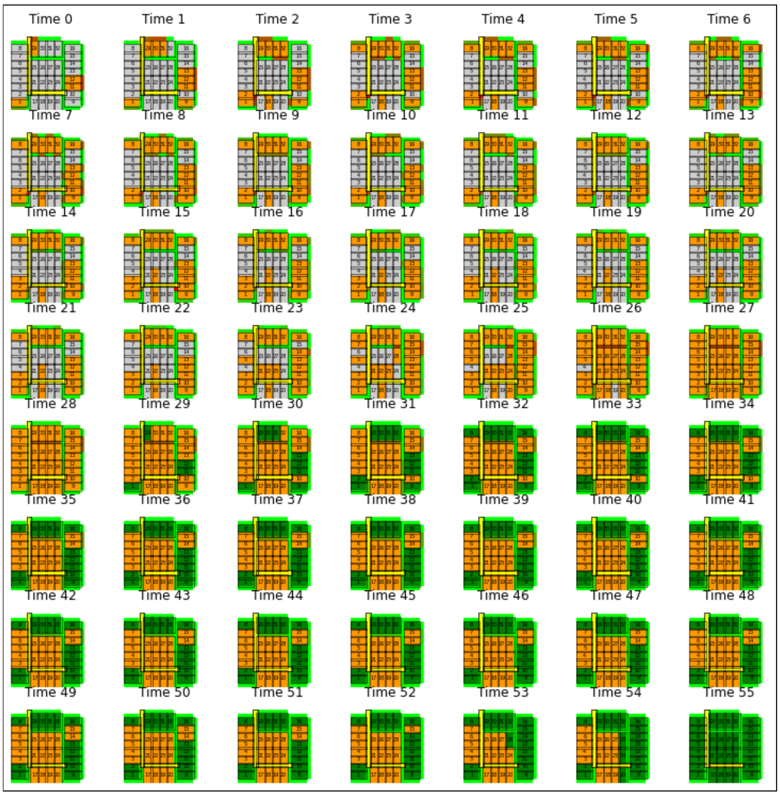

Figure D.32: *Scenario 45. Source: author.*

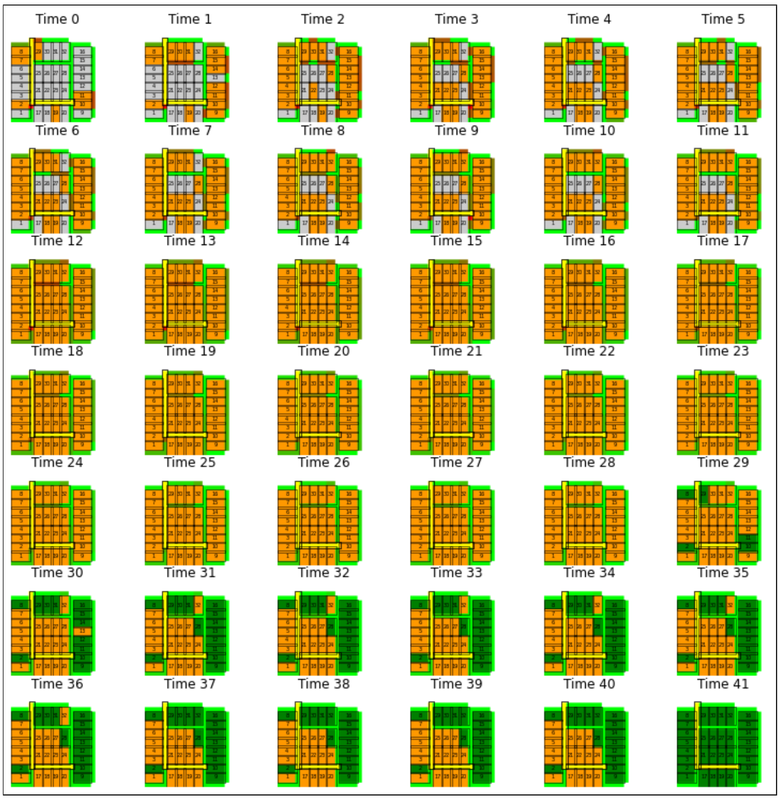

Figure D.33: *Scenario 47. Source: author.*

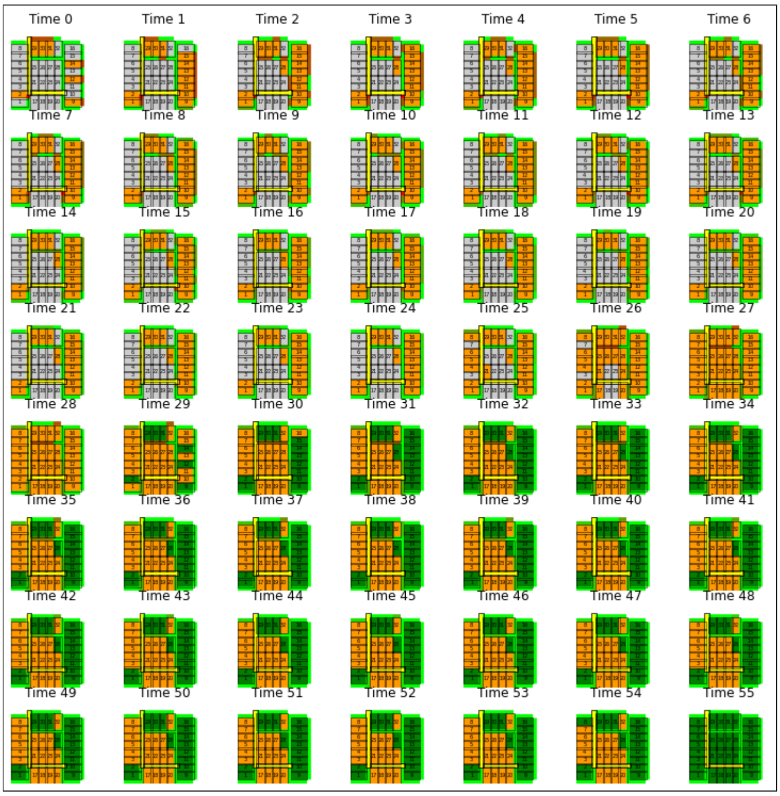

Figure D.34: *Scenario 48. Source: author.*

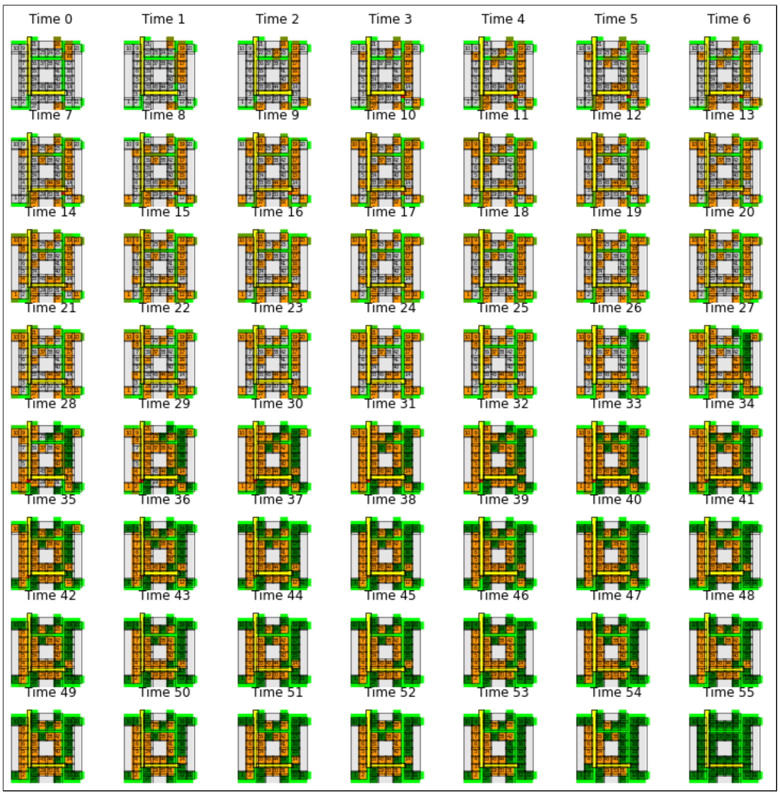

Figure D.35: *Scenario 51. Source: author.*

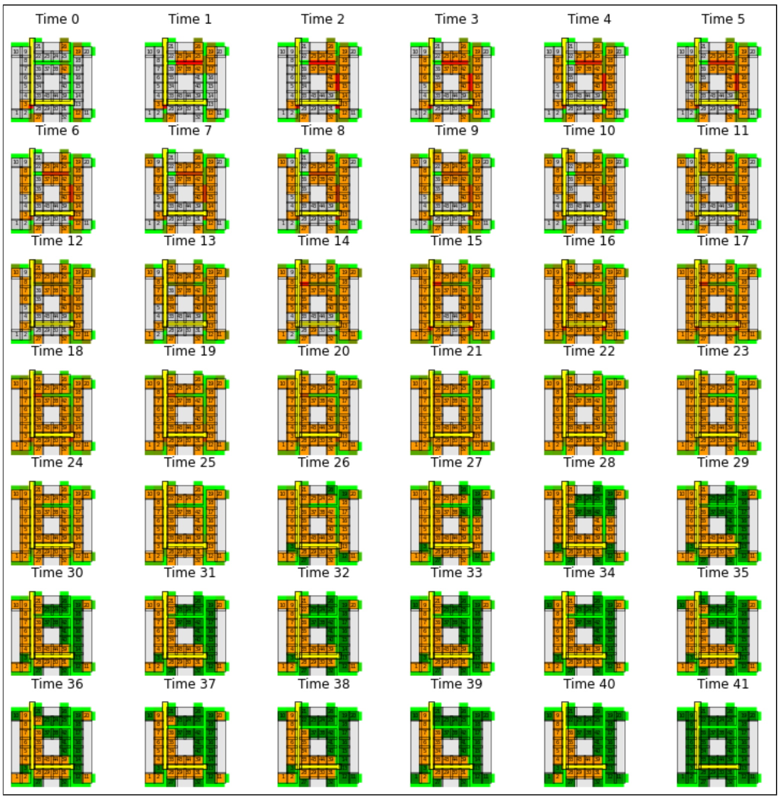

Figure D.36: *Scenario 53. Source: author.*

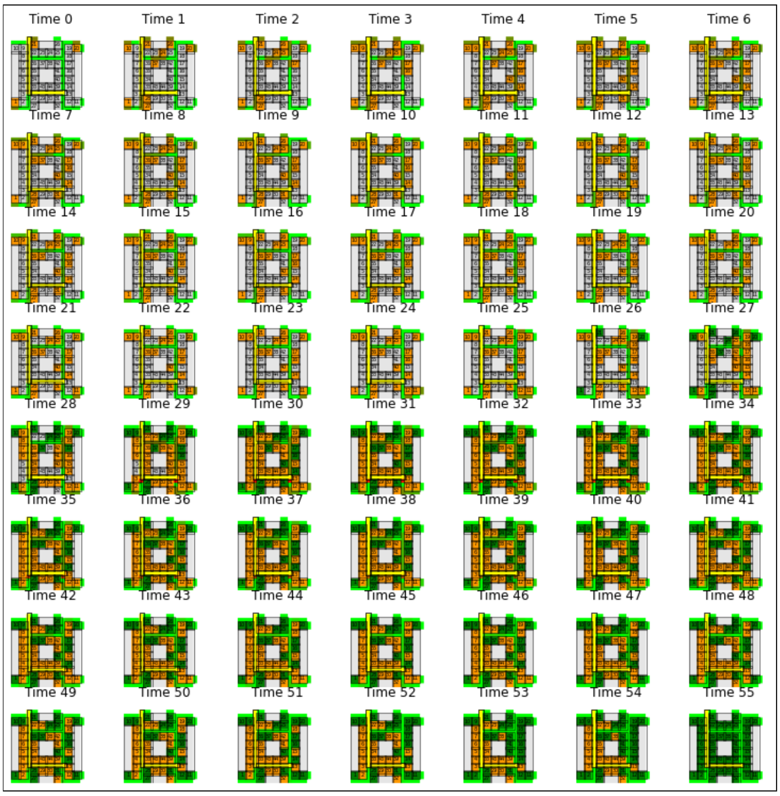

Figure D.37: *Scenario 54. Source: author.*

E

Start and finish times, baseline scenario

Stand Number	Start time	Finish time	Construction duration
10.001	3	53	50
10.002	15	51	36
10.004	17	51	34
10.007	17	51	34
10.008	2	53	51
10.009	15	52	37
10.01	7	55	48
10.011	9	50	41
10.012	15	52	37
10.016	44	52	8
10.021	39	48	9
10.027	16	51	35

Table E.1: *Start and finish times of stands in hall 10. Source: author, based on data from RAI Amsterdam.*

Stand Number	Start time	Finish time	Construction duration
11.001	32	51	19
11.003	32	53	21
11.024	8	35	27
11.025	15	48	33
11.038	29	50	21
11.043	18	54	36
11.044	31	52	21
11.051	16	41	25
11.059	16	42	26
11.060	2	47	45
11.062	20	26	6
11.069	15	48	33
11.076	2	47	45
11.077	15	31	16
11.087	16	46	30
11.091	15	51	36
11.093	16	55	39
11.096	16	49	33
11.106	29	51	22

Table E.2: *Start and finish times of stands in hall 11. Source: author, based on data from RAI Amsterdam.*

Stand Number	Start time	Finish time	Construction duration
12.005	17	48	31
12.008	18	46	28
12.009	16	52	36
12.01	43	50	7
12.011	29	45	16
12.015	16	53	37
12.017	17	20	3
12.043	16	51	35
12.044	15	51	36
12.049	6	42	36
12.056	21	56	35
12.058	29	42	13
12.093	19	39	20
12.094	25	54	29
12.095	29	45	16
12.096	19	39	20
12.097	9	54	45

Table E.3: *Start and finish times of stands in hall 12. Source: author, based on data from RAI Amsterdam.*

F

Case study strategies

F.1 Baseline scenario

Figure F.1: *Baseline scenario, hall 10. Source: author.*

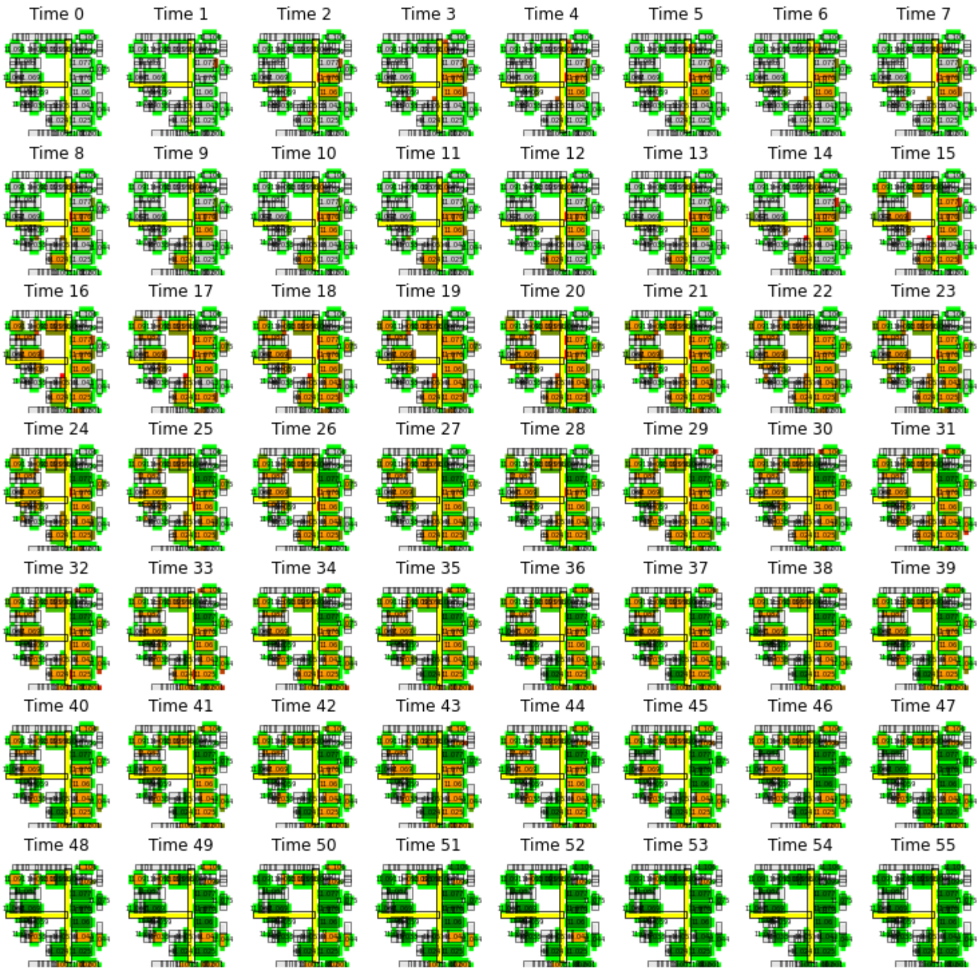

Figure F.2: *Baseline scenario, hall 11. Source: author.*

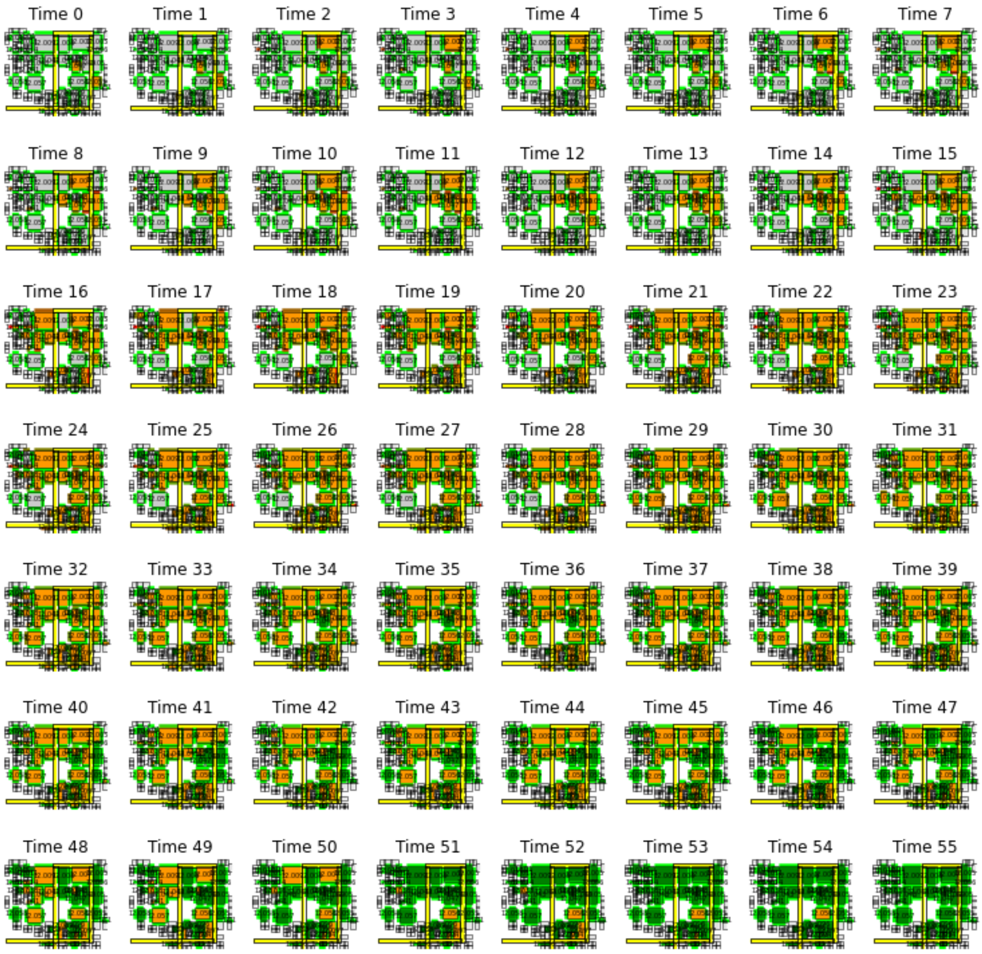

Figure F.3: *Delay policy scenario, hall 12. Source: author.*

F.2 Delay policy

Figure F.4: *Delay policy scenario, hall 10. Source: author.*

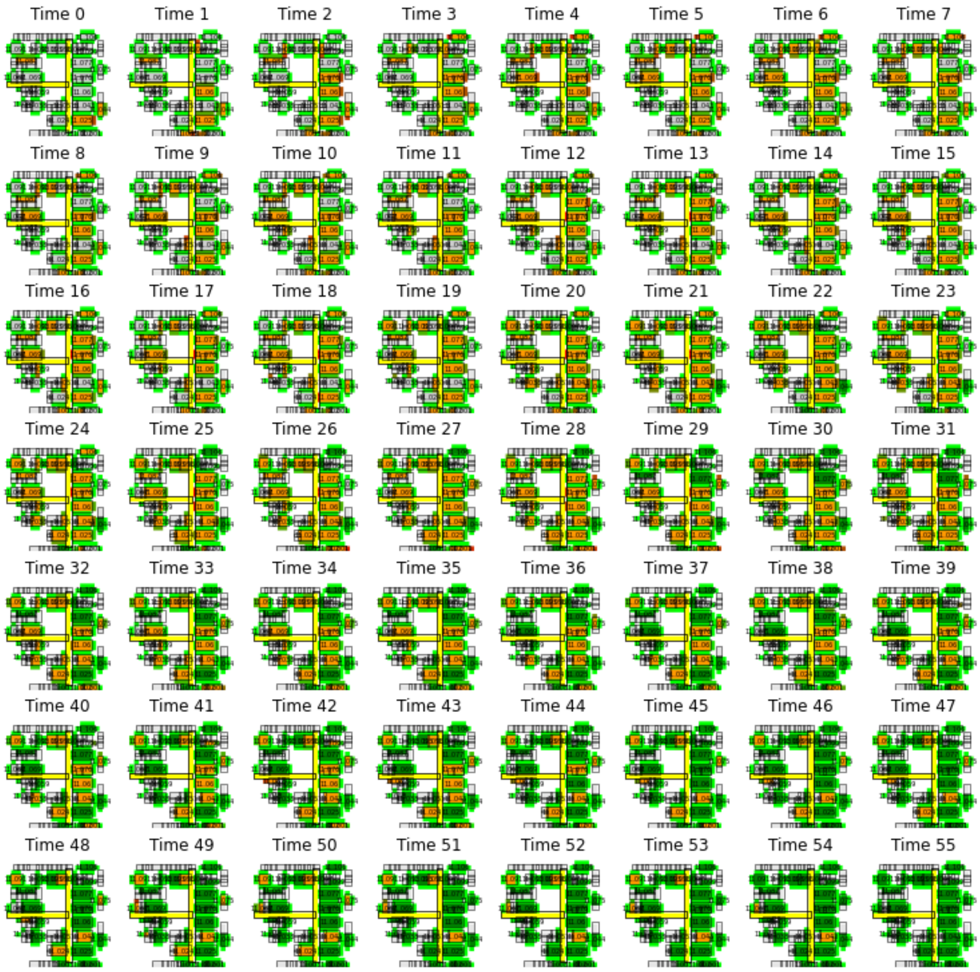

Figure F.5: *Delay policy scenario, hall 11. Source: author.*

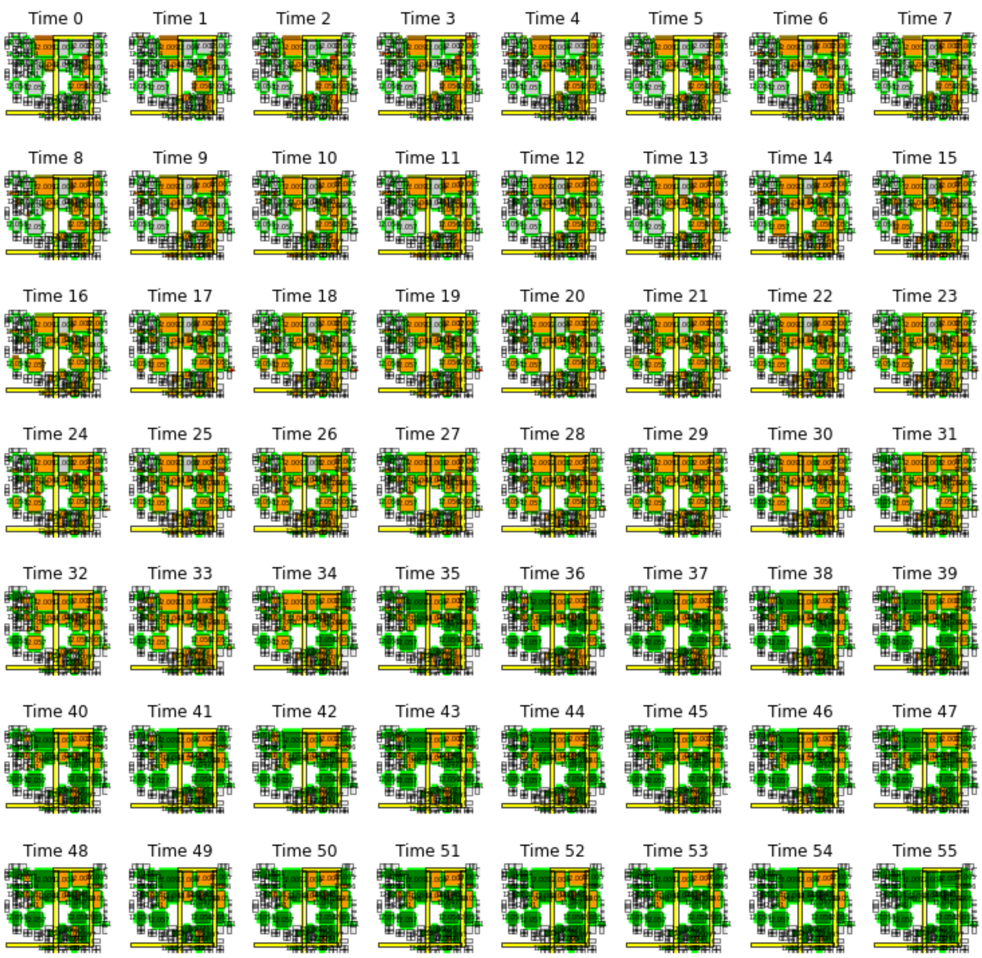

Figure F.6: *Delay policy scenario, hall 12. Source: author.*

F.3 Accessibility policy

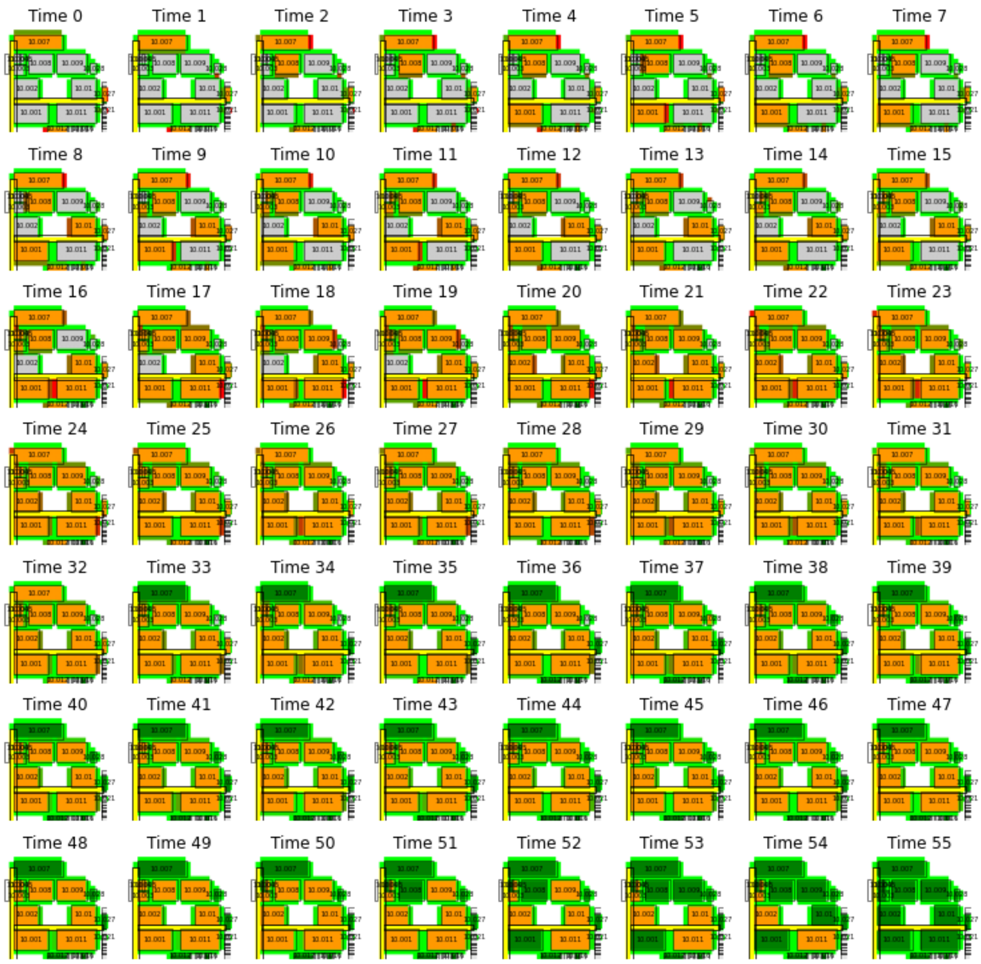

Figure F.7: *Accessibility policy scenario, hall 10. Source: author.*

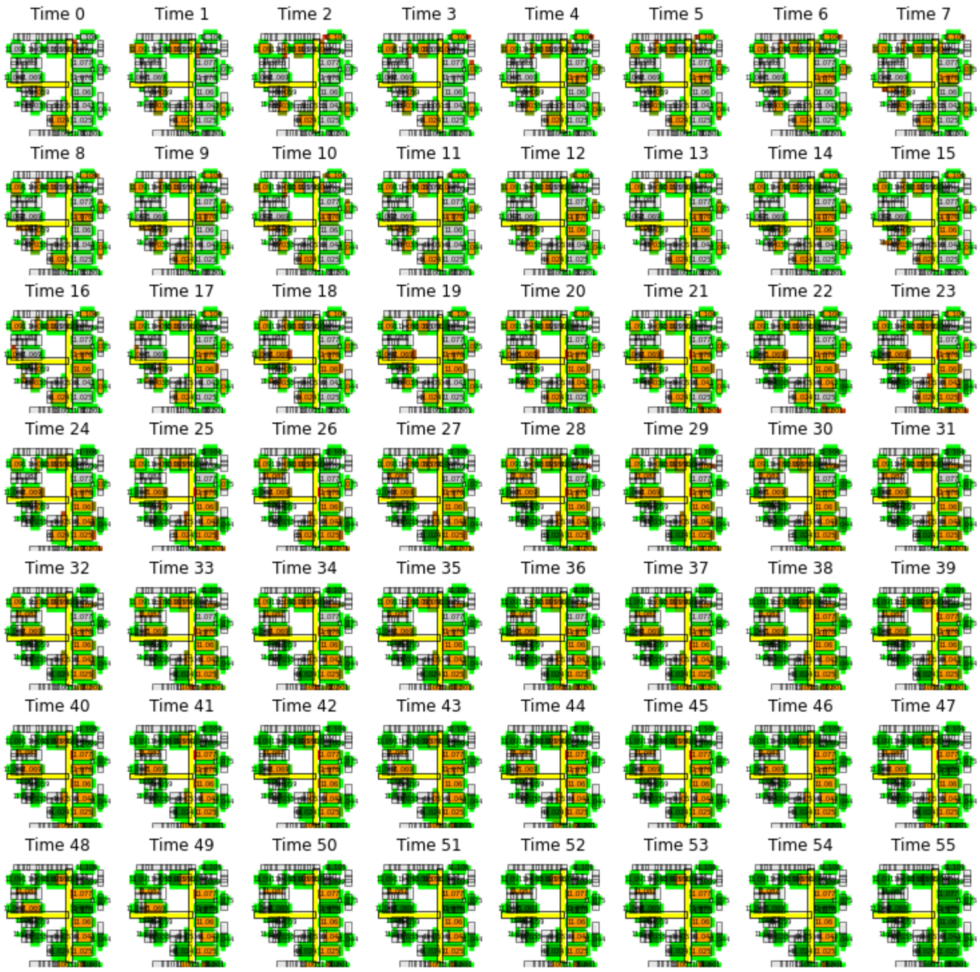

Figure F.8: *Accessibility policy scenario, hall 11. Source: author.*

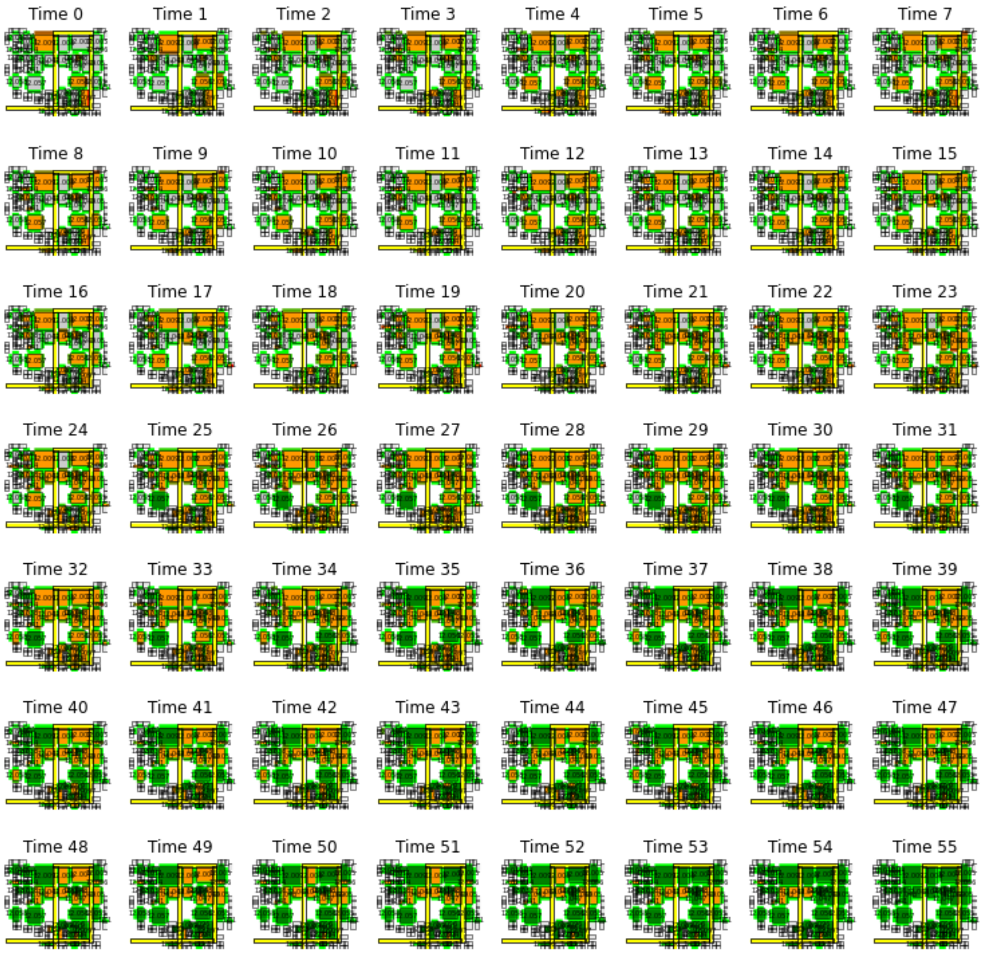

Figure F.9: *Accessibility policy scenario, hall 12. Source: author.*

G

Case study sensitivity analysis results

G.1 Hall 10

G.1.1 Duration

Figure G.1: *Hall 10, duration 75%. Source: author.*

Figure G.2: *Hall 10, duration 125%. Source: author.*

Figure G.3: *Hall 10, duration 150%. Source: author.*

G.1.2 Materials

Figure G.4: *Hall 10, material 75%. Source: author.*

Figure G.5: *Hall 10, material 125%. Source: author.*

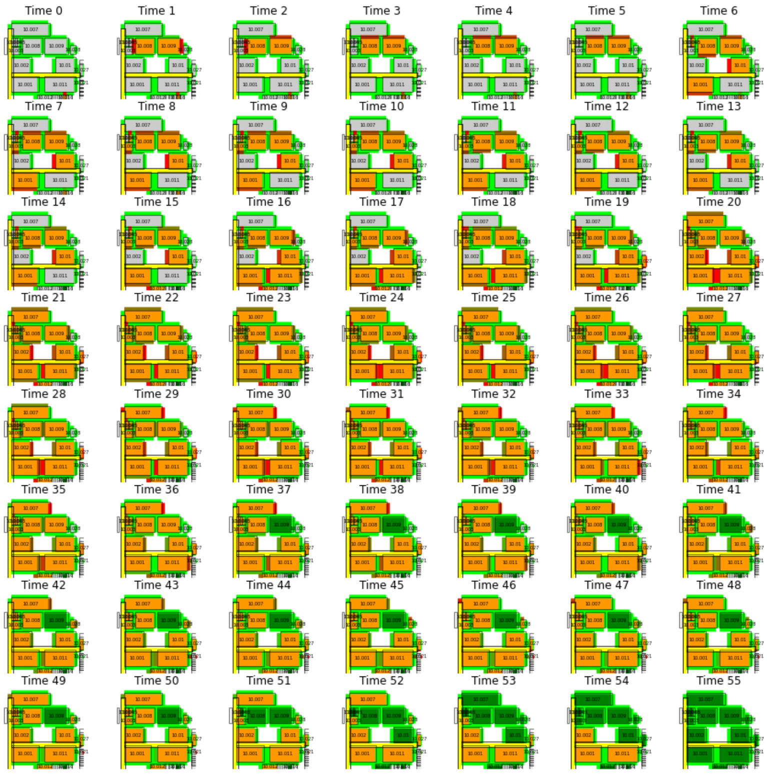

Figure G.6: *Hall 10, material 150%. Source: author.*

G.2 Hall 11

G.2.1 Duration

Figure G.7: *Hall 11, duration 75%. Source: author.*

Figure G.8: *Hall 11, duration 125%. Source: author.*

Figure G.9: *Hall 11, duration 150%. Source: author.*

G.2.2 Materials

Figure G.10: *Hall 11, material 75%. Source: author.*

Figure G.11: *Hall 11, material 125%. Source: author.*

Figure G.12: *Hall 11, material 150%. Source: author.*

G.3 Hall 12

G.3.1 Duration

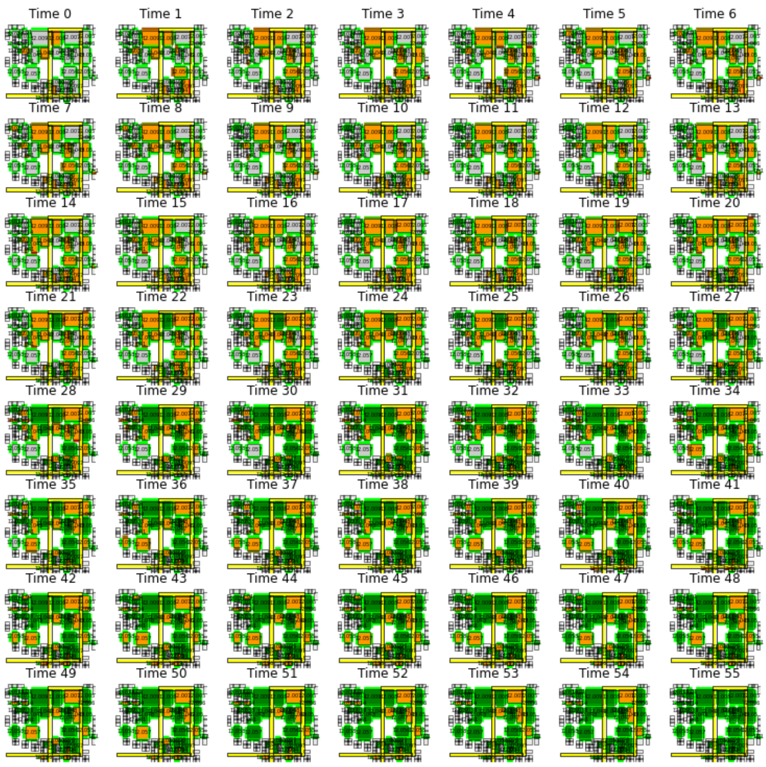

Figure G.13: *Hall 12, duration 75%. Source: author.*

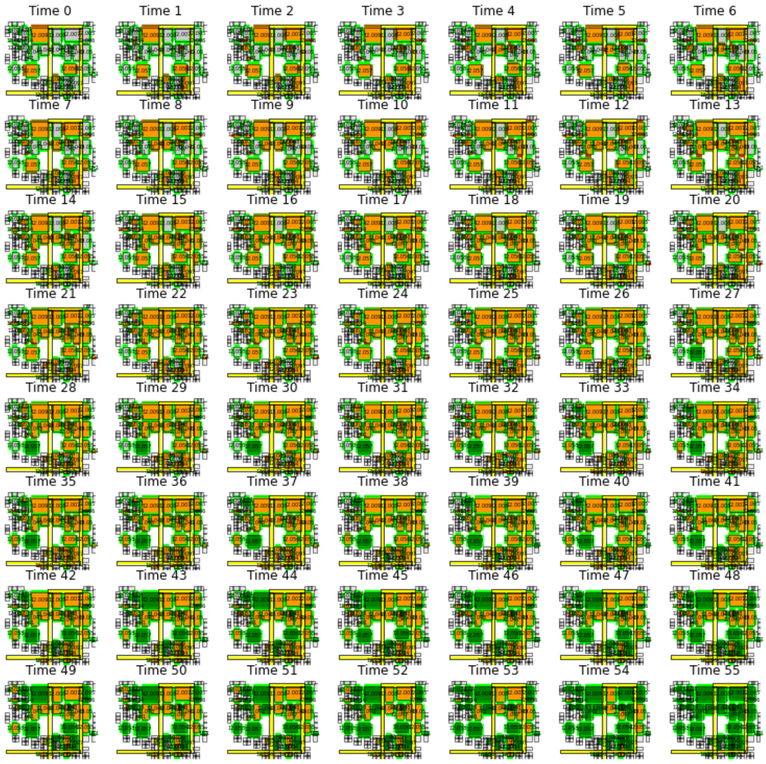

Figure G.14: *Hall 12, duration 125%. Source: author.*

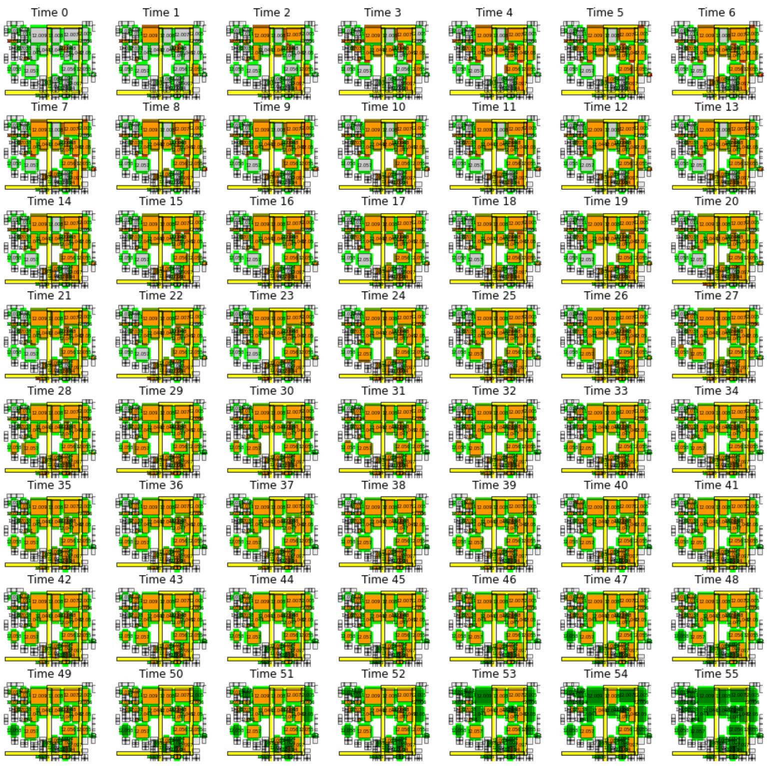

Figure G.15: *Hall 12, duration 150%. Source: author.*

G.3.2 Materials

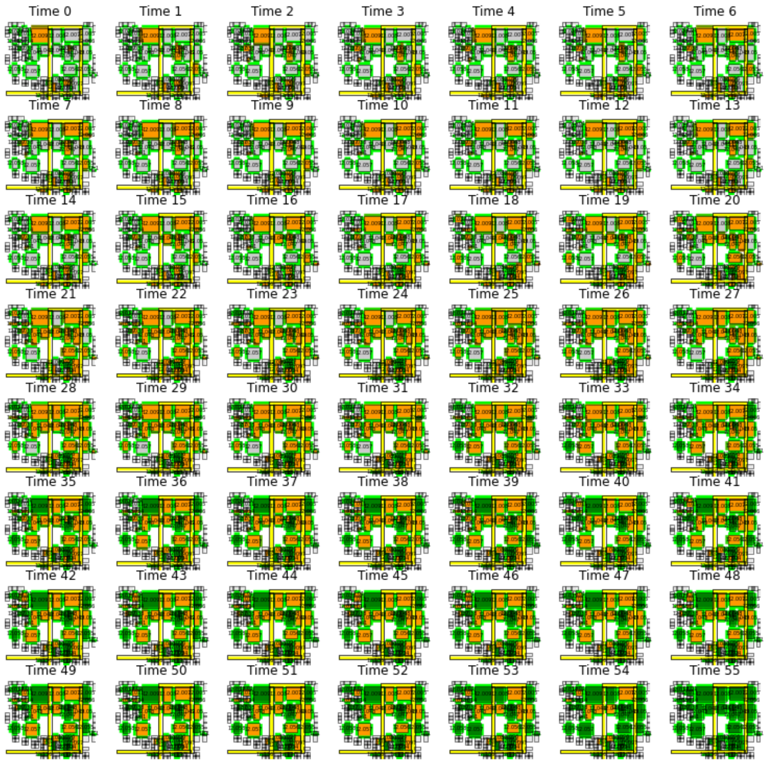

Figure G.16: *Hall 12, material 75%. Source: author.*

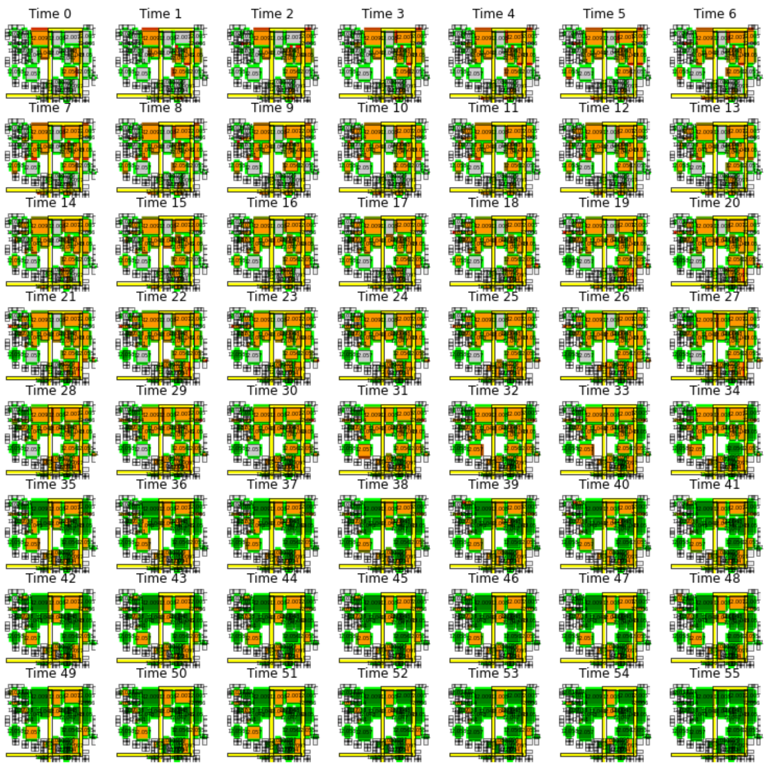

Figure G.17: *Hall 12, material 125%. Source: author.*

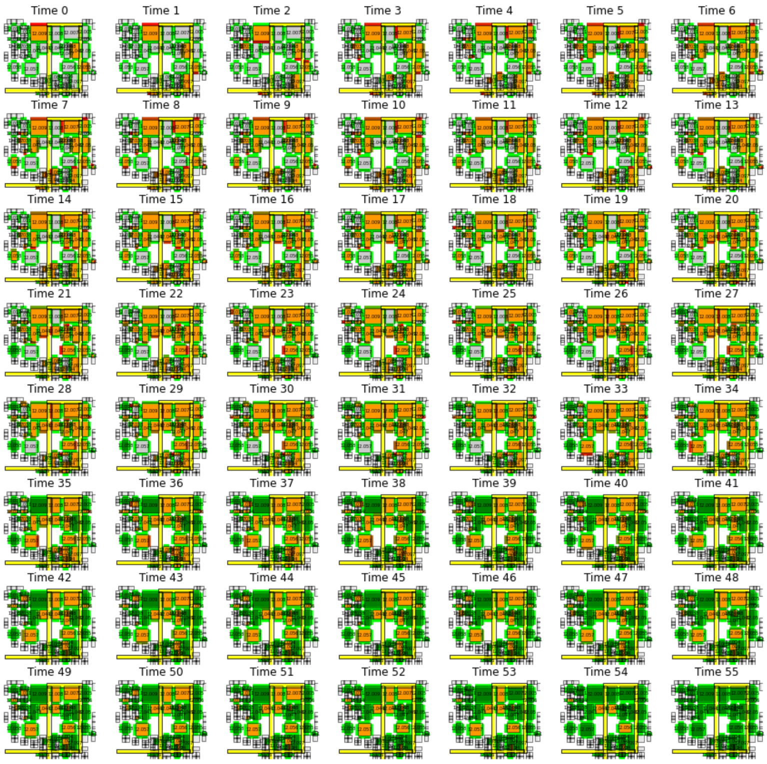

Figure G.18: *Hall 12, material 150%. Source: author.*