Evaluating a Water-based Intermodal Transportation System Using Hybrid Simulations in a Case Study

Master's thesis in Systems, Control, and Mechatronics

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Abstract

Major cities are rapidly expanding, which creates many construction projects with significant influences on inner city travel, particularly by heavy vehicles. Bigger construction projects create a sudden, and sometimes long lasting, influx of heavy vehicles in areas surrounding the construction sites which puts strain on the ordinary infrastructure in the area. Many bigger cities are now looking for untapped potential and are shifting their focus towards inner city waterways as a way to alleviate the traffic from the road. Masthuggskajen, a particularly large construction project that is part of RiverCity Gothenburg, is conducted next to the river and serves as a case study for a potential water-based intermodal transportation system for RiverCity as a whole.

This thesis project uses hybrid simulation, a combination of Discrete-event Simulation (DES) and Agent Based Modelling (ABM), in order to evaluate the proposed inner city waterway transportation system's capabilities. The project aims to evaluate the performance of the system regarding capacity and emissions, it also aims to identify issues with the system during periods of varying logistical intensity during construction.

The simulations show promising results for a partial transition to a water-based transportation system, both in regards to traffic reduction, but also to reduce emissions in the city.

Keywords: Hybrid Simulation, Discrete Event Simulation, Agent-Based Modeling, Intermodal Transportation, RiverCity Gothenburg, Masthuggskajen, Inland Waterways, Construction Logistics

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Filip Ödeen, Gothenburg, June 2021

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Aris Ramadhan, Gothenburg, June 2021

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1
Introduction

The introduction presents the background of the research topic, aim of this research project, and delimitations followed by research questions.

1.1 Background

RiverCity Gothenburg, or Älvstaden, is currently the largest urban development in Scandinavia, with the aim to create housing and work opportunities for city dwellers around the river in Gothenburg. Vision of RiverCity states that parts of the focus of its urban development will be embracing the water, i.e. Göta Älv river which runs through the central parts of Gothenburg. Just like many big cities around the World, Gothenburg is aiming to expand its capacity, which requires it to extend its infrastructure to accommodate more people to live and work. RiverCity comprises in many different areas surrounding the river, one of them in Masthuggskajen. The project is estimated to create 25,000 new housings as well as 50,000 workplaces before 2035. As the population becomes dense, movement of people and goods will increase significantly. Stakeholders are now considering the untapped potential in urban waterways to relieve the roads of traffic.

With the long time span of construction, this gigantic project will inevitable burden the current road network. Logistics of materials for example, have to be delivered to construction sites. Similarly will the produced waste need to be transported away. In order to alleviate more strain on the current road network, along with Vision of RiverCity to embrace the water, inland waterways for intermodal transportation is investigated for untapped potential.

1.2 Aim

The aim of this thesis is to use hybrid simulation to evaluate an intermodal transportation solution using the road and urban waterways in the Masthuggskajen construction project. The task is to create an accurate model of the system, as well as gather data so that the model can be used to draw conclusions regarding the systems capabilities- and performance, specifically compared to a strictly road-based transportation system. The project also aims to investigate the environmental impact such a system would have.

1.3 Delimitations

This thesis is creating a model of intermodal transportation on a software platform. However, the complexity of the model is heavily dependant on detail- and availability of data. In the areas where data is limited, assumptions has been made with the consultation of stakeholders. The logistical process is assumed to work flawlessly and automatically during loading-, and unloading-, and transportation of barges as well as containers. All material transports are assumed to come from outside the city via road delivery. This thesis does not focused on stakeholder interests and no interviews or investigations was performed for this reason. Stakeholders were contacted, but with the intent of data- and information collection for a more accurate model.

1.4 Research questions

- What are the performance differences between a water-based and intermodal transportation system, compared to a strictly land-based transportation system?
- What are the limitations of water-based transportation?
- How would the intermodal transportation system contribute to environmental impact from CO_2 emissions?

2

Theory

This chapter covers the basics of the relevant modelling and simulation concepts for this thesis as well as some brief construction logistics and intermodal transportation theory. This chapter also contains a description of the the case study.

2.1 Modelling and Simulation

Modelling and simulation is largely used to describe real world problems mathematically in order to solve them. The process aims to capture the dynamics of a physical or theoretical system using key parameters and using simulations to see how it behaves under different circumstances or external disturbances. If done correctly, the method provides the benefits of testing without the drawback of disrupting the real system or possibly damage it in the process. It can also be used to test systems that does not yet exist, without having to actually manufacturing a possibly faulty prototype beforehand. Modelling and simulation is an important tool in operational research to acquire a better understanding of the system and its behaviour. The model is, however, less complicated compared to the real-world system, but it is often not required to make an exact replica of the real system to get useful results. The model should be fed data according to its abstraction levels as a rule of thumb.

When the model has been created, the next step is to run the simulation. A simulation model is always executable, giving the user a trajectory of the system's state changes. With a given set of rules defined, the system is running from the current state, to the future states. The result of the simulation is produced and can often be observed while the model runs, giving valuable insight into the dynamic changes of the system in real time. The model created in software can be considered a digital copy of the real system. Modelling and simulation can serve as a test-bed to evaluate various strategies and solutions, regardless of its technological readiness level.

2.2 Hybrid Simulation

Hybrid simulations is a modelling and simulation approach that utilizes a combination of Discrete Event Simulation (DES), Agent-based Modelling (ABM) and System Dynamics (SD), as described by S.C. Brailsford et al. [6]. Brailsford states that in order for a model to be considered hybrid, it needs to have some sort of interaction between subsystems. Brailsford brings forward the ideas of P.G Bennett that describes the three main approaches to hybrid simulation, i.e. Comparison, Enrichment and Integration [5]:

- **Comparison** uses the methods separately to solve isolated problems and then combines the results, the idea is that one of the methods would not be capable of solving the the problem as a whole. One approach is to use the simulations subsequential, meaning that the output of one simulation serves as the input to another [6].
- **Enrichment** mostly relies on one main method and uses the other(s) to improve the capabilities of said main method.
- **Integration** combines two or more methods and treats them jointly in the model. This is considered the highest level of method combination and uses different elements of each method to forge a simulation approach that is, in itself, something new. This is also the approach used in this thesis.

Hybrid Simulation combines the benefits of the different methods to make problems that were historically convoluted-, or even impossible to solve by a single method, simpler by a multitude without the need for oversimplification of dynamics.

2.2.1 DES

Discrete Event Simulation, as the name implies, is used for systems that can be roughly translated to a discrete sequence of events. The main difference between a continuous system and a discrete system is that continuous system's states changes continuously over time, whereas a discrete system change a finite amount only when an action/event happens [20]. For instance, the push of a button would be considered a discrete event, while a pendulum is a continuous system.
DES is a method that sees the system as process-centric, or a series of discrete events. The main properties of DES are entities, objects or resources that moves through a process. Events are triggered which enables entities to move from one process to another. DES is commonly used in manufacturing and supply chain modelling as processes in such systems often follows one another.

2.2.2 ABM

Agent-Based Modelling is known for its flexibility to draw out single agent behaviors in a system. ABM is commonly used when the aim of simulation modeling is to study behaviour of individual entities. ABM allows for smaller components in a model to be considered their own individual subsystems with internal dynamics, as described by A. Crooks et al. [9]. Crooks describes numerous features that agents can have, though only a few of them is presented here:

- **Autonomy**, agents are capable of processing information and are free to interact with other agents, under predefined circumstances. Agent can make independent decisions.
- **Heterogeneity**, agents can possess its own attributes, such as mass, volume and origin. Each agent type is created from the same "template", or "class", but are free to change their internal dynamics and variables independently from other agents.

- **Mobility**, agents can be free to roam around the environment if so specified, though they can also be fixed in the model or only move under certain external conditions.

Agents can be both proactive and reactive, as well as contain dynamics that describe their surroundings. Though in this thesis, agents are mostly used to store internal variables and only interact with each other/the model through external directives from the model itself. Though these directives are based on the internal variables of the agents.

2.2.3 AnyLogic

In order to use any modeling and simulation technique, a digital platform or software is required as a simulation environment. There exists countless variants of simulation software, though many are only designed for one specific approach. AnyLogic is a software platform that is specifically designed to handle hybrid simulation. AnyLogic can incorporate DES, ABM and SD using the integration approach, making it a very powerful tool. One key aspect that make AnyLogic popular among companies worldwide, is the use of visually-designed elements to faster build models that represent physical objects and flows. It also has an extensive range of libraries, e.g. pedestrian, factory, transportation, port and airport, as well as supporting these with 3D simulation. AnyLogic also provides a Geographical Information System (GIS) interface that utilizes map providers for large scale simulations. GIS is very useful when mapping supply chains and transport operations, especially when combined with ABM since entities can navigate the GIS interface independently from each other.

2.3 Banks Method

J. Banks has formulated a concrete method, also known as Banks Model, with a set of steps to guide through the process of a thorough and sound simulation study [4].The method has proven to be a reliable and straight forward method that is sufficient when dealing with process-centric modeling using DES. Banks method is displayed in Figure 2.1 below.

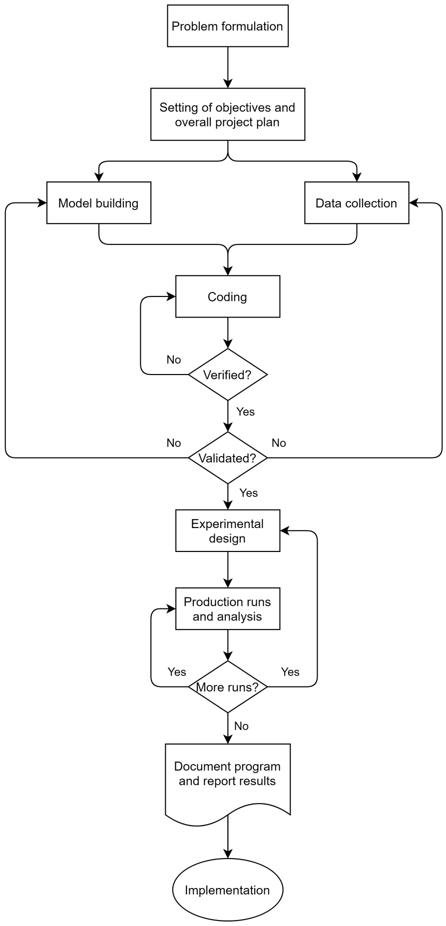


Figure 2.1: Banks method

Banks method, consists of a series of iterative steps. The first step is *Problem Formulation*, in this step the problem should be clearly formulated and understood, as to lay the foundation for a simulation study that answers the questions asked. The problem formulation should be thoroughly discussed with the stakeholders involved.

The second step is *Setting of objectives and overall project plan*. This step defines the methodology and scope of the study. The overall objective and relevant aspects needs to be carefully considered. This step should also define the hardware and software, as well as a time estimation. Even though Figure 2.1 shows that these two steps are performed once in the beginning, the problem might need to be reformulated throughout the study [4].

The third step is *Model Conceptualization*. This step includes a breakdown of all parameters required and makes a rough conceptual model as a basis to start building the model. The conceptual model will often be updated when new data is acquired. This ties together with the fourth step of *Data collection*.

The fifth step is *Coding* or *Model Translation*, which consists of translating the conceptual model onto the software platform.

The sixth step is *Verification*. Verification is performed to ensure that the code is logically correct, as well as error- and deadlock-free. Verification is performed each time complexity is increased to make sure that the model works as intended.

The seventh step is *Validation*. This step is crucial since the purpose of a simulation study is to obtain a digital representation of a physical system, which should accurately reflect the systems properties and behaviour. Validation can be done in many different ways, one common way is to compare the results to with historic data from the physical system, e.g. in manufacturing by comparing breakdown time with MTTF data. The model verification- and validation are among the critical parts of building the model. A. Law argues that verification and validation are the pitfalls of building a simulation model [19].

The eighth step is to create *Experimental Design* to test "what-if" scenarios. Alternative scenarios are set up to run the simulations so that relevant conclusions can be drawn from it. This ties in with the ninth step, *Production runs and analysis*. However, this thesis does not cover production runs since the system is strictly hypothetical.

2.4 Construction Logistics

Logistics refers to activity of procurement, movement and storage of materials and equipment from where they originate to the point of use. Hence, construction logistics means the logistical process from the source to the construction site [11]. Construction logistics is an area that poses many challenges, especially in bigger construction project where many stakeholders and construction companies are involved. M. Janné describes the three main challenges in construction logistics setups as; *"management of transport to and from construction sites, management of logistics at construction sites, and managing the inter organizational relationships amongst construction project stakeholders"* [16]. Furthermore, Josephson et al. argues that actors have a tendencies to create large uncertainties in products and processes due to, among others; choosing to work with large tolerances, loosely defined project goals, and rough project and activity plans [18]. Josephson states that it is crucial for organizations to strive towards better planning and organizing in order to achieve results, and meet customer requirements.

2.5 Consolidation Center

In construction, material is often purchased from many different suppliers, each with their own separate delivery vehicles and schedules as described by Andersson et al. [2]. Andersson further argues that often times there is little or no coordination between these companies and consequently, there is an influx in delivery vehicles to construction sites, often with only a few packages or small quantities. Hamzeh et al. proposes a solution with a logistics center that can offer services such as: temporary storage, transport, distribution, *consolidation*, sorting and breaking bulk [14]. A logistics center for consolidation, further referred to as a consolidation center, is a way to reduce the total number of deliveries to a construction site by bulking up multiple smaller deliveries, into fewer bigger ones. The concept is displayed in Figure 2.2 below.

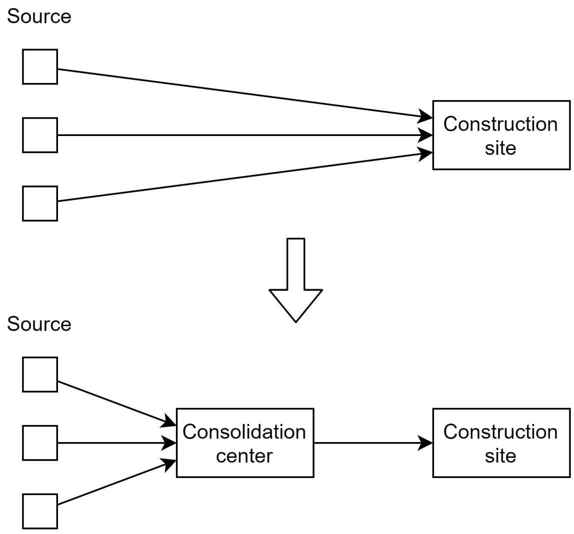


Figure 2.2: The consolidation center concept

A consolidation center can temporarily store larger quantities of material until it is needed, saving up valuable space at the construction site wile also reducing the activity created by heave vehicles in the area [2]. A consolidation center that is utilized by multiple construction companies and stakeholders simultaneously, does however require increased cooperation and planning from all parties.

2.6 Intermodal Transportation

Intermodal transportation referrers in this context to intermodal freight transportation. Intermodal transportation is the concept of utilizing more than one mode of transportation, like rail, truck and barge, without handling the goods itself during mode shift. Transportation of freight is considered intermodal if the goods can easily be transferred between modes, e.g. by utilizing an intermodal shipping container for storage. The use of intermodal transportation can enhance the capabilities of a transportation chain by utilizing the transport mode that is most efficient in the travel region. The efficiency and capabilities of a train can be used to transport large quantities of cargo over long distances, while the flexibility of a truck can be used to reach a specific destination with shorter travel distance. An intermodal transport chain is effective when continuous flows of goods are required, especially when they are similar in quantity, such as in construction logistics.

Demir et al. describes that the complexity introduced by intermodal transportation in regards to scheduling and increased risk of delay, drives transportation planners to prefer strictly road based transportation before intermodel, where they have less experience [10]. Though Demir argues that, even though road transportation is considered a flexible transportation mode, it is more susceptible to disruptions from the ever increasing traffic volumes on the roads. Congestions and limited infrastructure capacities results in a limitation in accessibility, especially for heavy road vehicles. Janjevic et al. links the accessibility problems to traffic density and congestion [15]. Janjevic further argues this point by comparison between road- and river traffic in London, stating that *"freight moves faster on the river than on central London's roads as there is no traffic build-up"* [15]. Although inner city London is multitudes more crowded than Gothenburg for example, it raises an important point.

2.6.1 Urban Waterways

One of the ways to implement intermodal transportation is by boat. Container ships are used to transport large amounts of cargo container overseas. Meanwhile, smaller barges can be used for last mile distribution, as part of an intermodal transportation solution, using urban waterways for inner city travel.

Gothenburgs inner city waterways is largely unutilized when considering its potential. While the River of Gothenburg see some commercial use in the form of public transport and ferries, the northern parts of the river is hardly utilized at all. The river stretches through most of central Gothenburg and has close access to otherwise intricate areas, while simultaneously bypassing the heavily congested roads surrounding it.

Zacharopoulos et al. argues that achieving a modal shift to water transportation is significant for making the transport industry more sustainable [29]. Furthermore, Zacharopoulos states that water transportation produces less CO_2 emissions, less congestion and less noise, when comparing with road transportation. Though they further clarifies that even though CO_2 emissions would be reduced, emissions from Sulphur- and Nitrogen Oxides would increase.

2.6.2 Emission Calculation

The European Chemical Industy Council (CEFIC) has developed the *Guidelines for Measuring and Managing CO_2 Emission from Freight Transport Operations*, which as the name implies, can be used to estimate CO_2 from freight transport [8]. The guide is made for institutions to calculate their emissions so that all actors in the industry can have impact to achieve goals in reducing emissions globally. Although significant efforts has been made by the industrial sector to cope with carbon emission, the growth remains large due to increasing global trade. As a result, contribution from the transport sector is important, for instance from their activities in construction logistics.

The guidelines describes two ways of calculating CO_2, namely the *Activity-based approach* and the *Energy-based approach*.

2.6.2.1 Activity-based Approach

The Activity-based approach is used to estimate CO_2 emissions in the absence of data. The emissions is calculated for each mode of transportation individually. The calculation is done as;

$CO_2\ emissions = Transport\ volume\ by\ transport\ mode * average\ transport\ distance\ by\ transport\ mode * average\ CO_2{-}emission\ factor\ per\ tonne{-}km\ by\ transport\ mode.$

Or more easily readable as;

$$CO_2\ emissions\ [Tonnes] = \frac{Cargo\ mass\ [tonnes] \times transport\ distance\ [km] \times [g\ CO_2\ per\ tonne\ km]}{1,000,000} \tag{2.1}$$

This method is best suitable in the absence of data in order to make estimations. The method uses a $gCO_2/tonne-km$ factor that is dependent on the transportation method, payload weight and the estimated percentage of distance that is traveled without cargo. The Activity-based approach is suitable for intermodal transportation since it separates the different modes of transport.

2.6.2.2 Energy-based Approach

The Energy-based approach is the most accurate, and with direct access to fuel- or energy consumption data, the easiest way to calculate emissions. It is calculated as;

$CO_2\ emissions = fuel\ consumption\ *\ fuel\ emission\ conversion\ factor.$

Or as;

$$CO_2\ emissions\ [Tonnes] = \frac{fuel\ [liters] \times CO_2\ per\ liter\ fuel\ [kg]}{1,000} \tag{2.2}$$

This method is, however, not recommended to make estimations, unlike the Activity-based approach, and should only be used when accurate data is available.

2.7 Case description

This section contains a brief summary of the case, a brief overview of the Älvstaden project in general, and Masthuggskajen in particular.

2.7.1 Älvstaden

Älvstaden, internationally known as RiverCity Gothenburg, is currently the largest urban development program in Scandinavia [13]. The project is constructed around three ideas, namely; connecting the city, *embrace the water* and reinforce the regional core. RiverCity Gothenburg aims to make Gothenburg visible to the world and will be used as a testing ground for new technologies [24]. The area stretches along the Göta älv river thoroughout the central parts of Gothenburg. The project consists of seven construction areas, all of which with multiple construction sites managed by different contractors. The seven areas are: Backaplan, Central Station area, Frihamnen, Gullbergsvass, Lindholmen, *Södra Älvstranden* and Ringön, as displayed in Figure 2.3 below.

Figure 2.3: River City Gothenburg, *Picture: Björn Södahl*

2.7.2 Masthuggskajen

Masthuggskajen is a smaller part of Södra Älvstranden and is located in its most northern end, see Figure 2.3. The area will see 21 new constructions from 2019 to 2026, with 7 different contractors.

Figure 2.4: Masthuggskajen in 2035, *Visionsbild: Kanozi Arkitekter*

Masthuggskajen aims to be a green and accessible addition to Gothenburg. Specifically is one of the aim to reduce the number of transports in the area, which will be achieved by collaborative transports of goods and waste. However, during construction there is very little collaborative efforts to achieve this and most, if not all, contractors have their own schedules for material delivery from its own suppliers. On top of this, most of the construction companies use different waste disposal companies for produced waste, which furthers the influx of construction related vehicle movement in the area.

Masthuggskajen has direct access to the river, and a portion of construction will even be conducted on a future land extension (see top left corner of Figure 2.4). Stakeholders are now investigating the untapped potential of the river as part of delivery to and from the construction area, in an attempt to reduce construction related movement in the area. Furthermore, using Masthuggskajen as a case study for a potential water-based intermodal transportation system, serves as a case study not only for further construction in other parts of RiverCity, but for inner city construction in general.

2.7.3 River Utilization

B. Södahl has conducted a study of how the river can be utilized to benefit RiverCity in regards to construction logistics [23]. Södahl proposes that a logistics center in Bäckebolsmotet could be used as a consolidation center and that barges could transport construction material to the construction areas. He further proposes the conveniently located recycling center, *Renova Skräppekärr*, across the river as a checkpoint for waste consolidation on the way back. The idea is to combine material- and waste transport into a single transportation solution.

3

Methodology

This chapter describes the working process of this project taken to employ the research approach. The process is performed iteratively as per Banks method, shown in Figure 2.1.

3.1 Model Overview

The first step in the modelling process is to understand the context and characteristics of the real-world system. This would correspond to the *Problem formulation* and *Setting of objectives and overall project plan* steps in Banks method in Figure 2.1. The system in this case can be separated in a number of ways. Firstly, one should consider how much detail is actually needed for the model to produce useful results, while avoiding introduction of unnecessary complexity and potentially embroil the functionality and thereby skew the results. There are two different flows that needs to be considered, namely the material- and the waste flow.

Construction material is delivered by truck from a supplier warehouse or factory, often from outside the city. When using an inland waterway as transportation system, the routes for travel would be identical up to the point when the truck needs to deviate from the route to the construction site in order to reach a consolidation center for the water-based transportation system. Since the two routes are almost identical, it is logical to only look into the parts where they differ, namely the material flow inside the city. The second assumption is that long distance transportation by truck is traveling on highways when possible, which would mean that trucks entering Gothenburg would do so by one of the main highway entrances to the city.

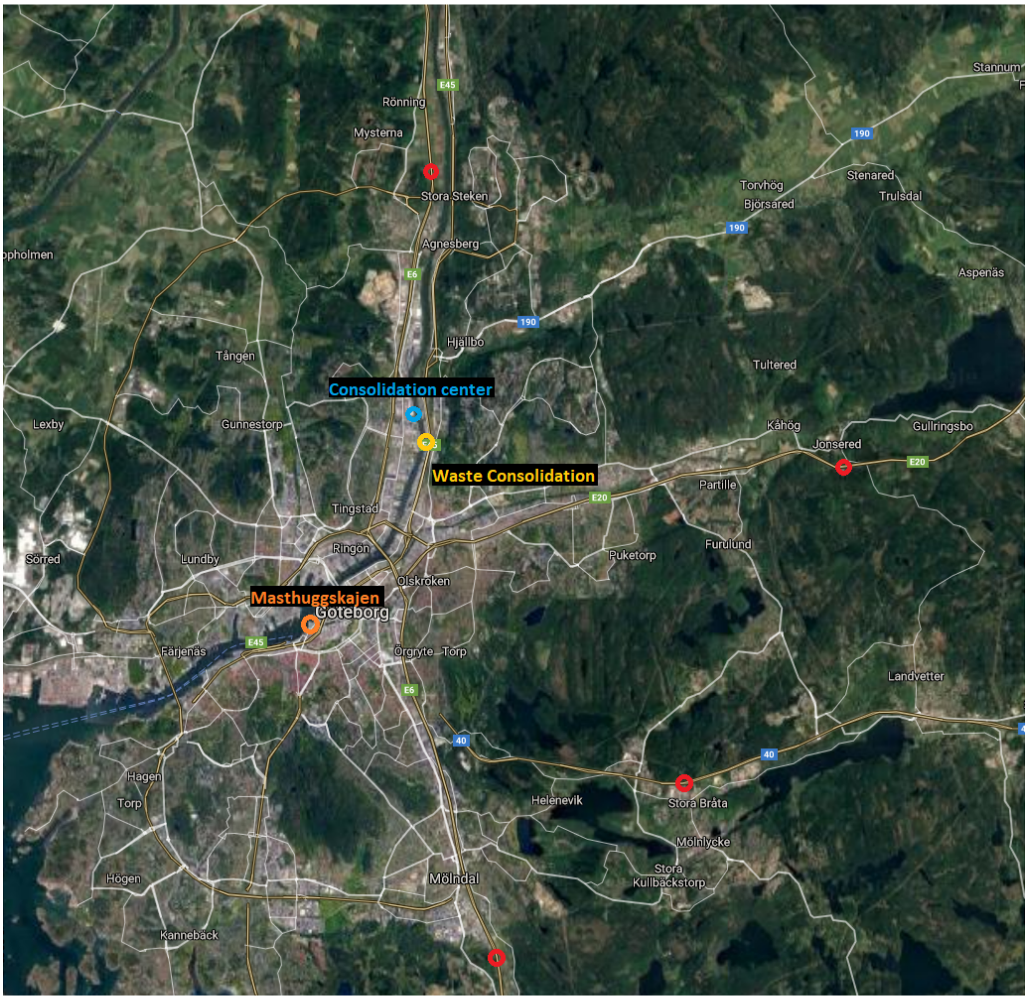


Figure 3.1: Map of Gothenburg with the main entrances marked in red, *Google Maps*

The distribution of trucks arriving from these four entrance points is one of the significant factors to consider. Since the proposed consolidation center for a barge is located in the northern part of the city, naturally trucks entering from that part of the city will have a shorter distance to travel. Trucks entering from the southern part of the city might however be closer to the construction site, depending on the path it takes. Related distances are displayed in Table 3.1 below.

Table 3.1: Distances

Origin	Destination	Distance [km]	Comment
E6 - North	Consolidation center	6.6	
E20 - East	Consolidation center	17.1	
R40 - SouthEast	Consolidation center	15.7	
E20 - South	Consolidation center	15.5	
E6 - North	Construction site	24.6	Via Hisingsleden
E20 - East	Construction site	18.2	
R40 - SouthEast	Construction site	16	
E20 - South	Construction site	16.1	Via Västerleden
Waste consolidation	Construction site	6.9	

Once the material has arrived at the consolidation center, it is loaded into containers. The containers are then placed at a nearby dock where they wait for a barge to be loaded onto. The barges are always loaded with five containers, four of which are designated to construction material. A set of empty containers are replaced by full ones at the consolidation center. In the same way, the full containers are replaced by empty ones at the construction site. This process is illustrated in Figure 3.2, further down.

The second flow is the flow of waste produced by the construction. This waste needs to be transported away from the construction site. For simplicity, it is assumed that all waste containers are destined to the same place, which is the *Waste Consolidation* in Figure 3.1. One of the five container spaces on the barge is to be reserved for a waste container. An empty waste container is swapped with a full one (if one exists at that time) at the construction site. The full container is later swapped with an empty one that is waiting at the waste consolidation, as displayed in Figure 3.2 below.

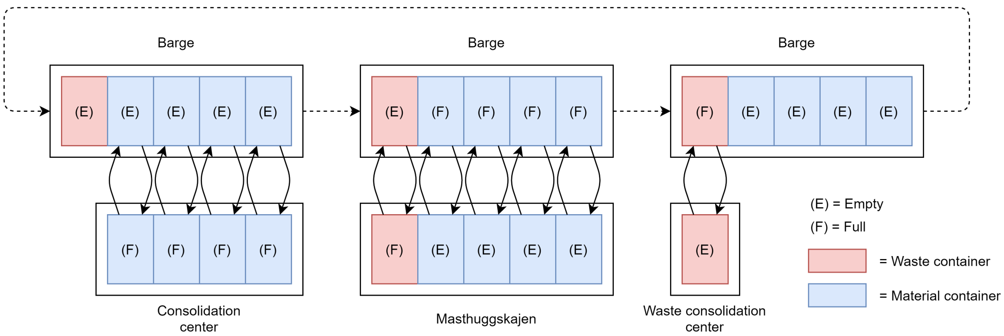


Figure 3.2: Loading-/unloading concept for containers at each checkpoint along the river

3.2 Data Collection

Data collection was carried out by collection and analysis of various pre-studies regarding the Älvstaden and Masthuggskajen projects as well as other studies specifically regarding intermodal transportation implementations of said projects. Stakeholders where contacted by phone and email and first hand observations of the construction site where conducted. For further details, see subsequent sections.

3.2.1 Documentation

The most substantial part of data collection has been done with secondary data gathering, i.e. studying the existing pre-study documentations for the Masthuggskajen project, as well as the pre-study for a potential inland waterway transportation system for the Älvstaden project as a whole [26][27][23]. The source material that these studies are based on also serve as the backbone on which the assumptions in section 3.5 are made. The source material consists of documents such as scheduling plans for the duration of the construction, as well as schematics of suggested checkpoint areas and traffic flow for the construction area at Masthuggskajen. Specific data collected in this way is displayed in section 3.3 and 3.4. Three previous master theses were also studied to get a better understanding and a broader overview of the project [17][29][7].

3.2.2 Semi-structured interviews

A number of semi-structured phone interviews were conducted with stakeholders in an attempt to gather data regarding material and waste delivery logistics. Although neither the construction companies nor the waste companies had the ability to gather- or the interest to share the specific data or schedules, the conversations still provide perspective and overview of the logistical problem at hand. Layouts and logistical problems were discussed with the intent to identify parameters that e.g. determine pathing for vehicles.

Notable interviews consist of B. Södahl (Södahl & Partners AB) and K. Lindman (Renova), but shorter conversations were had with employees at various construction companies and stakeholders at Älvstranden Utveckllling, K21, NCC and Inhouse Tech. All of which provided answers to the best of their ability via phone and email.

3.2.3 Observations

Two visits were made to the construction sites to get first hand impressions of the area. Combined with the schematics and documentation from 3.2.1, it served as inspiration and confirmation of the feasibility of a possible dock location at the construction site.

3.3 Material

Svensk Bygglogistik estimates that all material deliveries are spread out over a work day from 07-16 [26]. It is further estimated that an average of 90 deliveries per day is to be expected during the course of construction. By observing the phase schedule for the whole time period, the most intensive quarter estimates a total of 15 375 deliveries over three months [27], which would correspond to about 168 deliveries per day during said time period. The daily distribution and the corresponding amount of deliveries per hour is displayed in Table 3.2 below.

Table 3.2: Estimated delivery distribution schedule [26][27]

Time Interval	%	Deliveries	
		Average	Max
00:00-06:59	0	0	0
07:00-07:59	26	23	44
08:00-08:59	13	12	22
09:00-09:59	12	11	20
10:00-10:59	10	9	17
11:00-11:59	7	6	12
12:00-12:59	8	7	13
13:00-13:59	7	7	12
14:00-14:59	7	6	11
15:00-15:59	5	5	9
16:00-16:59	5	4	8
17:00-23:59	0	0	0
Total	100	90	168

Material deliveries are achieved by various road vehicles. In Table 3.3 below, the rough estimation of delivery vehicle types and distribution can be observed, as confirmed in an email (P. Lindgren - Svensk Bygglogistik to B. Södahl - Södahl & Partners AB, 16 September 2020). An estimation of the carrying capabilities for each vehicle type is also included, the volumes are the same as the ones used in the pre-study regarding river utilization for Älvstaden by B. Södahl [23]. The pre-study estimates a 95% degree of filling, though this is not included in the table.

Table 3.3: Estimated distribution of delivery types,

Delivery type	%	Volume [m^3]
Car + trailer	4	129.0
Truck	39	48.4
Semitruck	9	84.86
Courier's van	26	4.23
Unknown	22	

There is no information about 22% of the deliveries, it is therefore assumed that the unknown delivery types consists of more of the other four types. The new distribution can be seen in Table 3.4 below.

Table 3.4: Updated estimated distribution of delivery types

Delivery type	%	Volume [m3]
Car + trailer	5.1	129.0
Truck	50	48.4
Semitruck	11.6	84.86
Courier's van	33.3	4.23

3.4 Waste

Actual data or estimation for waste production for Masthuggskajen or Älvstaden is not available. An estimation of produced waste is instead made using data from historic waste disposal in the construction sector. Waste is estimated to an average of 34.9 Kg/BTA [28]. BTA is a swedish measurement of gross area in construction. BTA is, simply put, the "livable" area of all floors combined. Furthermore it is by law required that waste from construction is separated in at least six categories: wood, minerals (concrete, brick, clinker, ceramics, stone), metal, glass, plastic and plaster [3]. During first hand observations at the ongoing construction sites it was confirmed that there is exactly 6 waste containers per site. This law has not been in place more than a year as of writing which means that historic data for waste fractions for the six categories from construction is hard to come by. Specifically has glass and plastic not specifically been categorized. In this report it is assumed that glass was previously part of the deponi category [1] and plastic was the majority part of the flammable and mixed waste categories. Note that these assumptions are highly arbitrary, since produced waste is a minority of the total transport volume during construction.

Table 3.5: Estimated weight per volume for different types of waste [28][22]

Waste type	kg/m3	Comment	%
Wood	130		8
Minerals	615	Calculated as the average of "tile" and "light concrete"	13
Metal	190		10
Glass	370	Calculated as the average of "Glass packaging"	2
Plastic	20	Plastic packaging	53
Plaster	235		13

A total of 314 100 BTA will be built at Masthuggskajen [26]. Using the average of 34.9 Kg/BTA and the total BTA gives the total waste throughout the whole project to about 10 962 090 Kg. From table 3.5 it is now possible to estimate the total volume of each waste type.

Table 3.6: Average number of waste containers per day.

Waste type	m3	# containers (25 m3/cont)
Wood	6 745.9	269.8
Minerals	2 317.2	92.7
Metal	5 769.5	230.8
Glass	592.5	23.7
Plastic	290 495.4	11 619.8
Plaster	6 064.1	242.6
Total	311 984.7	12 479.4
Total/day	122.1	4.9

Note that this is an average over the whole project time of *seven years*, the actual number of containers of waste per day will vary throughout the course of construction.

3.5 Assumptions

The amount of available data is very limited due to the project being in such an early stage. As a result, assumptions has to be made, all of which has a varying impact of the accuracy of the model. This section contains the assumptions that was made in the model, as well as explanations for them.

- Material logistics when loading and unloading material from containers works flawlessly and automatically.
  - Not enough data is available to make an accurate model regarding the construction site logistics. It is also assumed that the real system would be designed in a way that gives leeway for variation in this process, such as having more than the bare minimum number of empty containers on standby.
- Truck unloading takes 30 minutes.
  - The logistical prestudy by Svensk Bygglogistik estimates that unloading a truck takes 30 minutes for a qualified worker [26]. Analysis of the simulation shows that the unloading process is never a bottleneck, even if smaller delivery vehicles with smaller volumes are used. The parameter is therefore chosen as a static time of 30 minutes for all delivery types.
- Replacing a container on a barge takes 5 minutes.
  - The time it takes to replace a container on a barge is ultimately determined by the means to do so. Using a crane would for instance take a different amount of time than if the containers are rolled onto the barge. 5 minutes was finally deemed a reasonable average by consultation with B. Södahl (Södahl & Partners AB).
- The containers used are 20-foot "dry containers" designed for intermodal freight transportation [12].
  - Using a common type of container would enable outside contractors to more easily prepackage material and ship deliveries in compatible containers already from the source, which could then be seamlessly transferred to the barges without the need for repackaging. Using 20-foot "dry containers" as the defining dimensions would overall make the water-based transportation system more able to interact with other intermodal transportations systems.
- All material transports come from outside the city via road delivery.
  - Svensk bygglogistik has made all their calculations based on land deliveries [27]. The information regarding the road deliveries origin is however unknown. It is therefore assumed that the delivery vehicles only arrive from the major highways that enter the city.
- Road deliveries entering the city is equally distributed between the entry points.
- Road deliveries enter Masthuggskajen from the west via *E45* and *Emigrantvägen*.

  - Confirmed by O. Valentin at Inhouse Tech in an email. Road deliveries to Masthuggskajen from the north and south are therefore rerouted to arrive via *E45* directly, as *Hisingsleden* and *Västerleden* provide a natural path for these entry points.
- Containers are 95% filled.
  - Containers uses the same degree of filling as the delivery vehicles are estimated to do [23].
- Only one dock is used for loading and unloading.
  - It is deemed by observing phase plan schematics- and by first hand observation that there will be room for one dock at most, before the planned land extension is finished.

3.6 Model Building

This section describes the methodology for constructing the conceptual model, to using the sowtware and building it. This section corresponds to *Model building* and *Coding* in Banks method in Figure 2.1.

3.6.1 Conceptual Model

The model can be divided into two main parts. The first part is the delivery vehicles that enter the model, described in Figure 3.3 below. The second part is the "barge-loop", where resources enters and leaves the system at the three checkpoints. The first part of of the model can be described as the link between the input of material into the model (city) and the barge-loop.

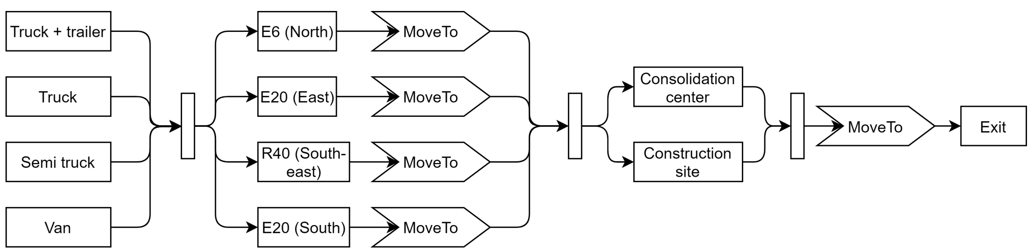


Figure 3.3: Delivery vehicle concept

A delivery vehicle enters the city, which can be from either one of the entrance points. The vehicle then navigates to its destination which is either the consolidation center or the construction site. After the vehicle has unloaded its contents at its destination, the vehicle travels back to its original entrance point and exits the model. The delivery vehicle always takes the same path to and from its destination.

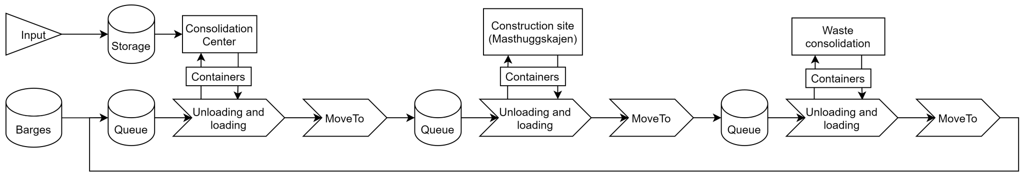


Figure 3.4: Barge-loop

The second part of the model is the barge-loop, as shown in Figure 3.4. The barge loop can be summarized as storage containers being moved around three checkpoints, as shown in Figure 3.2. The input to this system is the volume of material that was unloaded at the consolidation center in Figure 3.3. The volume is placed in "storage" until two conditions are met:

1. Storage $\geq$ container capacity
2. There exists an available empty container

When the two conditions are met, a container agent is loaded according to the defined container capacity and are now ready to be picked up by a barge.

Barge agents have a set population and once created, stays in the model for the rest of the simulation. When a barge agent enter the "loading and unloading" step, it first unloads the empty containers inside, then waits for a full container to be ready. Once it is ready, the container is loaded onto the barge.

If a barge is in the *unloading and loading* step and another barge tries to enter, it will be put in a queue until the occupying barge moves on. This is because each dock is meant to handle only one barge at a time. The delay for the loading and unloading step is dependent on the number of containers that will be replaced at that particular point, as presented in Figure 3.2. The time it takes to switch out one container on the barge is 5 minutes.

3.6.2 Agents

The agents in the model function very similar to "objects" in coding. Agents can have internal variables, but additional information can also be stored in them. An agent can for example be stored in another agent without manually specifying so in the internal variables, which is used in the model. Just like objects, multiple instances can be created of a single agent, each with its own internal variables. This section describes the three most important agent types in this model.

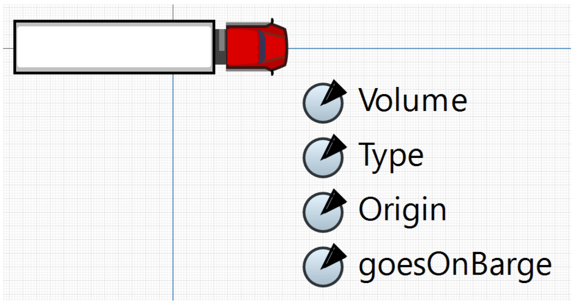


Figure 3.5: Truck agent

The truck agent shown in Figure 3.5, depicts the agent icon that is shown on the GIS map as well as the names of its internal variables. The internal variables and their functionality in the model are:

- **Volume:** A double which stores the volume in m^3 of cargo that a delivery vehicle is carrying. This variable is assigned as 95% (degree of filling %) of total volume from Table 3.4, once the agents delivery vehicle type is decided.
- **Type:** A string that stores the delivery vehicle type (truck, Van etc.). This is used to decide the material volume inside the agent as well as to distinguish between vehicles when calculating distances traveled.
- **Origin:** A string that stores the entrance point of where the vehicles originates (E6 north, E20 east etc.). This is used both when calculating distances, as well as to decide which path the agent should take when exiting the model.
- **goesOnBarge:** A boolean that helps navigate the agent to its intended destination, similarly to the Origin variable in many cases.

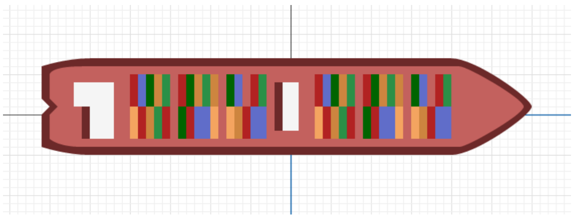


Figure 3.6: Barge agent

The barge agent shown in Figure 3.6, does not have any internal variables. The barge agent uses "Pickup" and "Dropoff" blocks in the model to store and release other agents from its contents.

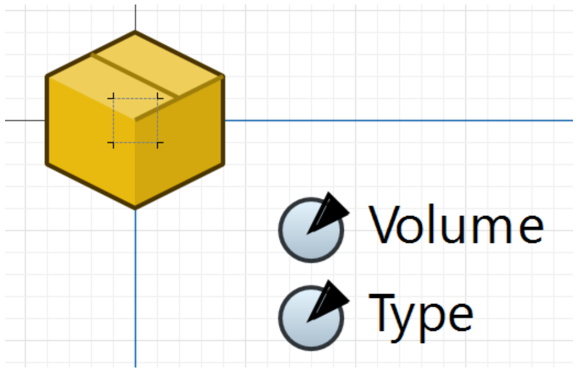


Figure 3.7: Container agent

The container agent shown in Figure 3.7, is the agent which is used for all containers in the model. It has two internal variables:

- **Volume:** A double that stores the current contents of the container in m^3.
- **Type:** A string that stores the container type (material or waste). This variable helps distinguish between what container agents, contained in the barge agent, that should be picked up and dropped off at each dock.

3.6.3 Implementation in the software

In the context of modelling material flow in a city, it is not efficient to model each and every road. Anylogic provides libraries for simulation, one of which is the GIS interface. Using the GIS interface for road traffic simulations is the preferable option since it has all the roads mapped out, but also because the software can automatically calculate the distance and closest routes between two points, much like a GPS.

Using agent based modelling in a hybrid simulation enviroment, it is possible to let individual agents, such as individual trucks and cargo containers, operate simultaneously in the model. The *moveTo* blocks in the following figures are used to navigate the agents in the GIS interface via predetermined paths.

This section describes the internal logic of the delivery vehicle process in Figure 3.3, as well as the three checkpoints along the barge-loop in Figure 3.4. Note that the logic presented in the following figures is somewhat reduced to only show functionality. Parts of the model that only serve to make the models run has been removed as they serve no purpose for interpretation of the logic (see Appendix B for the full logic). The models should be studied left to right, as in an agent enters from the left and leaves to the right.

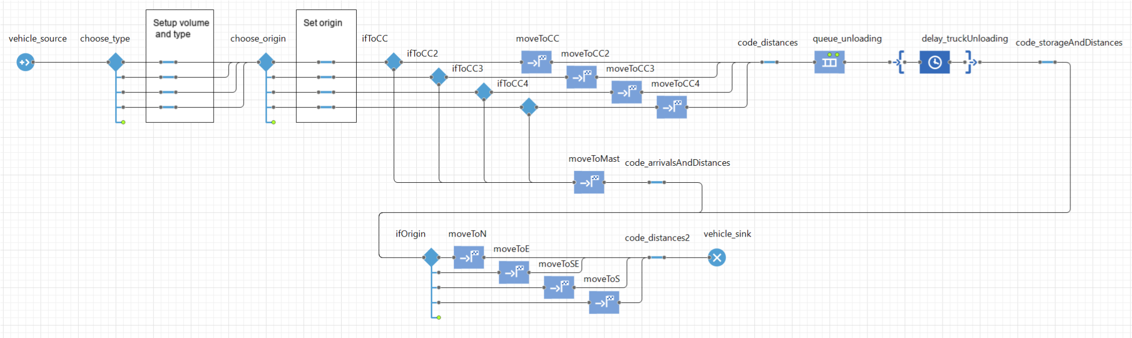


Figure 3.8: Delivery vehicle logic

The *vehicle_source* creates new truck agents according to one of the delivery schedule in Table 3.2. The vehicle is then randomly selected a type and volume according to Table 3.3 and an origin (entrance point). The delivery vehicle will then start to move to its destination, which is either the consolidation center or the construction site, where its contents will be unloaded. The *code_storageAndDistances* block in the top right corner is where the contents of the vehicle is transferred to the temporary storage at the consolidation center.

The bottom part of the process is where the agent returns to its original destination. The vehicle finds its way back to its origin with the origin variable that was set earlier. The distances of the vehicles are calculated throughout the process in the *code_distance* blocks.

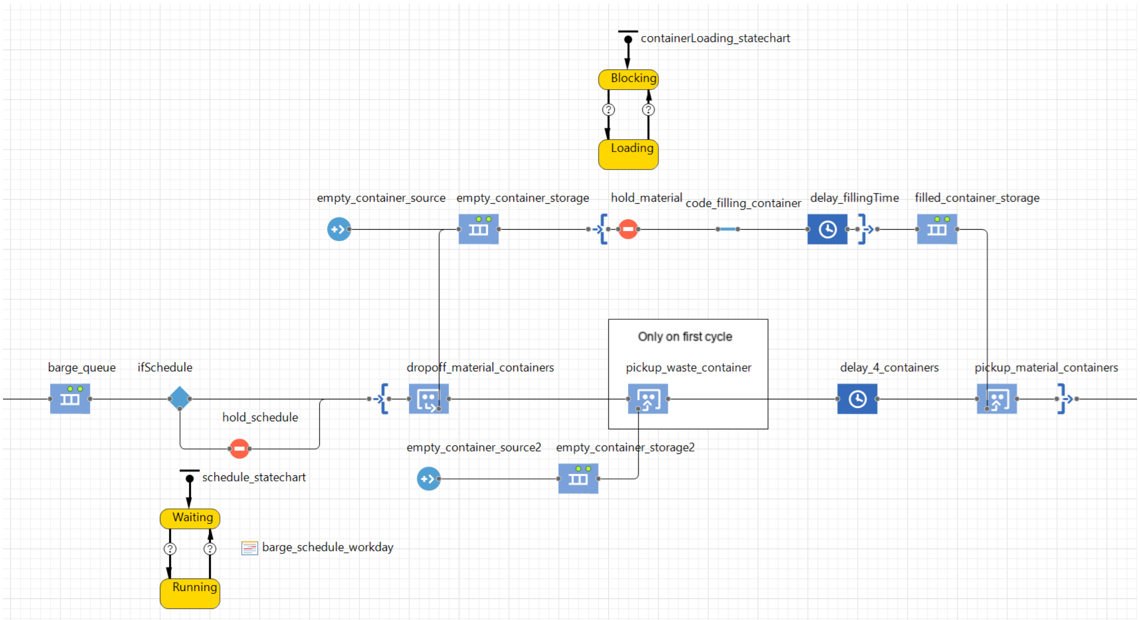


Figure 3.9: Consolidation Center logic

Figure 3.9 shows the internal logic of the consolidation center in the model. Barges enter from the left and are placed in the *barge_queue* block while it waits for permission to enter the consolidation center. There can only be one barge agent inside the section marked off with { and } at a time. When the barge is ready to enter, it starts of by unloading all containers of type *"material"*. The barge then waits for the delay block *delay_4_containers* to simulate the unloading/loading process of the four material containers, before proceeding to pick up the filled material containers, and finally exiting to the right.

The top part of the model represents the loading process of the containers contents. The *empty_container_source* is used during initialization of the model to produce the material containers that will be used. The empty containers are placed in a queue where they wait to be filled. They are then placed in a queue where they wait to be picked up by a barge.

The consolidation center logic contains two statecharts. The *containerLoading_statechart* continously checks the contents of the temporary storage, if the storage is greater than the container capacity, the state will change and let container agents pass through the *hold_material* block. The second statechart is the *schedule_statechart*, which continuously checks the *barge_schedule_workday*, to see if barges are running or not and the *hold_schedule* block is adjusted accordingly. The second statechart is only utilized if the barges are running on a schedule, otherwise the *ifSchedule* directs the barge agents to bypass the *hold_schedule* block entirely.

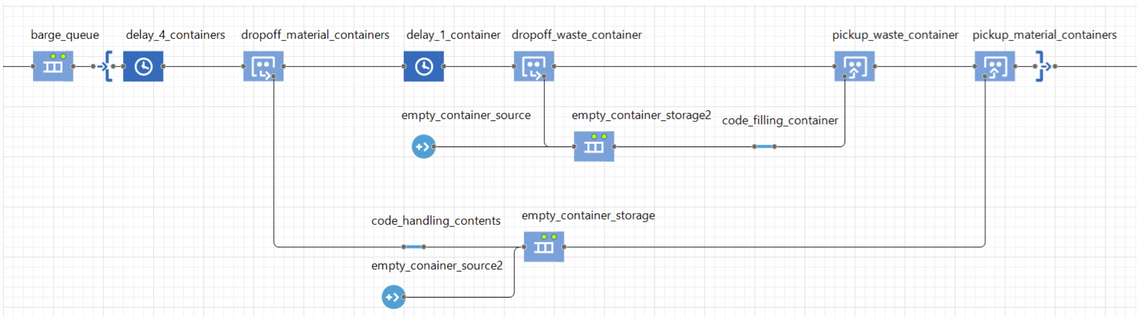


Figure 3.10: Construction site logic

Similarly to the consolidation center, the construction site logic in Figure 3.10, uses { and } to restrict the number of barges inside to one at a time. The barge enters from the left and starts off by dropping of its material- and waste containers. The contents of the containers are handled by the *code_handling_contents* and *code_filling_container* respectively, before a new set of containers are picked up by the barge. Delay blocks are used to simulate the unloading- and loading process. The *empty_container_source* blocks are used to produce empty containers at the start of the simulation.

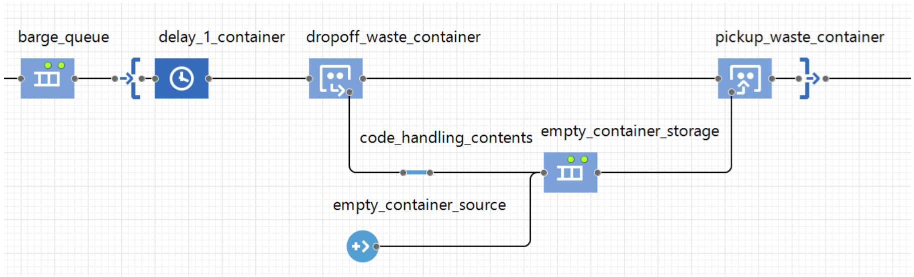


Figure 3.11: Waste consolidation logic

The waste consolidation logic in Figure 3.11 works exactly the same as the construction site logic, as is it uses the same restricions and method for unloading/loading, though scaled down to only a waste container.

3.7 Model Verification

Model Verification aims to ensure the conceptual model is successfully translated to the simulation platform. This also makes sure that the code is error-free and the model is successfully compiled. Some model verification techniques has been used during this project, such as checking the model in group, following the logic of each events that is triggered and moved to the next state, checking model outputs, and checked the animation when the simulation is running to see if the model behaved properly during development of the model. AnyLogic, provides error notification as well, which is helpful to ensure that the model runs error-free. Additionally, since AnyLogic uses a visual-design interface, the model serves as self-documentation and the logical flow is easier to follow and verify.

Verification was done, as with everything else, iteratively throughout the process. With each new addition to the model, a functionality check was performed to make sure that the model still behaved as intended. Agents origin and behaviour were monitored to make sure that they follow the path they are supposed to. Barges specifically needs to successfully store the correct amount of containers of each type. Input of delivery vehicles and their contents were monitored to make sure that their travel distances and material transfer is calculated as intended. Delivery vehicle were made sure to be distributed according to types and origins as specified etc.

3.8 Model Validation

Model validation is performed to find out if the model accurately represents the system according to its specifications. The validation process explores the assumptions made and the data used, as well as the behaviour and characteristics of the model.

Since the system does not yet exist, it is not possible to completely evaluate the accuracy of the model by comparison. Each part of the model is instead based on assumptions and reasoning. The method of *Strucured walkthrough* of the model has instead been used for validation. *"A structured walkthrough is an organized procedure for a group of peers to review and discuss the technical aspects of software development work products. The major objectives of a structured walkthrough are to find errors and to improve the quality of the product."* [25]. The idea is to go through each aspect of the model methodically and identify flaws and inconsistencies. Structured model walkthroughs has been conducted iteratively throughout the process. The final walkthrough of the model was done together with B. Södahl from Södahl & Partners AB for a final confirmation of parameters such as locations, loading/unloading times, carrying capacities of vehicles and containers, speed of barges, and distribution of delivery vehicle-types.

3.9 Emission Calculation

Emission calculations are based on equation (2.1) from section 2.6.2, i.e. the Activity-based approach.

Since vehicles travel with the same distance loaded as they do unloaded, the factor $gCO_2/tonne - km$ is based on 50% of truck-kms running empty [8] for trucks, truck+trailer, semi trucks and trucks transporting waste. Vans are however not based on volume, but instead on the average gCO_2/km [21], due to its low capacity. Barges $gCO_2/tonne - km$ factor is based on a small container barge running in a canal [8]. The density of material for land transports are based on the waterway prestudy for Älvstaden by B. Södahl [23], i.e. the maximum density that the vehicle can transport when it is full.

Table 3.7: CO_2 calculations

Type	$gCO_2/tonne - km$	Cargo weight [kg]	Comment	g co2/km
Truck + trailer	57.51	36 000	29 tonnes is the highest factor, $gCO_2/tonne - km$ estimated as 0.9 times that	
Truck	151.1	10 250		
Semi truck	72.4	24 000		
Courier's van	-	1 000		158.4
Barge	44.5	26 050		
waste truck (truck)	151.1	869.6	Cargo weight is the avarage weight per waste container	

The $gCO_2/tonne - km$ factors and the corresponding cargo weights in Table 3.7 are used in equation (2.1) to calculate the CO_2 emissions in the results, based on the distances each agent travels. An exception is vans which are calculated with gCO_2/km times the distance, due to their low cargo weight.

3.10 Experimental Design

In order to gain comparable results from the simulations, five different scenarios are set up. The scenarios are designed to examine how the system behaves under different levels of pressure put on by the incoming material flow, as well as the impact of the source of said material.

One hypothesis that the experiments are based on is that semi trucks are used to transport particularly large or awkward construction components such as e.g.

concrete frames, which would not naturally fit in the containers. Land delivery vehicles, apart from semi trucks, are removed from the system depending on their distance to the consolidation center relative to the construction site. This leads to five different scenarios, each one designed to relieve the consolidation center from more material input than the previous scenario:

1. All road deliveries go to the consolidation center.
2. Semi-trucks go directly to Masthuggskajen, everything else uses the consolidation center.
3. Semi-trucks and delivery vehicles from the south go to Masthuggskajen, everything else uses the consolidation center.
4. Semi-trucks and delivery vehicles from the south, and south east go to Masthuggskajen, everything else uses the consolidation center.
5. Everything go to Masthuggskajen directly.

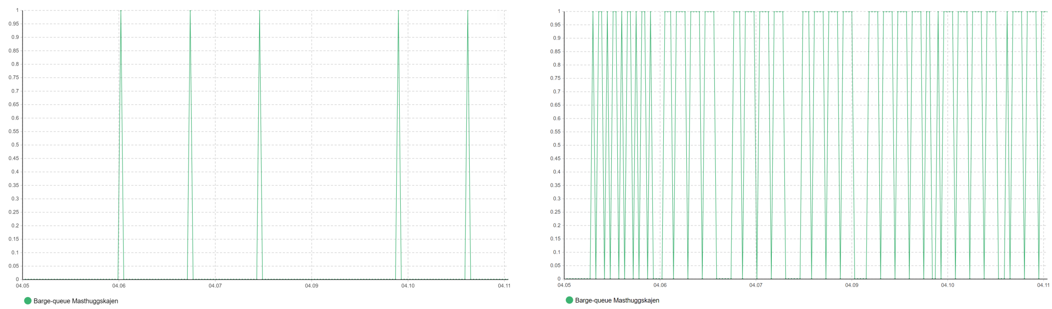
4

Results

This chapter contains the results of this study, all results come from a simulation period of one month. The simulation graphs displayed in this section are meant to display general characteristics and trends. See appendix for more detailed versions of the plots.

4.1 Number of barges

The first simulation is a test to investigate how many barges that can effectively be utilized in the system at the same time. This is done by giving the system unlimited supply of material and steadily increasing the number of barges until they start queueing up.



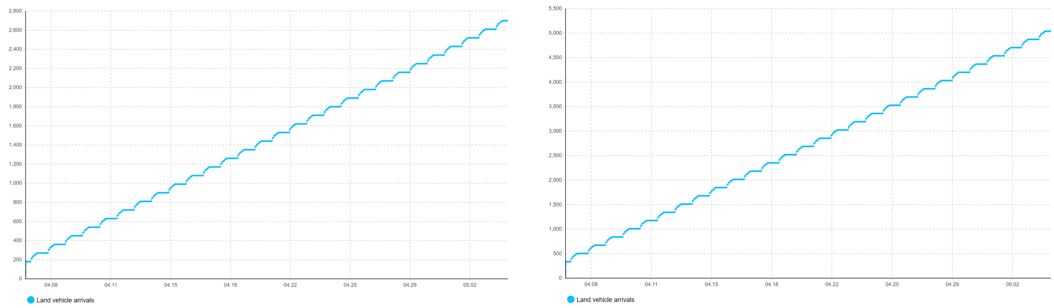
(a) 5 barges, $y \in [0, 1]$ **(b)** 6 barges, $y \in [0, 1]$

Figure 4.1: Queuing of barges over time at Masthuggskajen

From Figure 4.1 it can be observed that when more than five barges are active at the time, a consistent queue starts to form at the Masthuggskajen dock. The y-axis shows the number of barges currently in the queue, the queue varies between 0 and 1 in this case. The maximum number of barges is determined to be 5 and the Masthuggskajen dock is identified as a bottleneck, since this was the first dock to observe queueing behaviour.

4.2 Deliveries over time

All simulations are executed with one of two possible delivery intensities, see Table 3.2.



(a) Average intensity, $y \in [0, 2700]$ **(b)** Max intensity, $y \in [0, 5040]$

Figure 4.2: Road vehicle deliveries over a month

The average delivery intensity is visualized in Figure 4.2a and the maximum delivery intensity in Figure 4.2b. This is henceforth the characteristics referenced as Average- and Max delivery intensity in the simulations.

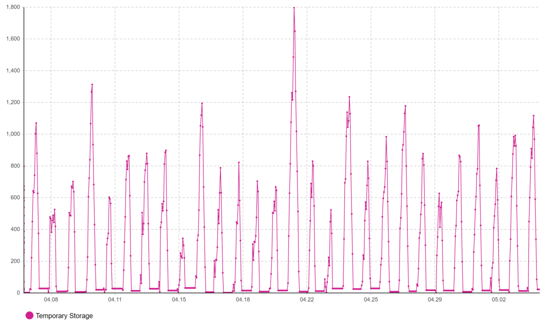
4.3 Simulation

All scenarios are tested with all variations of delivery intensity and barge scheduling. This means that all scenarios that utilize the water-based transportation is simulated four times with different setups. Scenarios that do not utilize the water-based transportation are simulated only two times. All simulations are done over a time span of one month.

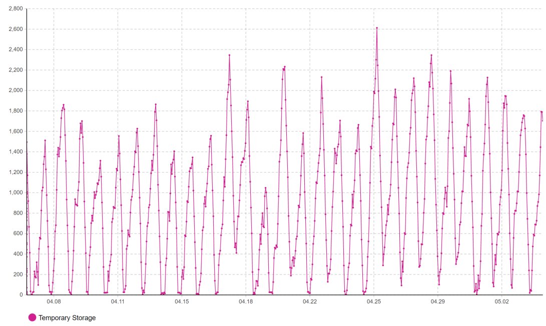
The scheduled barges only run between 06:00 to 16:00, 16:00 is however the last time they depart from the consolidation center. Barges that leave the consolidation center still travels to the construction site, the waste consolidation and then back to the consolidation center. The time that the barges actually stop running is therefore closer to 17:00.

4.3.1 Scenario 1: Everything goes on the barge

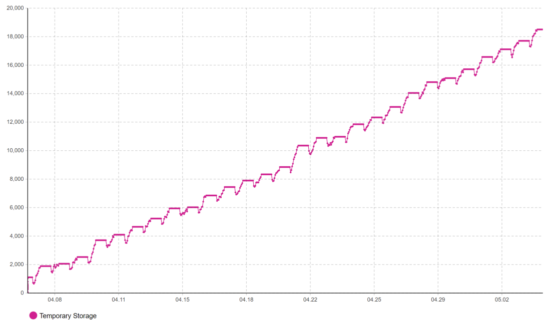
The first scenario to be tested was the scenario where all deliveries via road traffic is redirected to the barge. This includes all types of vehicles as well as vehicles from all four entry points.



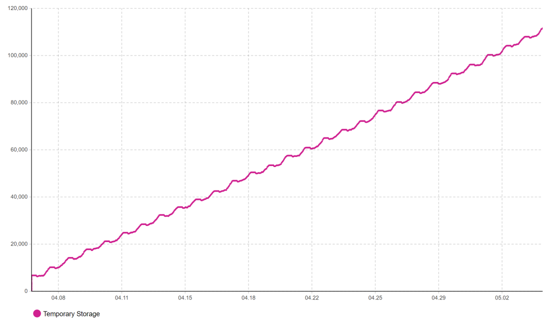
(a) Average delivery intensity, barges running 00-24



(b) Max delivery intensity, barges running 00-24



(c) Average delivery intensity, barges running 06-16



(d) Max delivery intensity, barges running 06-16

Figure 4.3: Temporary storage volume [m^3] (y-axis) at consolidation center over time (x-axis) for Scenario 1

As can be seen in Figure 4.3a and 4.3b, when the barges run all day round, the material flow is continuously taken care of and the temporary storage at the consolidation center is emptied each day before the next days shipment start to arrive. The higher delivery intensity lowers the resting period between each day, but the storage still returns to zero most of the time.

When the barges are running on a schedule, the flow of material is greater than the system is able to handle and the storage volume continues to increase over time. This behaviour can be observed for both average delivery intensity in Figure 4.3c and for maximum delivery intensity in Figure 4.3d, though the latter shows a much greater increase rate. See Appendix A for more detailed plots.

Table 4.1: Trips to Masthuggskajen and distances traveled in scenario 1.

			Average delivery intensity	Max delivery intensity
	Total number of delivery vehicles		**2 700**	**5 040**
Barges always running	**Arrivals at Masthuggskajen**			
	Truck combo		0	0
	Truck		0	0
	Semitruck		0	0
	Van (delivery vehicles)		0	0
	Barge		834	1 555
	Distance traveled (inside the city) [km]			
	Truck combo	Loaded	1 945.7	3 527.9
		Empty	1 945.7	3 527.9
	Truck	Loaded	18 226.1	34 945
		Empty	18 226.1	34 914
	Semitruck	Loaded	4 033.2	7 400.1
		Empty	4 033.2	7 400.1
	Van	Loaded	13 060.8	23 240.3
		Empty	13 060.8	23 240.3
	Barge	Loaded	5 672.9	10 581.7
		Empty	5 672.9	10 581.7
Barges follows fixed schedule	**Arrivals at Masthuggskajen**			
	Truck combo		0	0
	Truck		0	0
	Semitruck		0	0
	Van (delivery vehicles)		0	0
	Barge		687	687
	Distance traveled (inside the city) [km]			
	Truck combo	Loaded	1 945.7	3 527.9
		Empty	1 945.7	3 527.9
	Truck	Loaded	18 226.1	34 945
		Empty	18 226.1	34 914
	Semitruck	Loaded	4 033.2	7 400.1
		Empty	4 033.2	7 400.1
	Van	Loaded	13 060.8	23 240.3
		Empty	13 060.8	23 240.3
	Barge	Loaded	Inconclusive	Inconclusive
		Empty	Inconclusive	Inconclusive

In Table 4.1 it can be observed that the number of barges that arrive at Masthuggskajen is the same for both average- and max delivery intensity when barges are running on a schedule. This, combined with Figure 4.3c and 4.3d is a strong indication that this is the maximum achievable number of barge trips to Masthuggskajen over a month with the current configuration.

The only vehicle type that has arrivals at Masthuggskajen are barges since all the delivery vehicles are redirected to the consolidation center for repackaging onto barges. The distance travelled for each type of vehicle is the sum of all vehicles of that type over the one month period.

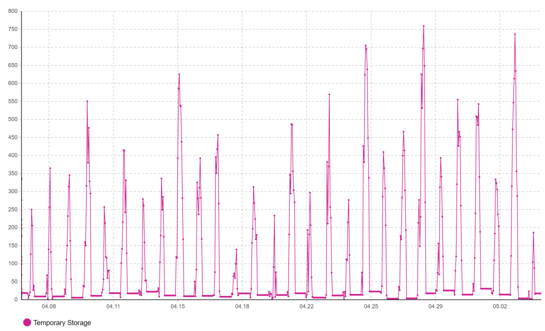
For the scheduled results the barge travel distance is *inconclusive*. This is because not all material were successfully handled by the system and the resulting travel distance for the barges would therefore be misleading. The same goes for the CO_2 footprints in Table 4.2 below.

Table 4.2: CO_2 footprint for scenario 1.

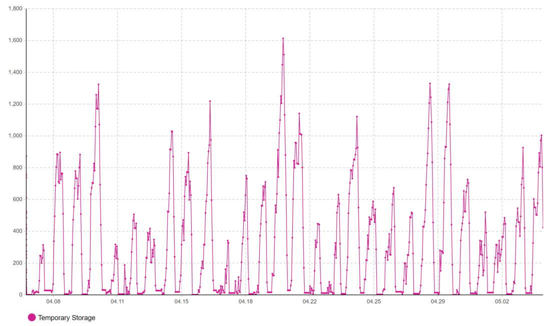
		Average delivery intensity	Max delivery intensity
	Total number of delivery vehicles	**2 700**	**5 040**
Barges always running	CO_2 from delivery vehicles [Ton]	82.7	155.9
	CO_2 from barges [Ton]	13.2	24.5
	Total	95.8	180.4
Barges follows fixed schedule	CO_2 from delivery vehicles [Ton]	82.7	155.9
	CO_2 from barges [Ton]	Inconclusive	Inconclusive
	Total	Inconclusive	Inconclusive

4.3.2 Scenario 2: Everything except semitrucks go on the barge

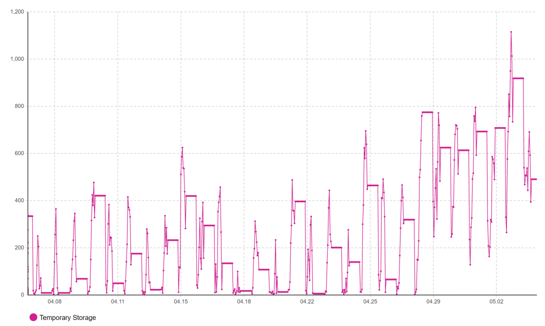
In the second scenario, vehicles from all four entry points are going on the barge, but all semitrucks are redirected to go straight to Masthuggskajen.



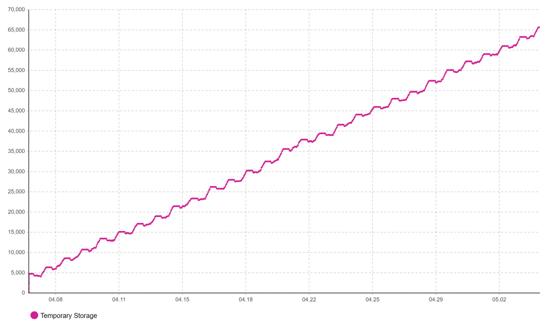
(a) Average delivery intensity, barges running 00-24



(b) Max delivery intensity, barges running 00-24



(c) Average delivery intensity, barges running 06-16



(d) Max delivery intensity, barges running 06-16

Figure 4.4: Temporary storage volume [m^3] (y-axis) at consolidation center over time (x-axis) for scenario 2

When the material flow that arrives with semi trucks are relieved from the water-based transportation system, an immediate change can be seen in in the performance. Specifically is the resting period longer between daily delivery intervals in both Figure 4.4a and 4.4b.

It can also be observed in Figure 4.4c that an average delivery intensity combined with workday scheduled barges are almost able to handle the material flow. The graph shows that the temporary storage is not at zero, but the volume at its highest plateau is only about 900 which equates to about 7 barge trips. The plot also shows that this is a trend that has accumulated over time, which means that the difference per day might be even smaller than 7 barge trips.

Table 4.3: Trips to Masthuggskajen and distances traveled in scenario 2.

			Average delivery intensity	**Max delivery intensity**
	Total number of delivery vehicles		**2 700**	**5 040**
Barges always running	**Arrivals at Masthuggskajen**			
	Truck combo		0	0
	Truck		0	0
	Semitruck		297	572
	Van (delivery vehicles)		0	0
	Barge		654	1 200
	Distance traveled (inside the city) [km]			
	Truck combo	Loaded	2 024.1	3 303.3
		Empty	2 024.1	3 303.3
	Truck	Loaded	18 257.1	34 252
		Empty	18 257.1	34 252
	Semitruck	Loaded	5 635.2	10 647.9
		Empty	5 635.2	10 647.9
	Van	Loaded	12 631.7	23 219.4
		Empty	12 631.7	23 219.4
	Barge	Loaded	4 448.5	8 167
		Empty	4 448.5	8 167
Barges follows fixed schedule	**Arrivals at Masthuggskajen**			
	Truck combo		0	0
	Truck		0	0
	Semitruck		297	572
	Van (delivery vehicles)		0	0
	Barge		650	686
	Distance traveled (inside the city) [km]			
	Truck combo	Loaded	2 024.1	3 303.3
		Empty	2 024.1	3 303.3
	Truck	Loaded	18 257.1	34 252
		Empty	18 257.1	34 252
	Semitruck	Loaded	5 635.2	10 647.9
		Empty	5 635.2	10 647.9
	Van	Loaded	12 631.7	23 219.4
		Empty	12 631.7	23 219.4
	Barge	Loaded	4 421.3	Inconclusive
		Empty	4 421.3	Inconclusive

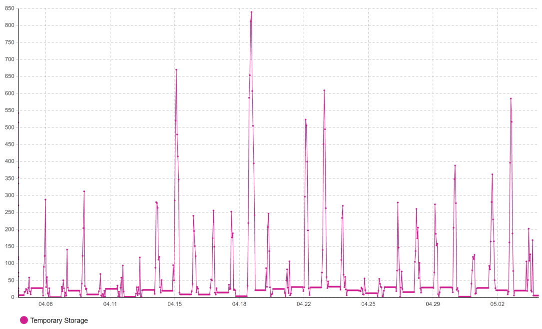
A total of 650 barges arrive at Masthuggskajen when the average delivery intensity and scheduled barges are used, as can be seen in Table 4.3. This is a difference of 4 barge trips compared to when the barges run all the time, which could mean that the behaviour in Figure 4.4c is a result of a couple of lagging behind delivery vehicles arriving right before the barges stops for the day.

Table 4.4: CO_2 footprint for scenario 2.

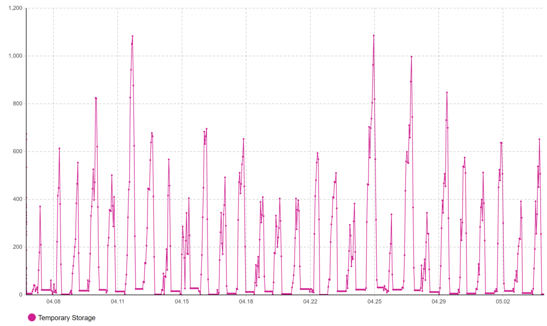
		Average delivery intensity	**Max delivery intensity**
	Total number of delivery vehicles	**2 700**	**5 040**
Barges always running	CO_2 from delivery vehicles [Ton]	88.5	164.1
	CO_2 from barges [Ton]	10.3	18.9
	Total	98.8	183.1
Barges follows fixed schedule	CO_2 from delivery vehicles [Ton]	88.5	164.1
	CO_2 from barges [Ton]	10.3	Inconclusive
	Total	98.8	Inconclusive

4.3.3 Scenario 3: All semitrucks- and all delivery vehicles from the South go straight to the construction site

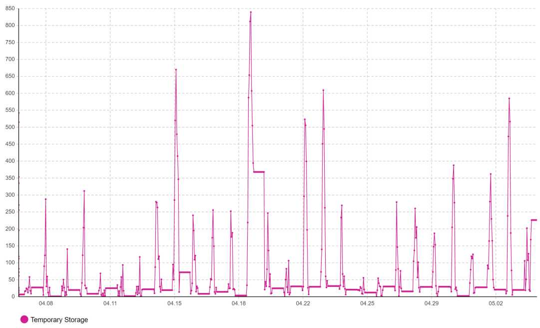
In scenario 3, delivery vehicles entering from the south entry point as well as all semitrucks go straight to the construction cite, all other material transports go to the consolidation center.



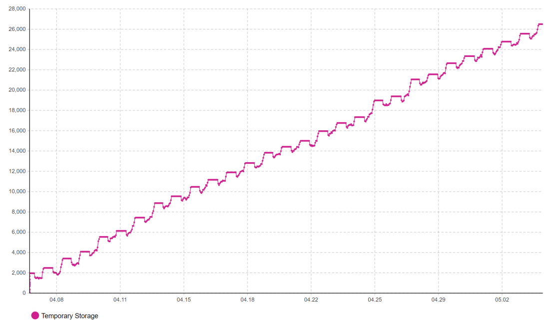
(a) Average delivery intensity, barges running 00-24



(b) Max delivery intensity, barges running 00-24



(c) Average delivery intensity, barges running 06-16



(d) Max delivery intensity, barges running 06-16

Figure 4.5: Temporary storage volume $[m^3]$ (y-axis) at consolidation center over time (x-axis) for scenario 3

For the average delivery intensity, the temporary storage now looks almost identical between a scheduled- and an always active barge transportation system as can be observed in figure 4.5a and 4.5c. The consolidation center is now empty in the resting periods between workdays with only one exception. The resting periods are almost exactly equal, which means that the material flow is successfully handled each workday. Some spikes can be observed in the plots that can be explained by randomness in the model and delivery vehicle arriving right before a sample is taken.

The scheduled barge system during the period with maximum delivery intensity is still not able to handle the incoming material to the consolidation center as seen in Figure 4.5d. Though the rate of which the temporary storage increases has been more than halved compared to Figure 4.4d in Scenario 2.

Table 4.5: Trips to Masthuggskajen and distances traveled in scenario 3.

			Average delivery intensity	Max delivery intensity
	Total number of delivery vehicles		**2 700**	**5 040**
Barges always running	**Arrivals at Masthuggskajen**			
	Truck combo		22	49
	Truck		354	657
	Semitruck		308	596
	Van (delivery vehicles)		221	412
	Barge		501	898
	Distance traveled (inside the city) [km]			
	Truck combo	Loaded	1 890.9	3 251
		Empty	1 890.9	3 251
	Truck	Loaded	18 966.3	34 970.4
		Empty	18 966.3	34 970.4
	Semitruck	Loaded	5 728.7	11 189.5
		Empty	5 728.7	11 189.5
	Van	Loaded	12 352.4	23 366.3
		Empty	12 352.4	23 366.3
	Barge	Loaded	3 407.8	6 108.2
		Empty	3 407.8	6 108.2
Barges follows fixed schedule	**Arrivals at Masthuggskajen**			
	Truck combo		22	49
	Truck		354	657
	Semitruck		308	596
	Van (delivery vehicles)		221	412
	Barge		499	687
	Distance traveled (inside the city) [km]			
	Truck combo	Loaded	1 890.9	3 251
		Empty	1 890.9	3 251
	Truck	Loaded	18 966.3	34 970.4
		Empty	18 966.3	34 970.4
	Semitruck	Loaded	5 728.7	11 189.5
		Empty	5 728.7	11 189.5
	Van	Loaded	12 352.4	23 366.3
		Empty	12 352.4	23 366.3
	Barge	Loaded	3 394.2	Inconclusive
		Empty	3 394.2	Inconclusive

A total of 500±1 barge trips are now happening per month for periods with average delivery intensity, as can be seen in Table 4.5. This is a reduction of 150 barge trips per month compared to Scenario 2, which resulted in less stress being put on the consolidation center as seen in Figure 4.5c. A total of 905 delivery vehicles are now delivered directly to Masthuggskajen but the difference in distance traveled for the road vehicles has increased only slightly, this is because the entrance point in the South is 15.5 km from the consolidation center and 16.1 km from the construction site.

Table 4.6: CO_2 footprint for scenario 3.

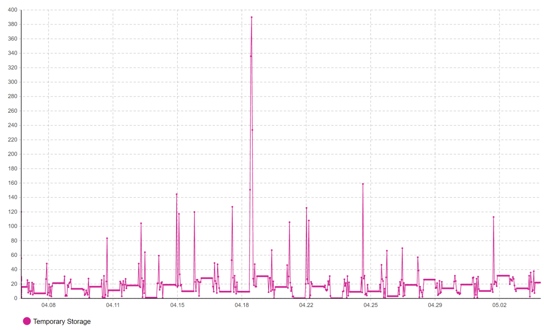
		Average delivery intensity	Max delivery intensity
	Total number of delivery vehicles	**2 700**	**5 040**
Barges always running	CO_2 from delivery vehicles [Ton]	90.4	168.1
	CO_2 from barges [Ton]	7.9	14.2
	Total	98.3	182.2
Barges follows fixed schedule	CO_2 from delivery vehicles [Ton]	90.4	168.1
	CO_2 from barges [Ton]	7.9	Inconclusive
	Total	98.3	Inconclusive

As a result of the minimal difference in distance from the Southern entrance point to the construction site versus. the consolidation center, the CO_2 footprint for the feasible solutions displayed in Table 4.6 shows a slight decrease from that of scenario

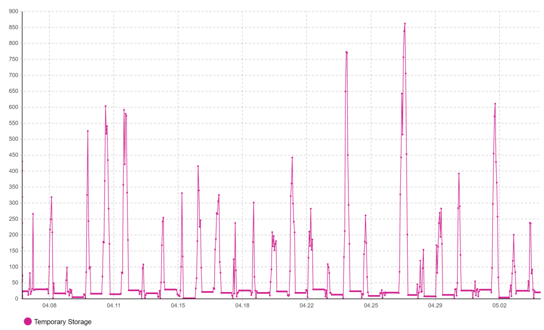
2. The reduce in barge trips weighs higher than the increased distance traveled for the road vehicles when only considering CO_2 emissions.

4.3.4 Scenario 4: All semitrucks- and all delivery vehicles from the south- and southeast go straight to the construction site

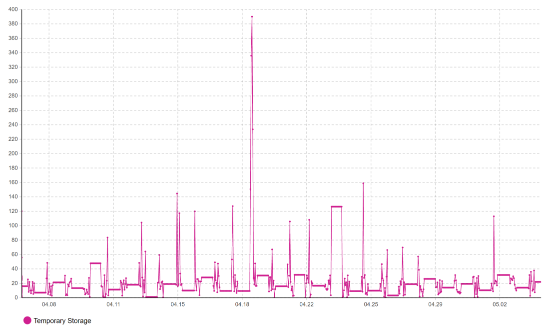
In scenario 4, all road vehicles that arrive from the southeast entrance point now go straight to the consolidation center, in addition to semitrucks as well as all road vehicles from the South. This scenario is meant to test feasibility for a scheduled barge system during the period with maximum delivery intensity.



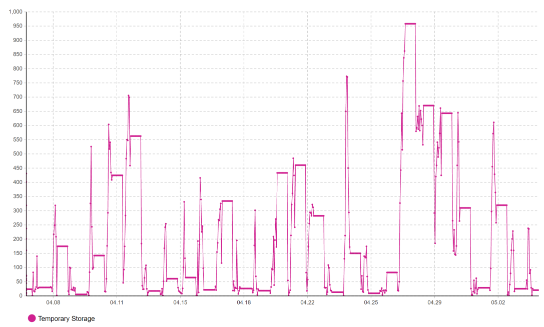
(a) Average delivery intensity, barges running 00-24



(b) Max delivery intensity, barges running 00-24



(c) Average delivery intensity, barges running 06-16



(d) Max delivery intensity, barges running 06-16

Figure 4.6: Temporary storage volume $[m^3]$ (y-axis) at consolidation center over time (x-axis) for scenario 4

The temporary storage at the consolidation center no longer increases over time, as shown in Figure 4.6d. With the additional relieved pressure from the southeastern entrance point, a scheduled barge system is now able to handle the periods of maximum delivery intensity, if barely. The resting periods between workdays does not always leave the consolidation center empty but the remaining material is most often successfully taken care of the following day.

Table 4.7: Trips to Masthuggskajen and distances traveled in scenario 4.

			Average delivery intensity	Max delivery intensity
	Total number of delivery vehicles		**2 700**	**5 040**
Barges always running	**Arrivals at Masthuggskajen**			
	Truck combo		65	129
	Truck		645	1 284
	Semitruck		316	544
	Van (delivery vehicles)		460	837
	Barge		337	620
	Distance traveled (inside the city) [km]			
	Truck combo	Loaded	2 133.4	3 918
		Empty	2 133.4	3 918
	Truck	Loaded	18 233.7	34 995.6
		Empty	18 233.7	34 995.6
	Semitruck	Loaded	5 972.6	10 245.7
		Empty	5 972.6	10 245.7
	Van	Loaded	12 935.1	23 677
		Empty	12 935.1	23 677
	Barge	Loaded	2 292.3	4 217.2
		Empty	2 292.3	4 217.2
Barges follows fixed schedule	**Arrivals at Masthuggskajen**			
	Truck combo		65	129
	Truck		645	1 284
	Semitruck		316	544
	Van (delivery vehicles)		460	837
	Barge		337	620
	Distance traveled (inside the city) [km]			
	Truck combo	Loaded	2 133.4	3 918
		Empty	2 133.4	3 918
	Truck	Loaded	18 233.7	34 995.6
		Empty	18 233.7	34 995.6
	Semitruck	Loaded	5 972.6	10 245.7
		Empty	5 972.6	10 245.7
	Van	Loaded	12 935.1	23 677
		Empty	12 935.1	23 677
	Barge	Loaded	2 292.3	4 217.2
		Empty	2 292.3	4 217.2

A total of 620 barge trips over a month is now true during the period of maximum delivery intensity with both a scheduled- and an always running barge system, as can be seen in Table 4.7. This means that the scheduled barges now successfully manages to handle all the incoming material during a workday. A total of 2794 delivery vehicles now travel to the construction site, which is more than half of the total 5040.

Table 4.8: CO_2 footprint for scenario 4.

		Average delivery intensity	Max delivery intensity
	Total number of delivery vehicles	**2 700**	**5 040**
Barges always running	CO_2 from delivery vehicles [Ton]	90.2	167.7
	CO_2 from barges [Ton]	5.3	9.8
	Total	95.5	177.5
Barges follows fixed schedule	CO_2 from delivery vehicles [Ton]	90.2	167.7
	CO_2 from barges [Ton]	5.3	9.8
	Total	95.5	177.5

Looking at the CO_2 footprints presented in Table 4.8, there is further reduction in emissions compared to Scenario 3. The South-East entrance point is close enough to the construction site that shipping material from this entrance point to the consolidation center, combined with the additional barge trips, does increase the amount of CO_2 emissions slightly.

4.3.5 Scenario 5: Exclusively using road transport

Scenario 5 is meant to resemble the existing transportation solution for Masthuggskajen, where all vehicles go straight to and from the construction site by road. Scenario 5 also includes waste trucks, although the same number of waste trucks are used for both the average- and the maximum delivery intensity periods in the simulations. The reason for not increasing the amount of waste in the maximum intensity period is that the waste calculations are highly speculative and most likely an overestimation in the first place, as is explained in section 3.4.

Table 4.9: Trips to Masthuggskajen and distances traveled in scenario 5.

		Average delivery intensity	Max delivery intensity
Total number of delivery vehicles		**2 700**	**5 040**
Arrivals at Masthuggskajen			
Truck combo		161	264
Truck		1 315	2 529
Semitruck		279	574
Van (delivery vehicles)		945	1 673
Waste truck		150	150
Distance traveled (inside the city) [km]			
Truck combo	Loaded	2 987.1	4 910.8
	Empty	2 987.1	4 910.8
Truck	Loaded	24 446.1	47 229
	Empty	24 446.1	47 229
Semitruck	Loaded	5 235.4	10 743.7
	Empty	5 235.4	10 743.7
Van	Loaded	17 605.6	31 414.5
	Empty	17 605.6	31 414.5
Waste truck	Loaded	1 035	1 035
	Empty	1 035	1 035

Naturally, Table 4.9 show an increase in both *Arrivals at Masthuggskajen*-, but also in *Distance traveled* for all road vehicles compared to previous scenarios.

Table 4.10: CO_2 footprint for scenario 5.

	Average delivery intensity	Max delivery intensity
Total number of delivery vehicles	**2 700**	**5 040**
CO_2 from delivery vehicles + waste trucks [Ton]	112.1	214.2

The CO_2 footprint when all material is delivered to the construction site via road vehicles and waste is handled by trucks, is shown in Table 4.10. The total emissions produced is now higher than when the water-based transportation system was in place. The reason being that the entrance to the East, and especially the entrance to the North, are closer to the consolidation center than they are to the construction site.

5
Discussion

This chapter discusses the results in more detail as well as its limitations. It also covers possible improvements that can be made.

5.1 Simulations

All results that are compared in this section are from the conclusive simulations, some of which had the barges always running. If a solution is conclusive then there is no difference in travel distance and CO_2 emissions, but it is important to keep in mind when studying the tables.

5.1.1 Carbon emissions

This section discusses the differences in CO_2 emissions for Scenario 1-5.

Table 5.1: CO_2 footprint for scenario 1-5.

		Average delivery intensity	Max delivery intensity
	Total number of delivery vehicles	**2 700**	**5 040**
Scenario 1	CO_2 from delivery vehicles [Ton]	82.7	155.9
	CO_2 from barges [Ton]	13.2	24.5
	Total	**95.8**	**180.4**
Scenario 2	CO_2 from delivery vehicles [Ton]	88.5	164.1
	CO_2 from barges [Ton]	10.3	18.9
	Total	**98.8**	**183.1**
Scenario 3	CO_2 from delivery vehicles [Ton]	90.4	168.1
	CO_2 from barges [Ton]	7.9	14.2
	Total	**98.3**	**182.2**
Scenario 4	CO_2 from delivery vehicles [Ton]	90.2	167.7
	CO_2 from barges [Ton]	5.3	9.8
	Total	**95.5**	**177.5**
Scenario 5	CO_2 from delivery vehicles + waste trucks [Ton]	112.1	214.2
	Total	**112.1**	**214.2**

When looking at the comparison between CO_2 footprints in Table 5.1, one might think that less transportation via barge equals less emissions. It is important to remember that it is only the two entrance points that are the furthest away from the consolidation center that is redirected to the construction site in Scenario 3 and 4. When comparing scenario 2- where only one type of vehicle is redirected to the construction site, to Scenario 1- where everything is using the water-based transportation system, the emissions actually increase. It is the other way around for Scenario 5- where all delivery vehicles travels straight to the construction site, the CO_2 footprint goes way up. Scenario 4 is able to reduce CO_2 emissions by as much as 16%, compared to Scenario 5.

If one is only consider the carbon footprint as a means to evaluate the system, it is clearly preferable to use the water-based transportation system for deliveries that are closer to the consolidation center than the construction site. However, something that has not been considered is that the barges will only transport material downstream, while transporting mostly empty containers on the way back upstream. Since the weight has a significant impact on the amount of CO_2 that is produced and there is a constant accelerating force to help the barge while it is fully loaded, the CO_2 produced by barges might be even lower than shown in Table 5.1.

5.1.2 Travel distances

This section discusses the differences in travel distance for Scenario 1-5.

Table 5.2: Distances traveled for scenario 1-5

		Distances traveled [km]	
		Average delivery intensity	**Max delivery intensity**
Scenario 1	Road vehicles	74 531.6	138 195.6
	Barges	11 345.8	21 163.4
	Total	**85 877.4**	**159 359**
Scenario 2	Road vehicles	77 096.2	142 845.2
	Barges	8 897.2	16 334
	Total	**85 993.4**	**159 179.2**
Scenario 3	Road vehicles	77 876.6	145 554.4
	Barges	6 815.6	12 216.4
	Total	**84 692.2**	**157 770.8**
Scenario 4	Road vehicles	78 549.6	145 672.6
	Barges	4 584.6	8 434.4
	Total	**83 134.2**	**154 107**
Scenario 5	Road vehicles (material)	100 548.4	188 596
	Waste trucks	2 070	2 070
	Total	**102 618.4**	**190 666**

As shown in Table 5.2, there are relatively minor differences in the total distance traveled for scenario 1-4. In Scenario 5, however, with the absence of transportation by water all together, there is a spike in travel distance. The reason being that the northern and eastern entrance points are also redirected to the construction site directly, eventhough they are closer to the consolidation center than the construction site.

It is worth mentioning that the northern entrance point from E6 travels via Hisingsleden, a road that goes around the city, when traveling to the construction site directly. It does this partly to avoid the inner city, but also to arrive from the correct side when arriving at Masthuggskajen without having to turn around. This adds about 7 km to its travel distance in each direction. Keep in mind that transport vehicles are supposed to arrive from that direction when traveling to the construction site.

5.1.3 Consolidation center utilization

The total number of delivery vehicles that arrive at the construction site is displayed in Table 5.3 below.

Table 5.3: Arrivals at Masthuggskajen for scenario 1-5

		Arrivals at Masthuggskajen		%
		Average delivery intensity	**Max delivery intensity**	
	Total number of delivery vehicles	**2 700**	**5 040**	
Scenario 1	Road vehicles	0	0	0
	Barges	834	1 555	
Scenario 2	Road vehicles	297	572	11
	Barges	654	1 200	
Scenario 3	Road vehicles	905	1 714	34
	Barges	501	898	
Scenario 4	Road vehicles	1 486	2 794	55
	Barges	337	620	
Scenario 5	Road vehicles	2 700	5 040	100
	Waste trucks	150	150	

The scheduled barge system with average delivery intensity started showing manageable behaviour already in scenario 2, with only 11% of delivery vehicles being alleviated from the consolidation center. When 66 % of delivery vehicles used the consolidation center in scenario 3, the scheduled barge system was almost indistinguishable from the system that was always running. It would be reasonable to assume that the scheduled barge system would be fully capable to handle the incoming material during these circumstances. The scheduled barge system could be kept between 89% and 66% utilization, although it is capable of performing closer to 89%.

The scheduled barge system during the most intensive period however, did not show manageable characteristics before scenario 4. In this scenario, 55% of delivery vehicles traveled straight to the construction site, meaning that the most intensive periods of construction would require a much larger amount of road vehicles to be temporarily redirected to the construction site directly.

5.1.4 Feasibility

There are some edge scenarios in the simulations where it seems like the scheduled barge system is barely/almost able to handle the incoming material flows. Specifically scenario 2- and 4, with average- and maximum delivery intensity respectively. In the simulations there are no planning ahead and material arrives pretty much at random which leads to the flow being uneven. If you were to implement the system in reality, some logistical planning for the incoming material would help smooth out the peaks. Planning can also help predict when the system will not be able to handle the incoming material, and make adjustments accordingly.

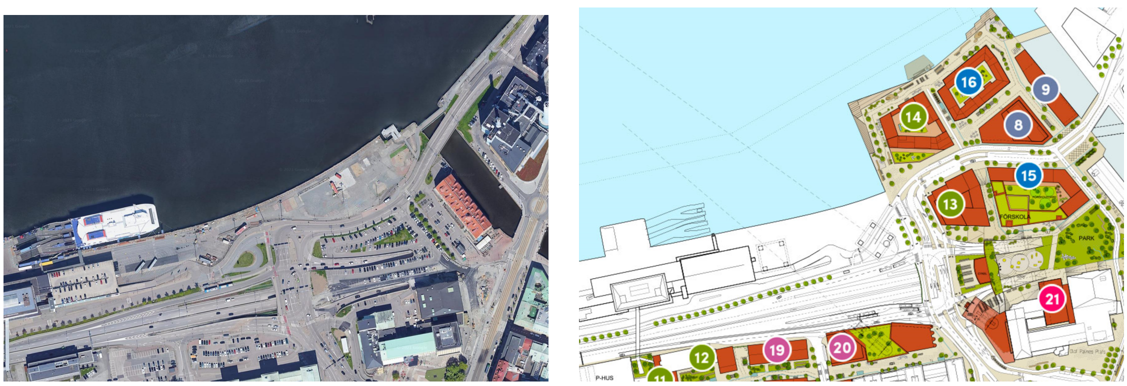
All scenarios are utilizing four shipping containers per barge for material and reserving the fifth space for a waste container, even though roughly every 5th or 6th trip actually transports waste. Using the 5th container space for material when available would further increase the throughput of the system.

Additional factors that contributes to uncertainty however, is that there are no disturbances in the model. At no point does a barge break down for example, though this could be counteracted by having an additional tugboat on standby, however cost effective that might be. Unloading and swapping out a container always takes 5 minutes, which could be both higher or lower depending on the method chosen to do so but also varying overall. The filling time of the containers could be neglected-, and the loading time for said containers could possibly be reduced if material was to be prepackaged in said containers already from the source. Prepackaging containers would also save on the logistical challenge overall at the consolidation center.

There is also a discussion to be had regarding the handling of container contents at the construction site. In this report it is assumed that the containers are continuously handled flawlessly, but in reality that might not be the case.

5.1.5 Scaling up

The model is currently limited to only one dock for each checkpoint. At the moment this is deemed to be the maximum number of docks at Masthuggskajen. Unloading at Masthuggskajen is the current bottleneck in the system due to the number of containers that has to be replaced there. If opportunity arises to give room for another dock at Masthuggskajen, this would effectively double the capabilities of the system as long as an equal addition is done on the other end. It might for example be possible to place another dock somewhere on the planned land extension down the line.



(a) Map of current layout of Masthuggskajen, *Google Maps*

(b) Map of planned layout of Masthuggskajen, *Projektöversikt: Masthuggskajen.se*

Figure 5.1: Layout before and after land extension at Masthuggskajen

It would however be difficult to find space for another dock at Masthuggskajen if the land extension can not be used, as can be seen in Figure 5.1.

The system could further be extended to work for multiple construction sites in the RiverCity project, these sites might not suffer from the problem of docking space along the river. Though if the barge system where to be utilized for multiple construction sites simultaneously, additional docks- or possibly even additional consolidation centers would be needed.

5.2 Limitations

Modelling and simulation is a technique to replicate physical entities or process in real world to better understand the root problems and finding solutions by running simulations and testing if solution is feasible. However, in order for the model to get as close to the reality, rich data is paramount. Beside delimitation that has been set in the beginning, some limitations regarding model building in this project can be found as follows.

5.2.1 Data

The accuracy- and availability of data was the biggest obstacle throughout this project. The available data is almost exclusively provided by the Masthuggskajen construction pre-study and the waterway utilization pre-study for River City as a whole. Specifics regarding types of material and its sources is not available, the same goes for schedules for the specific construction sites. Scarcity of such important data have a negative impact on the overall accuracy of the model, and consequently the results.

5.2.2 Entrance points

The basis for the simulations is that there is an equal chance for deliveries to arrive from each of the four entrance points. In reality, it is not stated where the deliveries originate. It is possible that one or more entrance points is eliminated completely by merging paths outside of Gothenburg. It is also possible that a large part of deliveries originate from the same place, or even from inside Gothenburg itself. Where the deliveries originate from does not change the in-city travel distance- and emission factors in regards to their entrance points however.

There is also a possibility that deliveries arrive from the west via the sea, or that this would be implemented once a construction site dock is established. Such deliveries could in that case skip land vehicle transportation all together, and arrive at the construction site directly or after reloading the contents on to barges somewhere along the river.

5.2.3 Only one waste disposal company

The waste consolidation that was chosen for this model is run by a single waste company, where in reality there are multiple different waste companies involved in the constructions at Masthuggskajen. In order for the waste to be handled by the same transportation system as the material, construction companies would either have to switch to the same waste company or the waste companies would have to agree on sharing the dock as the sole point of waste consolidation. Though picking up waste containers and transporting them with truck to a waste center located somewhere else would somewhat counteract the purpose of the system in the first place.

5.3 Future work

The model can be improved in some ways. The current data is very speculative at the moment, precise scheduling and information regarding origins of material and their destinated construction site would greatly improve the accuracy of the model. Just like simulation studies in general, with better availability of data, less assumptions has to be made, and consequently, a more accurate model can be achieved. Furthermore, this kind of data would make it possible to model material containers with a specific destination other than just Masthuggskajen. A quantitative study would enable for a much more accurate model that could include specifics regarding last mile delivery in the construction area. Information regarding specific vehicles whose contents should be transported together would provide insight into the logistical problem at the consolidation center as well.

The model could be extended to include multiple- or all construction sites related to Älvstaden. Additional docks- or entire consolidation centers could be added along the river to evaluate the performance of the system when it is scaled up, though this would also greatly benefit from a more thorough quantitative study in preparation.

Additionally, with availability of traffic data one could draw accurate conclusions regarding the systems impact on congestion levels in the city. However, obtaining such traffic data would take time, and would also probably require cooperation with Trafikverket or some GPS provider.

6 Conclusion

The purpose of this thesis was to evaluate the possibilities and limitations of a water-based intermodal transportation system for construction logistics at Masthuggskajen. Based on current information and data, a water based transportation system would not be able to completely substitute the current transportation solution. The system is able to handle upwards of 89% of the incoming material transports on average, but would have to be temporarily decreased to around 45% of deliveries during the most intensive periods. With more data and planning however, these numbers might differ. Deliveries that arrive from the northern parts of the city benefit more from the system than those that arrive from the southern parts, in regards to travel distance and CO_2 emissions. Depending on the vehicle routes, delivery vehicles that enter from the southern-most parts of the city might not benefit at all in these regards. The system would be able to reduce CO_2 emission inside the city by up to 16%, though this reduction only utilizes the barge-system for material transports from the northern parts of the city, with 45% of material transports utilizing the barge-system in total. An intermodal transportation system would poses a logistical challenge that needs to be solved jointly by all stakeholders involved in the construction in order to make it work.

This report is meant to be a guidance, used together with other logistical analysis, and for future research in related subjects. This report should not become the basis for decision-making unless complemented with more research or data.

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A

Appendix 1: Plots

A.1 Scenario 1

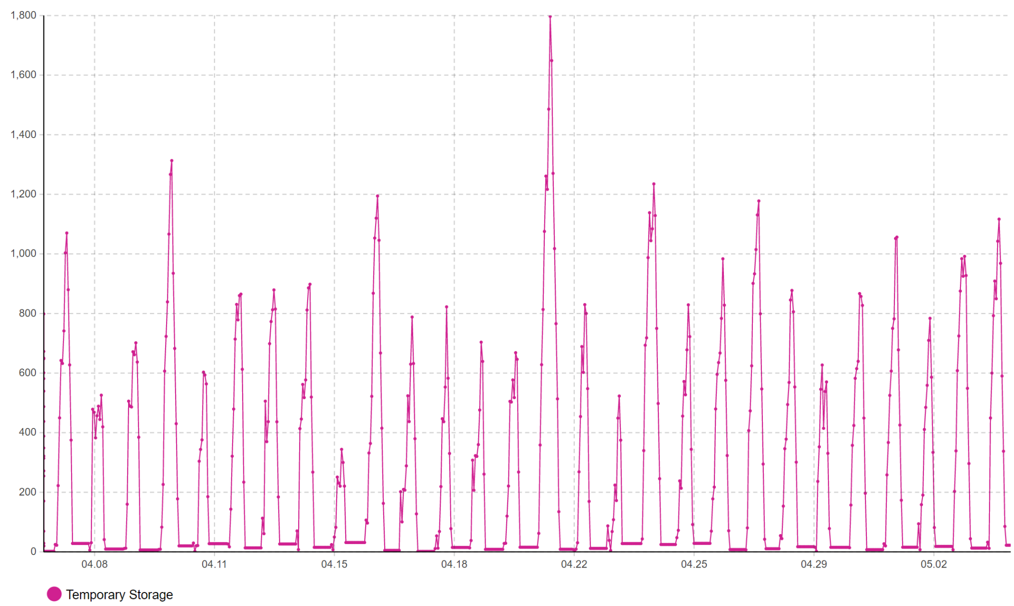

Figure A.1: Average delivery intensity, barges running 00-24

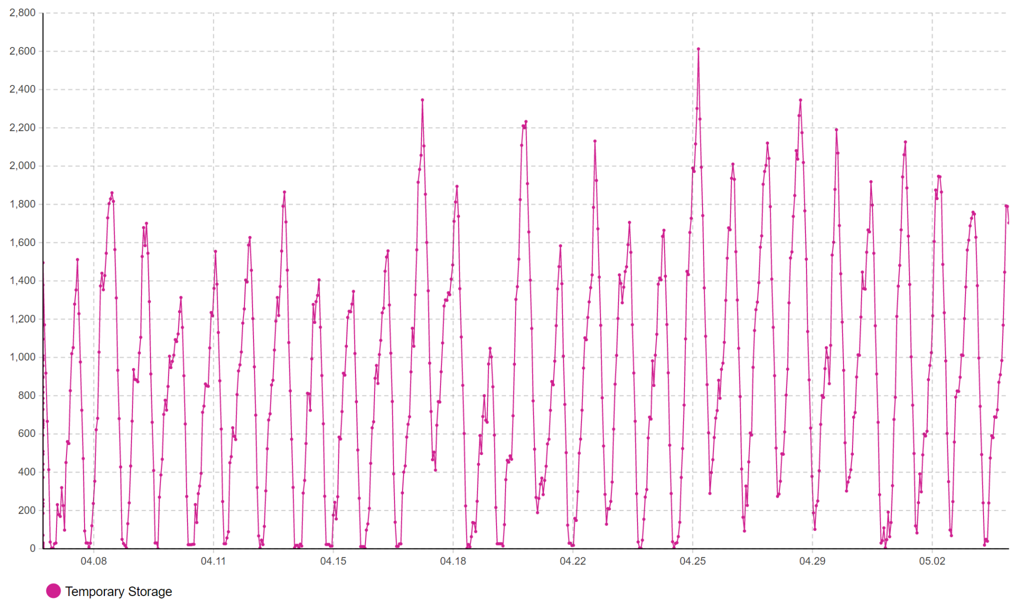

Figure A.2: Max delivery intensity, barges running 00-24

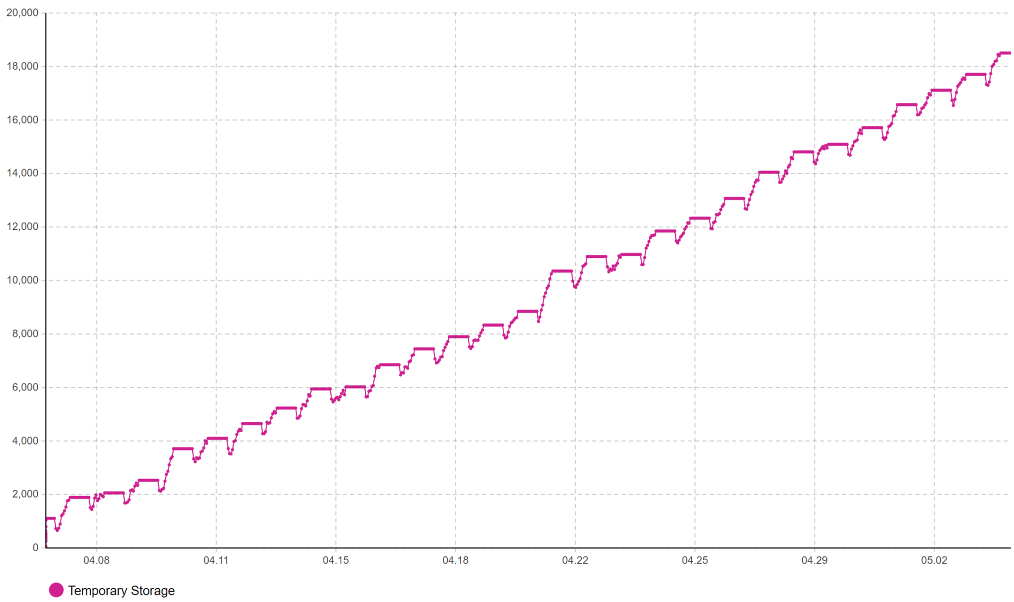

Figure A.3: Average delivery intensity, barges running 06-16

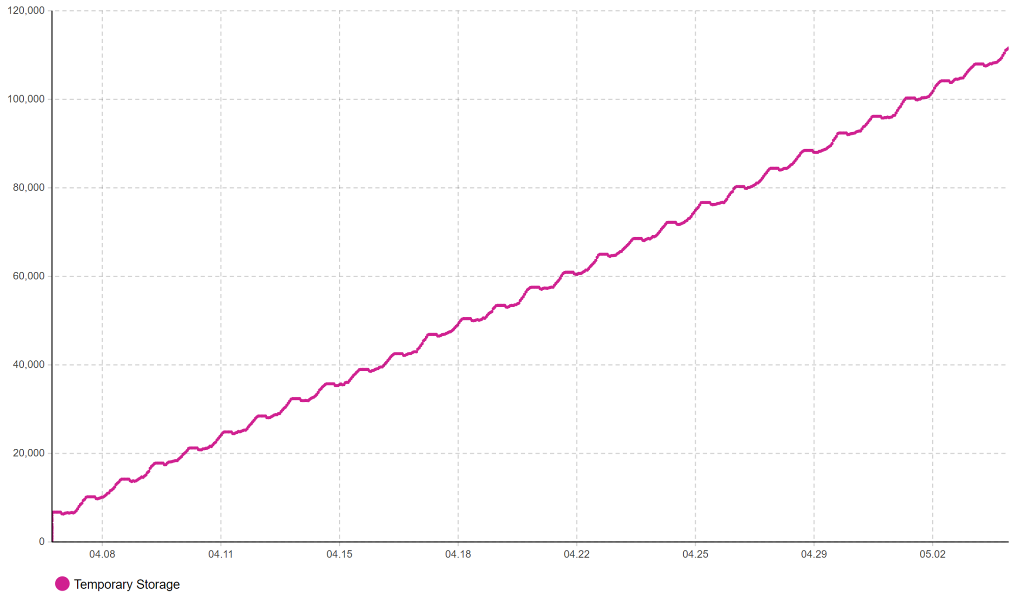

Figure A.4: Max delivery intensity, barges running 06-16

A.2 Scenario 2

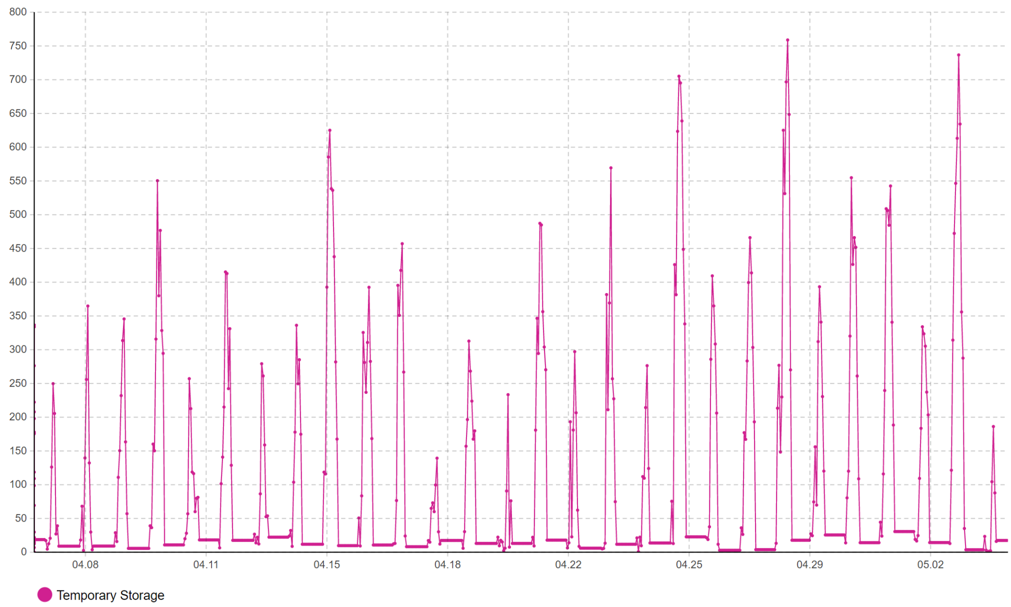

Figure A.5: Average delivery intensity, barges running 00-24

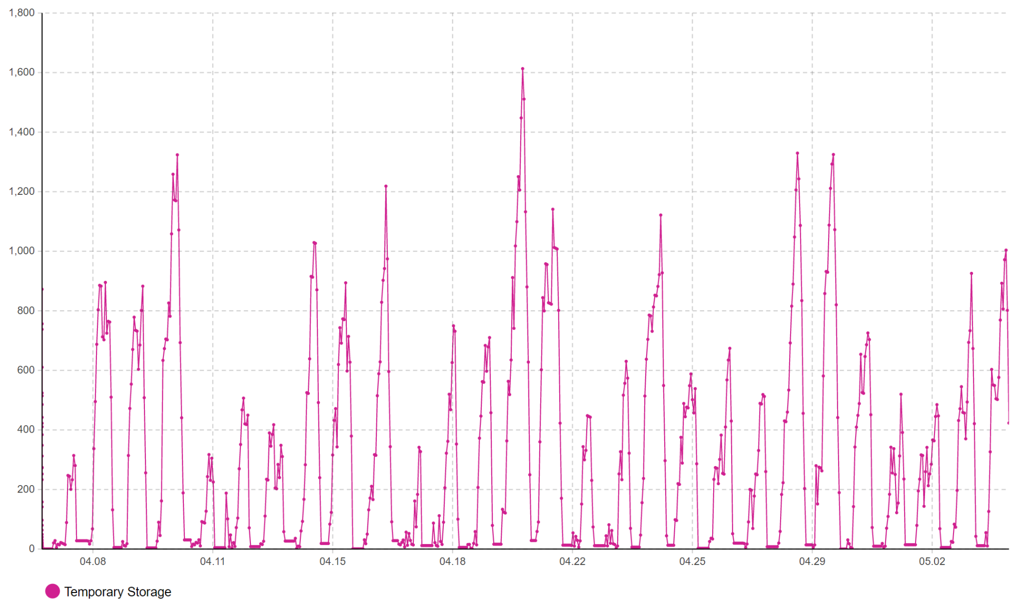

Figure A.6: Max delivery intensity, barges running 00-24

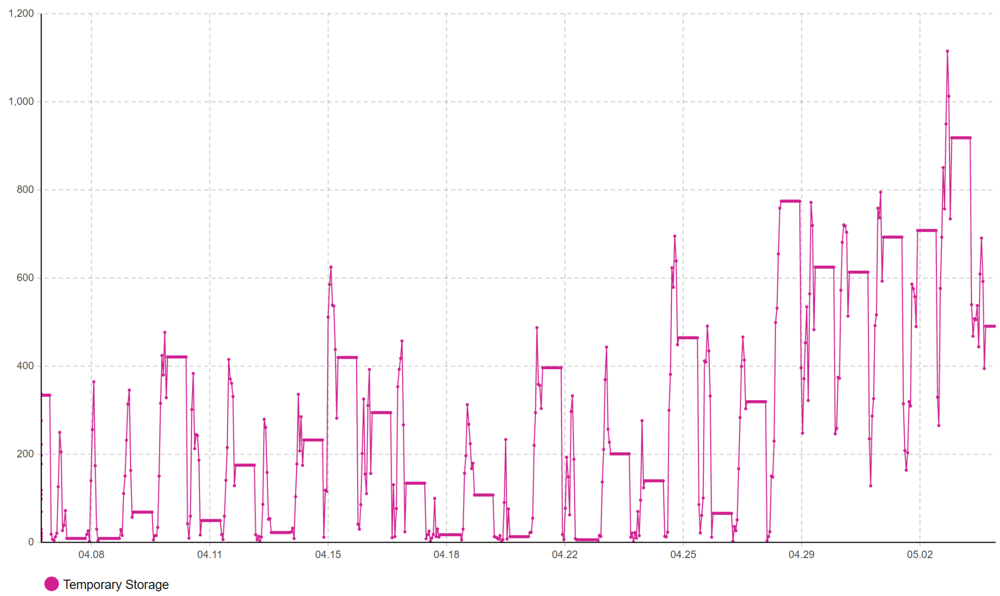

Figure A.7: Average delivery intensity, barges running 06-16

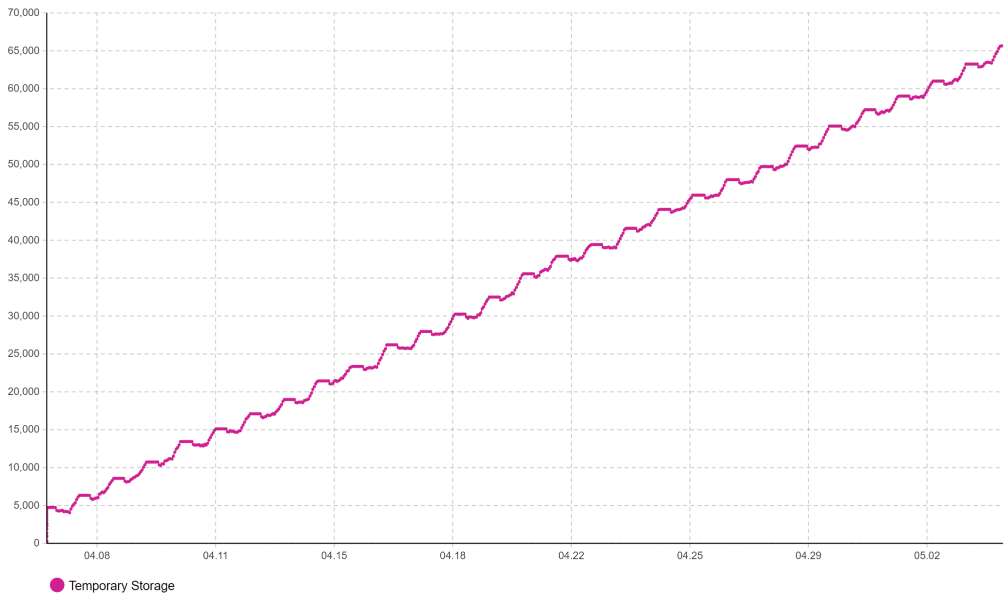

Figure A.8: Max delivery intensity, barges running 06-16

A.3 Scenario 3

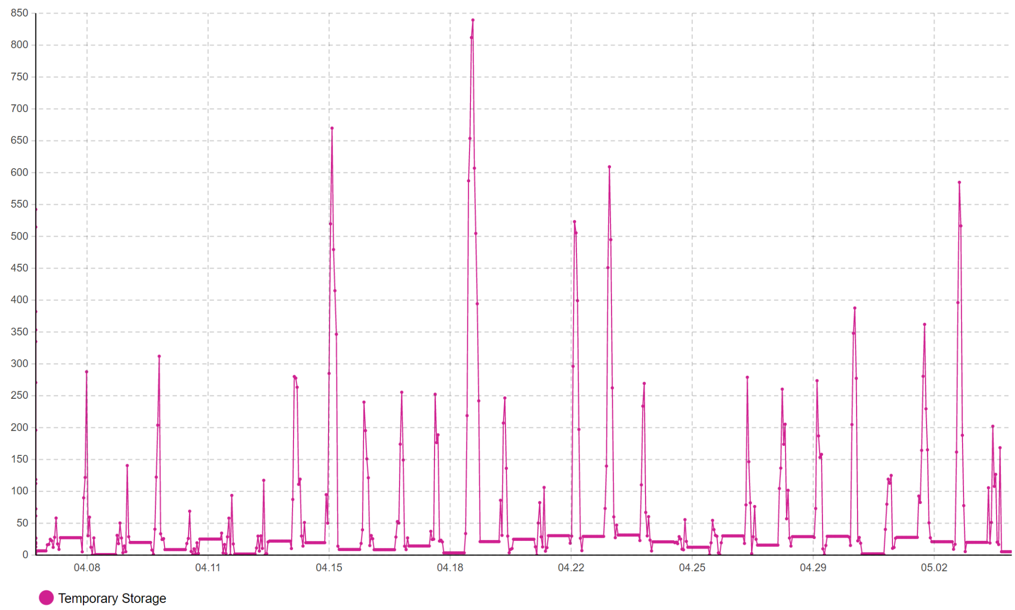

Figure A.9: Average delivery intensity, barges running 00-24

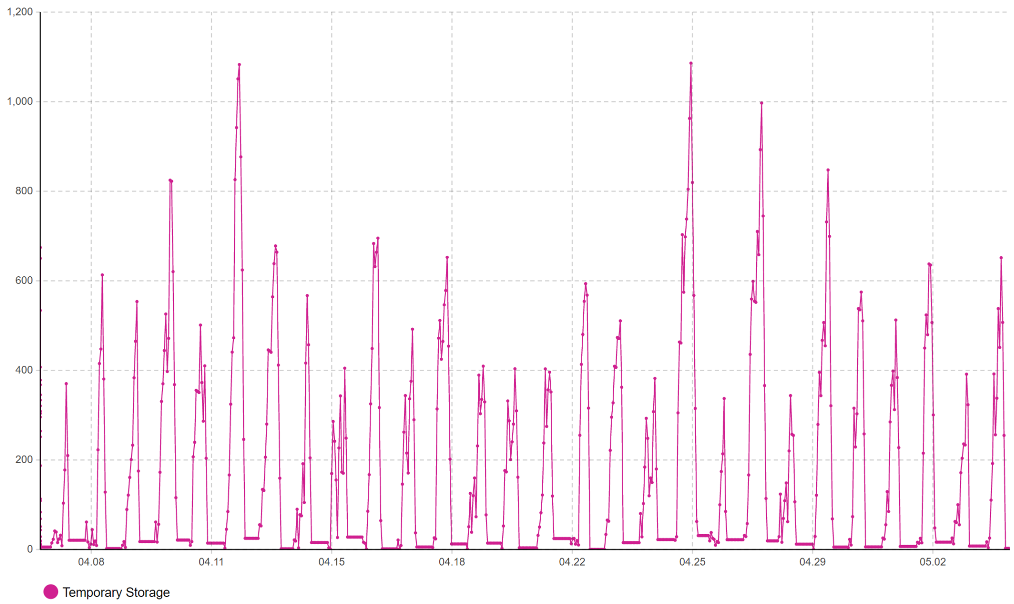

Figure A.10: Max delivery intensity, barges running 00-24

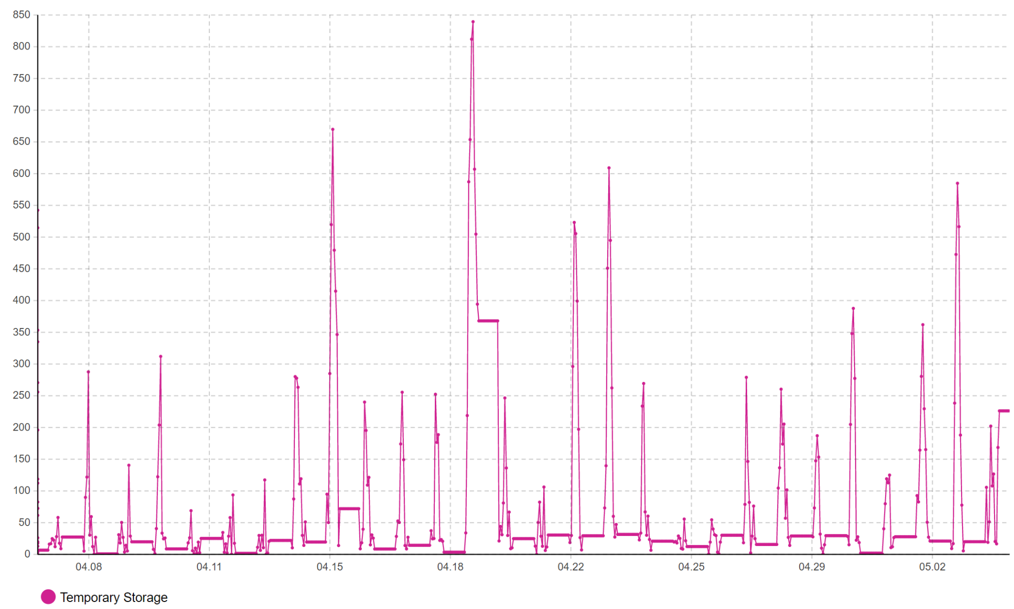

Figure A.11: Average delivery intensity, barges running 06-16

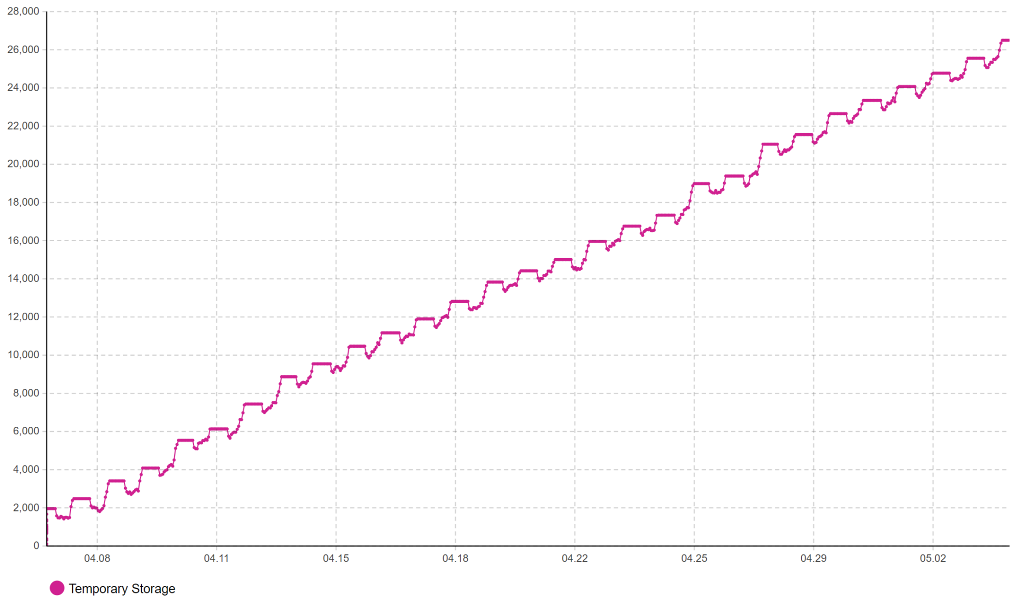

Figure A.12: Max delivery intensity, barges running 06-16

A.4 Scenario 4

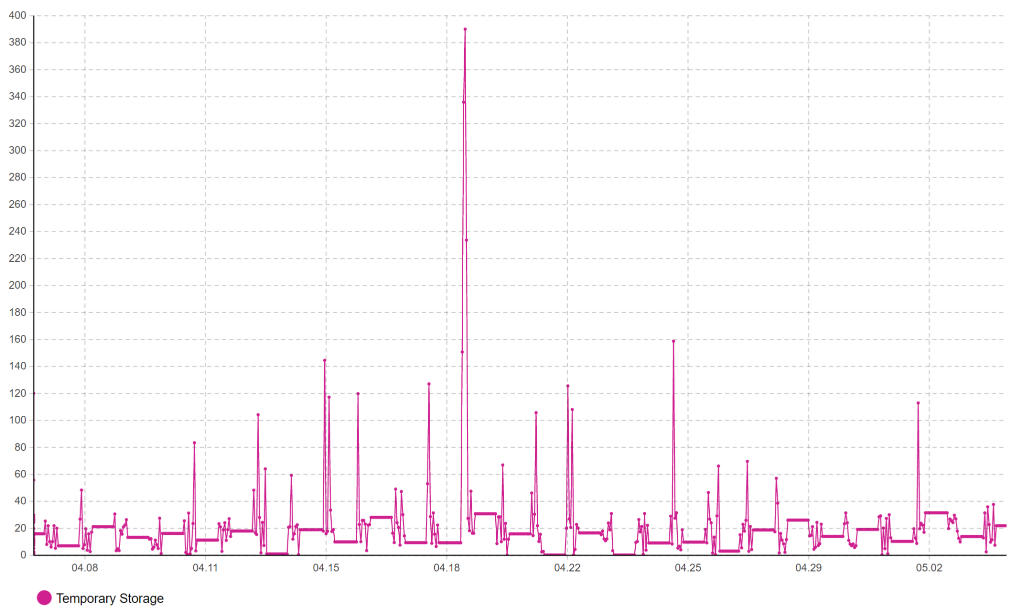

Figure A.13: Average delivery intensity, barges running 00-24

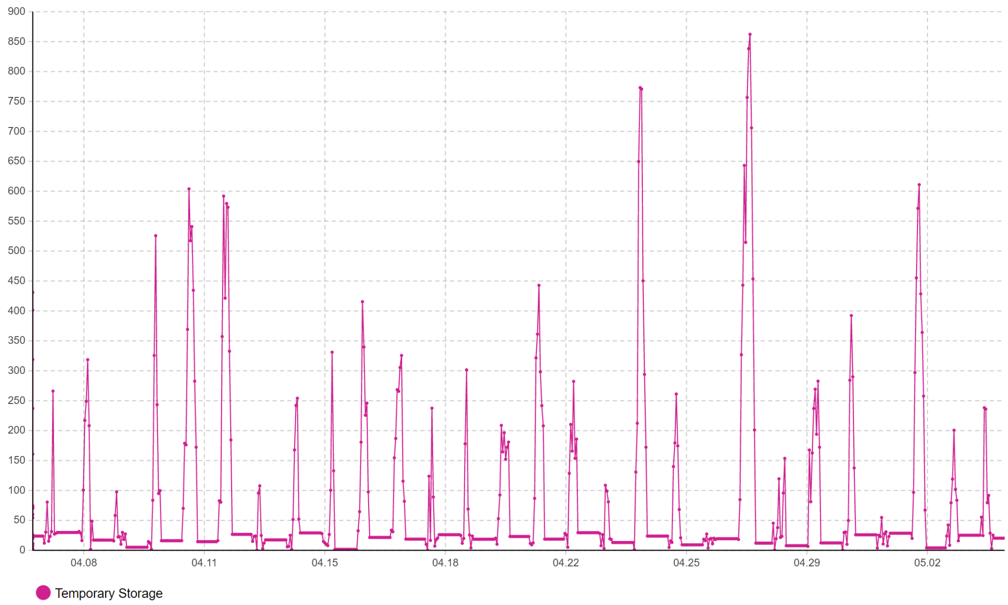

Figure A.14: Max delivery intensity, barges running 00-24

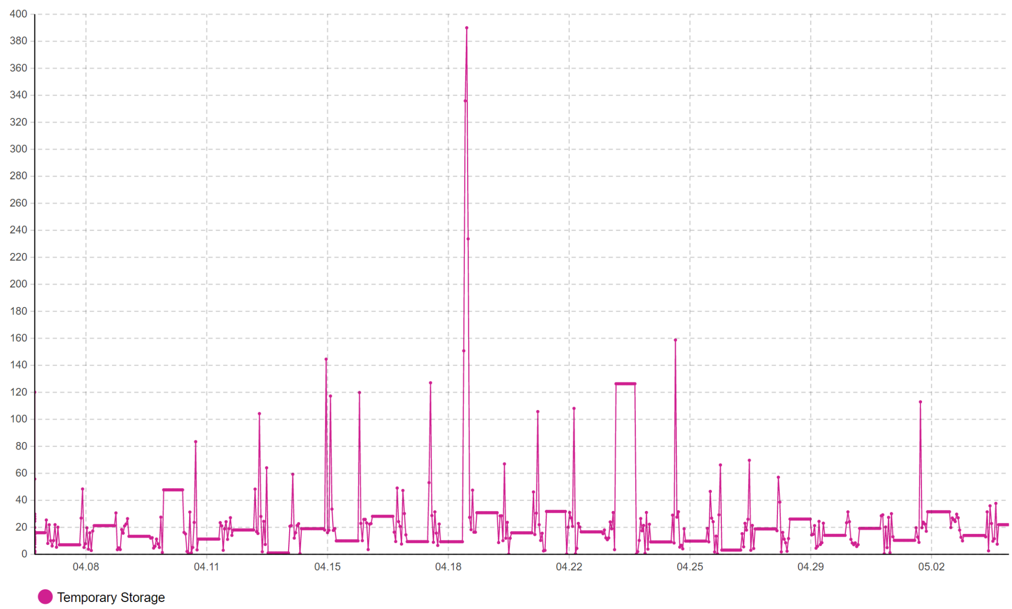

Figure A.15: Average delivery intensity, barges running 06-16

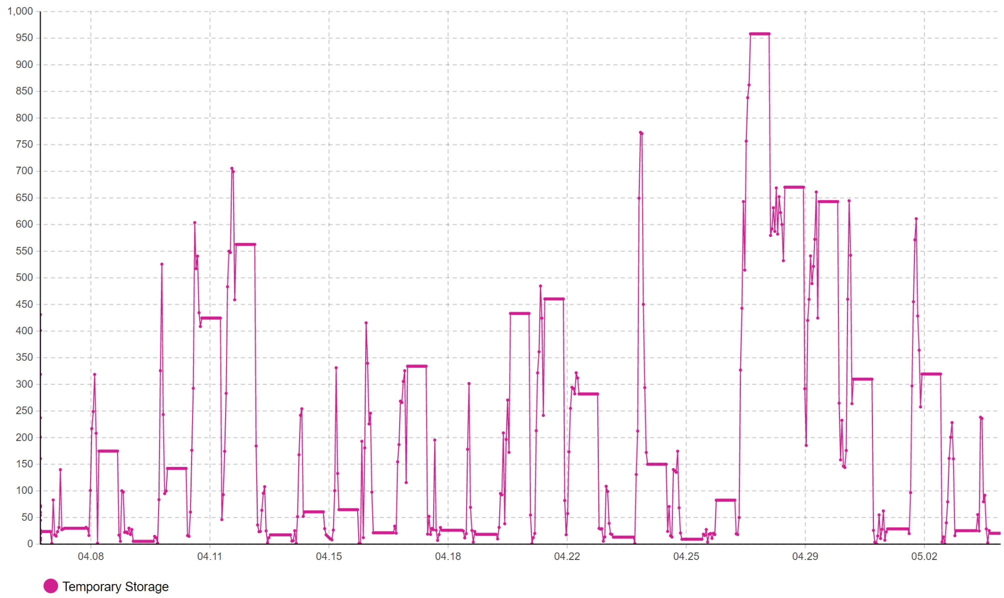

Figure A.16: Max delivery intensity, barges running 06-16

B

Appendix 2: Unedited model

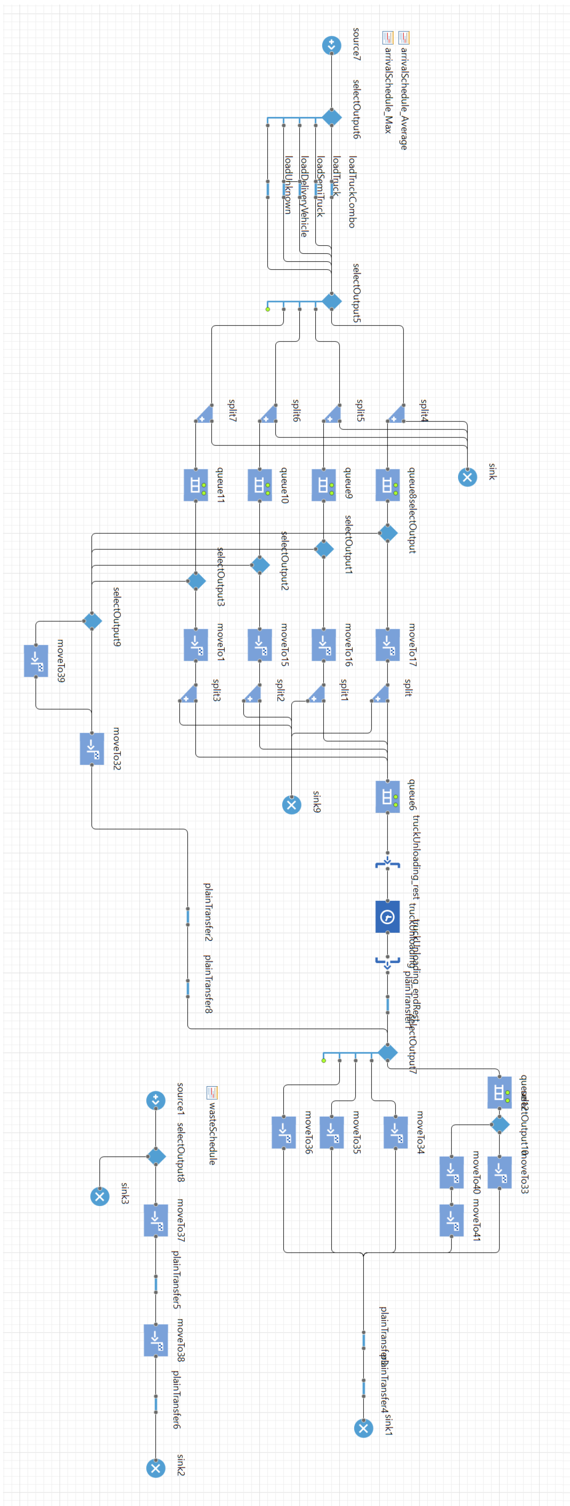

Figure B.1: Delivery vehicle and waste trucks

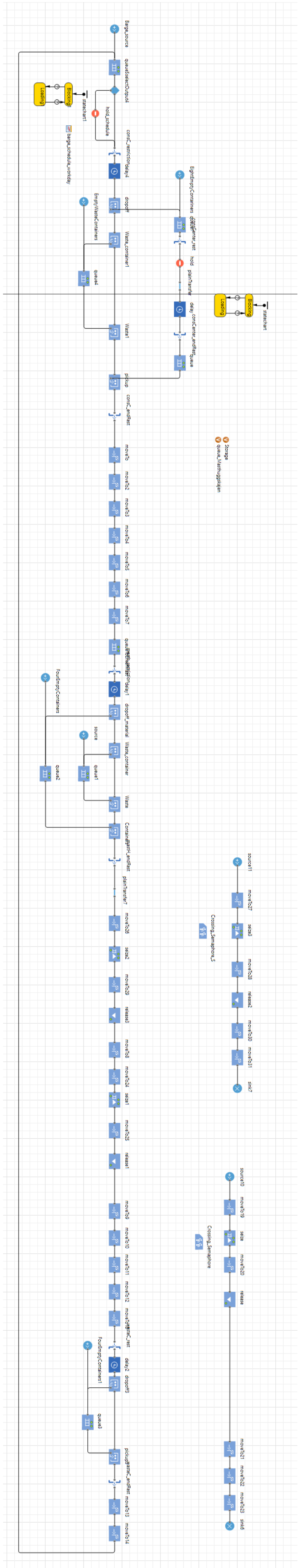

Figure B.2: Barge-loop

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