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# Design of prognosis model for transportation volumes related to construction methods

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# Design of prognosis model for transportation volumes related to construction methods

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by

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Have a pleasant reading!

*Panagiota (Penny) Charisi*
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# Summary


## Introduction

The current research stems from the motivation of controlling the phenomenon of traffic congestion in urban areas that can be deteriorated due to the implementation of a construction project. Nowadays, it is frequently observed that construction activities in complex urban environments appear undesirable effects on the communities surrounding the location of the construction project having as a focal point the “construction traffic”. However, existing literature indicates traffic congestion as a significant contributor to inefficient management of construction logistics. Unsuccessfully managing a project’s construction logistics is strongly correlated with unsatisfactory performance of construction process mostly due to the occurrence of delays in the implementation of the construction activities related to incorrect delivery of building materials and construction equipment. Since the multi-faced issue of traffic congestion can cause both a negative “domino effect” on the construction activities towards the realization of a construction project as well as unfavorable effects on urban city’s living conditions, positively impactful ways ought to be researched for reducing the adverse consequences of uncontrollable traffic. Consequently, practical solutions has to be disclosed, such as useful tools for achieving the aforementioned aim.

The objective of this thesis is to design a transportation prognosis model that will predict the extra transportation volumes on the given roads (the location of the construction project) due to the transportation activity of the needed vehicles along the construction process, offering an insight into traffic conditions of the examined relevant road. In this way, the designed prognosis model can be used as a proactive tool since it indicates if and when a potential uncontrollable traffic level can occur. The designed prognosis model is focused on three different scenarios with regard to the used construction method for the realization of a building project; conventional (also named as traditional) construction method, prefabrication, and “mixed” construction method. In a “mixed” construction a part of the project is constructed with prefabricated elements and another part using traditional construction methods. To accomplish the aforesaid objective, the following research question is formulated:

**“ How much impact does the construction process of a building, considering the type of the construction method, have on the transportation movements of the urban area of the project? ”**

## Research Design

Firstly, a literature review on the causes and the consequences of traffic congestion and construction logistics was conducted. On this ground, the complexity of a construction project from stakeholders management point of view was studied. Furthermore, one of the vital steps of this study was the comprehension and analysis of transportation modeling and its types in order to come to a proper decision with regard to the type of the designed prognosis model. Next, based on the aforesaid literature study in combination with exploratory interviews with experts of Logistics and Transportation Department of Gemeente Amsterdam, the requirements of the model and the appropriate software for the prognosis model’s development were selected. To

satisfy the decided requirements of the model, the input variables, the mathematical formula and the output of the model was chosen precisely. Last but not least, the designed model was validated (but not implemented in practice in many road networks for examining the contribution of construction processes in traffic conditions) via ex-ante evaluation with a single case study (Eleven Square project). This case study is in favor of the interest of Gemeente Amsterdam. For comprehending the interconnections between the input variables and the output of the prognosis model, a short sensitivity analysis was caried out.

## Findings and conclusions

The main finding of this research from the relevant literature review, the semi-structured interviews and the validation of the designed prognosis model via a selected construction project, is that the prefabrication derives substantially less traffic flows. For the less impactful usage of prefabrication on the traffic condition of a road network due to the implementation of construction process the main causes are mostly the less need for laborers communing on the location of the construction project as well as the shorter needed duration for the completion of construction activities and the project's realization.

The main expectation from the interviewees are a design of a prognosis model that can potentially assist the traffic management on the road that leads to the main construction site of the project. The proper time slots for the delivery of materials and the required construction equipment can be indicated through this model as well as the transportation flows that can possibly cause stalled traffic can be addressed. In this way, the need to take effective precautionary measures can be disclosed and thus the prognosis model can be a tool that facilitates efficient traffic management.

However, a significant difference was observed in the approaches of the stakeholders. Indisputably, the construction companies have an interest mostly in the implementation of project's construction activities and thus, their concern is focused on a proper management of construction logistics. On the other hand, the municipality is totally concerned for the traffic conditions related to construction activities since it is the responsible party for the preserving adverse living conditions. From the validation process it was revealed that the lack of interest of the construction companies (that is expressed from the involved contractors), for the potential traffic issues in the project's area lead to lack of relevant transportation data's availability which makes the use of the prognosis model difficult in practice. As a result, an efficient and informative communication between municipality and contractors regarding the need of effective construction logistics management and its impact on transportation movements is considered appropriate.

## Recommendations

It would be interesting and also useful to extent the designed prognosis model for a more reliable final output. Some potential suggestion is to extent the already designed prognosis model by adding extra routes which offers the opportunity to explore construction projects that have additional routes and more construction sites. Additionally, a useful extension of the designed prognosis model could be to explore and accurately quantify the influential parameters of weather conditions and population's growth on the road networks in urban area. The identification of these parameters was out of this thesis scope but the designed model introduces them as input variables so as to offer the room for the above explained model's extension. Also, since the Netherlands aims for a fully sustainable and resilient county by 2050 and vehicles are a great contribution to environmental pollution, an extension of this model by associating the traffic flows with the $CO_2$ emissions could be proven valuable.

In the context of improved communication between the involved interested parties with high power on the complex construction project, an extension of the model with regard to cost-transport relationship would seem appealing. Concerning the lack of interest from the construction companies about the impact of the construction activities on road conditions, introducing the cost in the model as another objective, it can be a behavior changer. Finally, a protocol which reassures that involved contractors provide to the responsible municipalities a detailed planning in terms of construction logistics, is crucial since from the simultaneously conducted interviews the lack of this type of data was a common issue.

**Limitations**

Firstly, it is worth mentioning that generalizing the results should be done with restraint, because of the prognosis model's validation with a single case and the specific sample of the interviewees. Also, from the sensitivity analysis it was confirmed (since it is apparent from the linear mathematical formula of the designed prognosis model) the importance of road's capacity value in the final output of the model. Due to the fact that it is difficult to accurately define the capacity of a road because its value depends on many parameters, introducing this variable bears uncertainty. Moreover, due to the design process of this model, the chosen variables as well as its linear formula, it is acknowledged that the model's validity strongly depends on the reliability of the input data. Considering the low availability level of this type of data, the reliability of input data cannot be reassured. Lastly, the prognosis model has not been implemented in practice in other case studies referred to densely populated urban areas, which implies that the implementation of this study's prognosis model in more cases might lead to different findings than the ex-ante evaluation.

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# Chapter 1

# Introduction

*This chapter is an introduction to the report. First of all, Section 1.1 mentions the research background of the current MSc thesis. Section 1.2 refers to the context of the current study and elaborates on the problem statement, while Section 1.3 defines the objective of the thesis. Lastly, Sections 1.4, 1.5, 1.6, and 1.7 encompass the research question, the research relevance, the practical relevance, and the deliverables of the research respectively.*

## 1.1 Research Background

Major construction projects considerably impact the economic growth of urban areas. Nonetheless, such projects can have a negative influence on the functionality of the area and its surroundings, especially on traffic congestion (Hyari et. al, 2015).

More precisely, it is frequently observed that construction activities in complex urban environments appear undesirable effects on the communities surrounding the location of the construction project, safety hazards, traffic congestion in the road network, and economic difficulties (Fuertes et al., 2013; Gangolells et al., 2011; Ahn et al., 2010; Gilchrist & Allouche, 2005; Chen, Li & Hong, 2004; Shen & Tam, 2002).

The main problems of the aforementioned adverse impacts can be divided into the following categories (Hyari et. al, 2015):

1) traffic congestion produced by the added traffic volume of the construction process,

2) lack of parking space,

3) problematic accessibility at the construction site and egress gates due to additional traffic loads on the road network, and

4) safety hazards associated with pulling heavy loads and large equipment.

In particular, due to traffic congestion, the traffic delays that take place are correlated with many negative consequences such as the perspective of social cost. Since traffic delays are one of the major and most immediate items of concern when it comes to social cost (Lee, 2009), traffic congestion is crucial for the economic efficiency of an urban city and has social value.

Additionally, building materials, construction components, construction equipment, and human force (laborers) are the first and foremost significant requirements for construction. Especially for the construction materials' usage, the transportation of construction materials on site is linked with construction logistics that provide customer service by guaranteeing materials are proper and available for operational activities (Wegelius-Lehtonen et. al, 1998). Therefore, the safe transportation of materials on site, their delivery on time, and their quality level play a major role in the realization of a time-driven and quality-driven construction project. Likewise, for the implementation of a high-quality construction project on time, the delivery of the needed construction equipment has to be made efficiently; without damages and on time.

Considering that materials' contribution to the total cost of a building project is between 30 and over 50 percent (Fellows et. al, 2009), transportation costs account for almost 39-58 percent of total logistics costs (Ying et. al, 2014). Consequently, the transportation of materials influences the cost profile of a construction project and thus, is of great interest to construction companies.

Furthermore, these days, sustainable construction practices are of paramount importance so as to achieve a reduction of sources exploitation and follow an environmentally friendly way of living. Abey et.al (2019) indicate that some of the construction activities that turn out to be energy-intensive involve those related to transportation. In order to select the type of construction building, one of the factors that should be considered is the transportation constraint in terms of the movement of vehicles (Pasquirel et.al, 2005). Different construction types (prefabricated and conventional building construction) vary in energy consumption in many phases throughout the construction process (Abey et.al, 2019). As a result, the transportation of materials has also ecological value and is linked with the decision-making process of the structure's typology. Moreover, due to the fact that different construction methods produce different amounts of emissions and the vehicles' movement substantially contributes to the total amount of the emissions, it is entailed that less vehicles movements lead to less environmental pollution.

To conclude, contractors, construction managers, regulatory bodies, and city residents have a great stake in the traffic conditions and the additional traffic volumes related to construction projects in urban areas because of the significant aforementioned reasons. Therefore, there is a need to predict and examine the impact of vehicles during the construction process in different types of constructions on the relevant road network.

## 1.2 Problem statement

A reasonable and accurate estimation of the transportation volumes in the road network of a densely populated area can be achieved by different methods such as deriving data from sensors in the examined transportation network or by creating a real-time traffic model (Eisenman et. al, 2006). These two methods has also been achieved by Gemeente of Amsterdam by using a visualized model due to smart mapping algorithms named as data fusion model.

Gemeente Amsterdam in order to estimate traffic volumes in the city's road network has used the annual average daily traffic (AADT). ADDT is the total volume of vehicle traffic on a highway or road for a year divided by 365 days (Yang & Davis, 2002). The annual daily traffic has been determined through sensors, but at this very moment, there are no available records of the road network during additional construction activities. In addition, during construction processes, extra transportation volumes occur due to logistics. The required amount of materials and the essential equipment has to be delivered on site efficiently so that delays in the construction activities to be avoided and traffic congestion to be prevented. In this way, the functionality and the livability of the area and the drivers' accessibility in the road network can be retained. In order a successful delivery of materials on site to be accomplished and a desirable living level to be retained, traffic congestion should be avoided.

Therefore, there is a need to gain knowledge about the extra transportation volumes of the road network, which are derived from the construction activity and influence the road's transportation flows. In this way construction processes can be completed smoothly (without delays and by following the safety regulations), accessibility on site can be reassured and a functional road network can be guaranteed. Hence, a prediction of the additional traffic volumes that can be produced from different types of building projects could facilitate this goal since the selection of the more suitable building type (construction method) could be indicated. Thus, a tool that provides a better insight into the extra transportation volumes in the road network due to the construction process for the implementation of a construction project is beneficial.

## 1.3 Objective

The objective of this thesis is to *design a transportation prognosis model that will predict the extra transportation volumes on the given roads (the location of the construction project) due to the transportation activity of the needed vehicles along the construction process.*

This model would be focused on three different scenarios with regard to the used construction method for the realization of a building project; conventional (also named as traditional) construction method, prefabrication, and "mixed" construction method. In a "mixed" construction a part of the project is constructed with prefabricated elements and another part using traditional construction methods. Additionally, the transportation prognosis model of this study examines the impact of the road's traffic conditions due to the building project's construction logistics. The volume of the building project is used for comprehending the project's needs in terms of construction logistics.

## 1.4 Research question

The problem statement and the objective explained in the previous sections contribute to the formulation of the main research question as well as the sub-questions of this study. *The main research question defines the design objective of this MSc thesis*.

**Main Research Question**

*How much impact does the construction process of a building, considering the type of the construction method, have on the transportation movements of the urban area of the project?*

**Sub-questions**

1. What are the characteristics and the main challenges of construction logistics for the realization of a construction project and why the pre-design phase is mostly related to the management of construction logistics? (Chapter 3)
2. What are the causes and consequences of traffic congestion in urban areas? (Chapter 3)

3. What are the critical stakeholders and why their behavior can affect the logistics of a large construction project? (Chapter 3)
4. What are the assumptions, the variables, the parameters, the coefficients, the extra influential factors, and the formula (which is the introduced mathematical expression for serving the model's objective) in order to design and develop the transportation prognosis model? (Chapter 4)
5. To what extent can the output of the transportation prognosis model facilitate the pre-design phase of a construction project concerning the additional transportation volumes along the construction processes and be used as a proactive measure (tool)? (Chapter 6)

## 1.5 Research Relevance

Transportation models can be distinguished in three main waves historically because of the level of detail that has been incorporated through time (Ran et. al, 2012). The common ground of all the transportation models is the relationship between light loads, medium loads, and heavy loads with the type of vehicles. This relationship can change the traffic flow of a road network dynamically. Besides, construction logistics have been recently introduced in the construction sector and are firmly connected with the development of the construction industry. Therefore, there is plenty of room for further research on these topics; transportation modeling and construction logistics.

One topic which is far from being investigated is the influence of construction activities on the traffic congestion of the existing road network of an urban area. It would be interesting to investigate how and if additional transportation volumes can aggravate traffic congestion and play a role in its management. Furthermore, the absence of reported research on traffic impacts of building construction operations hardens the raise of awareness of these impacts among contractors and regulatory bodies (Hyari et. al, 2015).

The present study is an attempt to create an initial rough model aiming to examine the contribution of transportation movements associated with the construction activities in the traffic loads of the road network. This study is based on empirical data retrieved from interviews with experts and logical assumptions for the design of the transportation prognosis model. Therefore, the present research can be the first step for researchers who are interested in this field of study to dive deeper into transportation modeling along construction processes.

## 1.6 Practical Relevance

Some informative, semi-structured interviews with contractors and project managers from different construction companies were conducted aiming to discuss the preferable construction method from a contractor's point of view, the awareness of traffic volumes that derive through the construction activities, the detailed record of the number of vehicles along the implementation of the construction project, and the major necessities for transportation when carrying out construction activities. It was admitted that there is a deficiency of detailed records and awareness regarding the number and the movement of vehicles along the construction process and that public actors are those that are mainly concerned about this quantitative documentation.

Moreover, experts from the Logistics Department and Transportation Engineering Department of Gemeente Amsterdam, stated that there is a need of gaining insight into the traffic volumes that could be created along the construction process since traffic congestion can cause difficulties in the functionality of an urban area and create social cost overruns. Consequently, there is a need to predict the traffic volumes of the reference road network taking into account the number of vehicles that deal with the implementation of the construction activities. A transportation prediction model, that demonstrates the different transportation volumes related to different types of construction methods in the referenced road network, is seen to be a proactive approach so that late changes in planning, cost losses, and public discomfort to be avoided.

## 1.7 Deliverables

The deliverable of this thesis is a transportation prognosis model, which can be used by interested stakeholders in order to gain insight into the impact of the usage of vehicles for construction activities on the traffic congestion of the road network. Moreover, this transportation prognosis model can be a way of comparing different construction methods, particularly traditional construction method with prefabrication, considering the produced transportation loads. The model proposed by this study is a synthesis of simplified assumptions from the literature review and valuable semi-structured interviews with experts. Lastly, this designed model endeavors to be a primary step for a more detailed transportation prognosis model.

# Chapter 2

# Thesis Methodology

*In this chapter, the methodology of this study is described. In this thesis, a "design-oriented" research approach is utilized, and it is formed in Section 2.1. In addition, in Section 2.2 the research steps are given as well as the methods that will be applied so as to carry out every step of the research. Finally, the outline of this thesis based on the aforementioned sections' analysis, is provided.*

## 2.1. Research Approach

According to Wieringa (2014), when a problem has to be tackled, the researchers should follow the down mentioned way of thinking: First and foremost, the problem is identified and an attempt for its remedy is followed. At last, this treatment is validated and implemented. To some extent, this research follows this line of thinking, and the problem-solving procedure is the design of a model.

## 2.2 Research steps & methodology

By applying the abovementioned structured thinking with the present research design, the steps that this thesis follows are mentioned and briefly explained below:

**1. Problem Identification**

The aim of the first step is the identification of the problem. This target is fulfilled through:

a) literature review about the causes and the impact of traffic congestion in urban areas as well as the usage of construction logistics throughout the building construction processes. Also, a stakeholders' analysis review regarding complex projects is considered necessary. Moreover, the characteristics of different construction methods are studied. Google scholar, Science direct, and Research Gate were the main databases that were used for reviewing literature. Along with these sources, books were also studied.

b) some exploratory interviews (with experts working in the logistics sector and transportation sector of Gemeente Amsterdam), were conducted during the initial phase of the research.
The exploratory interviews targeted defining the requirements, the challenges, and the main problems that urban road networks encounter in terms of traffic congestion during

a construction project. More precisely, the interviews aimed to establish the aspects of the research and discover the availability of potential models and tools in practice.

The outcome was that traffic congestion is a common problem in densely populated areas and municipalities in general, such as Gemeente Amsterdam, consider the number of vehicles related to construction processes during the implementation of a construction project as a great challenge. Thus, confirming the need of gaining insight into the additional traffic volumes that different types of construction methods produce and showing the direction for designing the model.

During the first stage of the research, the method of conducting some interviews and revisiting past research in order to refine the problem definition and clarify the requirements of the study is regularly used (Verschuren et al., 2010) (p.69). For the design of the model, some vital steps are defining the requirements of the model and the purpose that will serve (Benjamin S. et al., 1990). Therefore, this research follows this tactic.

### 2. Design of the model

The aim of this step is to design a model that facilitates the need to tackle the problem of traffic congestion. After the problem definition is done, the next step is the selection of the correct type of model, between interpolation and extrapolation, which can achieve the needed prediction. Furthermore, the identification of the model's requirements, the input, and the output of the model has to be defined. For that reason, the selection of the variables, the parameters, the coefficients, and the formula of the model is vital. In order to develop the model, a decision regarding the software of the model is made. In Chapter 4, the selected software and the detailed design of the model are explained. The elements of the model have been found in the literature review and the semi-structured interviews with the experts of Gemeente Amsterdam, experienced contractors, and logistics managers taking into consideration the model's main objective.

### 3. Validation of the model

Model validation is well-defined as the process of establishing the degree to which a model is reliable and realistic from the perspective of the expected use of the model (Kane, 2008).

Throughout this thesis and due to its time frame, is not feasible to gather the exact real data to test the designed model. The main difficulties appear in the availability of the needed data and the lack of prior detailed records and studies. For that reason, some assumptions are made concerning the extrapolation type of modeling in order to design the model. Considering the input data, the conducted estimations are based on the knowledge of Gemeente Amsterdam members, interviews with contractors and logistics managers of mega projects, and extensive literature study. In view of facing difficulty in collecting reliable data, a formative evaluation (ex-ante evaluation) is chosen so as to evaluate the model before its implementation (Verschuren & Hartog, 2005) (p.742).

In this thesis, the model will be assessed by experts of Gemeente Amsterdam having as main criteria the usability as well as the functionality of the model. The assessment will be achieved through personal meetings.

Yin (2018) (p.85) stated that using a common case of an everyday problem is a useful way to approach a problem and many lessons could be learned. For the aforementioned reason, the selected case for the evaluation of the model is the Eleven Square project (located in ArenAPoort West which is a congested urban area in Amsterdam) because is a common one, among complex construction projects, according to the opinions of the experts in Gemeente Amsterdam. More specifically, this case study bears the appropriate characteristics for validating the designed and developed model. In order to evaluate the model, the input data are estimations based on rough data either from previous cases or from the chosen case's available data retrieved under communication with contractors and grounded on rational analytical thinking in collaboration with experts from Gemeente Amsterdam.  Moreover, this case is interesting and challenging for many stakeholders. The chosen case is analyzed in chapter 5 of the report.

Figure 2.1 represents an illustration of the thesis methodology. In particular, this figure connects the chapters of this study with implemented steps (the design activities), as well as with fundamental means used for the accomplishment of these steps as part of the prognosis model's development. Last but not least, the research questions that each chapter answers are contained.

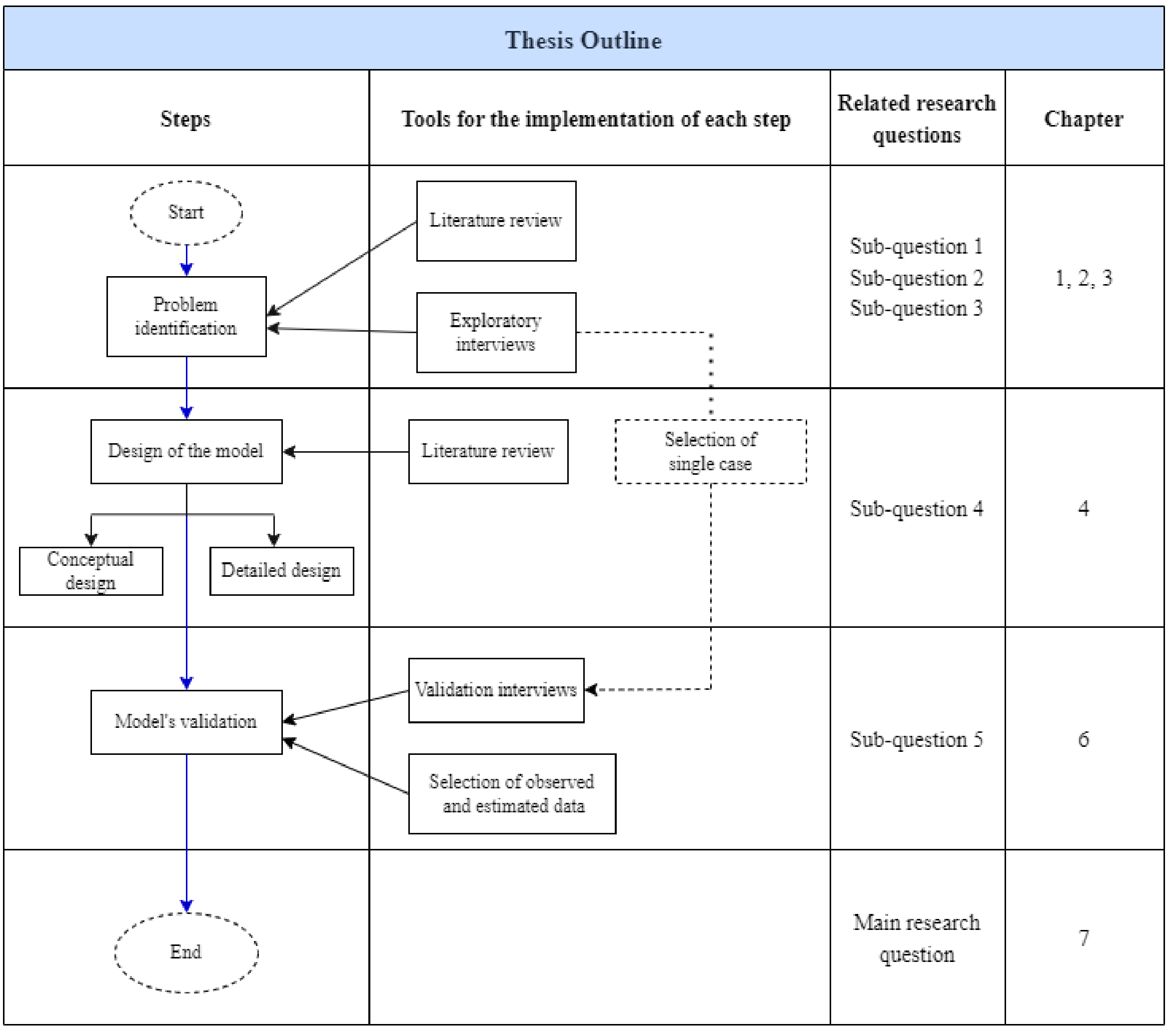



Figure 2.1: Thesis Outline

# Chapter 3

# Theoretical background

*This chapter presents the conducted literature review. The core elements that are related to the objective of this thesis are analyzed and a better comprehension of the two main subjects, traffic congestion and construction logistics, is achieved. Therefore, the following research fields which contribute to the context of this study are selected and literature reviewed; traffic congestion in urban areas, transportation of materials in construction phases, construction logistics in construction projects, stakeholders' analysis as well as model types and characteristics. The aforementioned research fields are stated in the sections of this chapter respectively. Also, the review of the prior literature replies to the following sub-questions:*

***Sub-question 1:*** *What are the characteristics and the main challenges of construction logistics for the realization of a construction project and why the pre-design phase is mostly related to the management of construction logistics?*

***Sub-question 2:*** *What are the causes and consequences of traffic congestion in urban areas?*

***Sub-question 3:*** *What are the critical stakeholders and why their behavior can affect the logistics of a large construction project?*

## 3.1 Traffic congestion in urban areas

Due to the dynamic development of urban areas, the provision of high-functionality transport services has become more challenging in recent years. Urban traffic is a quite common and major problem, mostly in developing districts, because there are more transport needs at the same time (Jain et al., 2012). Thomson & Bull (2001) define congestion as "the situation where the introduction of an additional vehicle into a traffic flow increases the journey times of the others". Specifically, traffic congestion is correlated with vehicles' movement that exceeds the capacity of a certain road and results in a reduction in the speed of vehicles' movement or overall disruption to traffic (Weisbrod et al., 2003; Goodwin,2004).

A review of the literature on the phenomenon of traffic congestion indicates that there are many contributing factors to creating traffic congestion as well as a wide spectrum of consequences. A road network without a sufficient capacity for transportation flows and insufficient investments in the infrastructure sector contribute to an increase in the traffic flow (Koźlak & Wach. 2018). The lack of investment in the transport infrastructure accelerates insufficient maintenance of the road network and sometimes is responsible for bad conditions on the surface of the road (Bull & CEPAL, 2003). Furthermore, additional influential factors for urban traffic are population density as well as the number of human force that commutes by car (Centre for Economics and Business Research, 2014). Regarding the human factor, the travel behavior of individuals, which is mostly determined by socio-economic factors, plays a significant role in urban traffic since it raises the level of travel demand (European conference of ministers of transport, 2007). Aggressive behaviors of drivers are a substantial factor in worsening the already existing traffic congestion. At last, since traffic congestion is a multi-faceted issue, there are other associated factors with the increase in traffic flows such as land-use patterns, weather conditions, the employment rate, car ownership developments, and the vehicles' movement due to logistics. In the scope of this study, the extra traffic congestion that is generated by the transportation of construction materials and laborers' commuting during a construction project is examined.

It is widely acknowledged that the harmful consequences of traffic congestion lower the quality of life in urban areas. More precisely, congestion holds ups those who have to travel, and these longer journey times are a "loss" in real terms. This loss is not only measured in travel time but also cost; operating cost of vehicles, mostly in fuel cost, and social cost since public transport also faces travel delays (Walters, 1961). Concerning the movement of vehicles, the public sector is also affected negatively by delays and faces difficulty satisfying the high level of civilians' transportation needs. In particular, traffic congestion has a negative influence on the transportation of goods that is correlated with the supply chain.

Likewise, adverse traffic conditions lead to a higher level of noise and air pollution. Transportation flows are a large contributor to the $CO_2$ emissions increase and as a result traffic congestion is a source of greenhouse emissions and is associated with global climate change (Bath & Boriboonsomsin, 2009).

Especially in the Netherlands in order to achieve a fully sustainable and resilient city by 2050, the reduction of $CO_2$ emissions is vital (Government of the Netherlands, 2017). More thoroughly, since the Netherlands aims to participate in the Green Deal Zero-Emission City Logistics that will start acting upon 2025 and can potentially result in a decrease of 0.1 Mton of $CO_2$ emissions, medium-large Zero-Emission (ZE) zones have been determined in 30 to 40 of the largest Dutch cities. According to Beerda (2019), the traffic related to construction processes is approximately thirty percent (30%) of the total urban traffic. Additionally, the Dutch Climate Agreement places a strong emphasis on urban cities, which is also where the development of the construction industry is occurring (Van de Meer, 2019). Therefore, the environmental aspect is another reason why traffic congestion has to be minimized and transportation management is essential. The objective of this thesis, the design, and development of the prognosis model, facilitates efficient traffic management for accomplishing this goal.

To conclude, traffic congestion is a multi-sited problem that is generated from several sources. Additionally, it hardens the daily life in urban cities and due to many direct and indirect negative side-effects in city life, it harms the civilians' physical and mental health.

By taking into consideration the aforementioned causes and consequences that are associated with traffic congestion, and achieving a better understanding of the relevant literature, a causal diagram that displays the correlation and the interrelationships of the various variables in traffic congestion is demonstrated in Figure 3.1. This casual diagram is a demonstration based on the literature review findings so that a better comprehension of the traffic congestion's causes as well as its direct and side effects to be provided.

More specifically, the causal diagram represents each relationship between the variables with an arrow from the cause variable to the caused variable. Additionally, an arrow with two directions entails that there is a mutual cause-effect relationship between both variables. The red arrows demonstrate the direct but also indirect consequences of traffic congestion, while the blue arrows indicate the direct and indirect causes of traffic congestion.

For better comprehension, an example is provided. As the causal diagram shows, additional transportation volumes related to construction activities are affected by three main factors; the typology of the construction method of the expected project, the lack of communication between the interested stakeholders, and inefficient planning. Also, inefficient planning as well as traffic congestion from the road network in combination with the extra transportation movements related to the construction process can lead to problems in the implementation of a construction project.

The resulting congestion effects in the construction sector, as well as its earlier mentioned societal and environmental negative impact is an argument in favor of managing transportation movements more efficiently and thus proactively. Therefore, a prognosis model aiming to predict the additional transportation movements that are derived from the construction process and thus the condition of the relevant road (the location of the construction project) during its implementation, stands as a useful tool for managing traffic conditions.

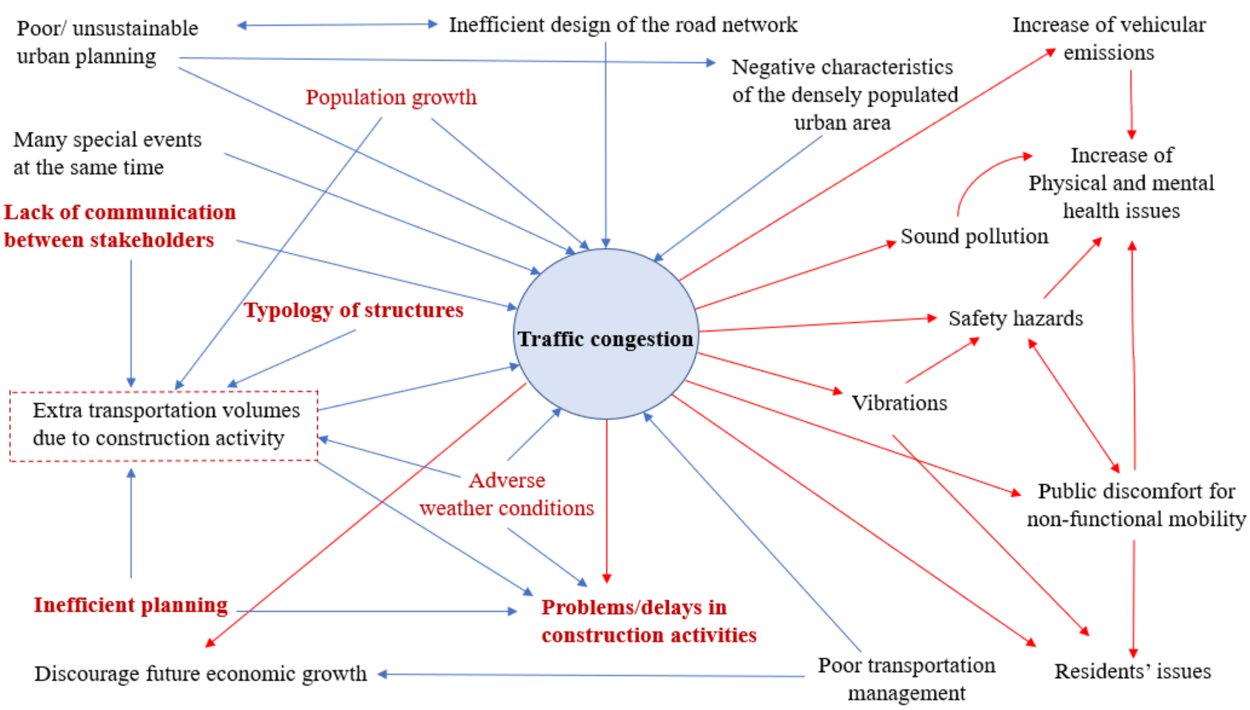



Figure 3.1: Causal diagram for traffic congestion in densely populated urban areas

In the scope of this study, the designed prognosis model is focused on the extra transportation volumes on the road that leads to the construction site of the project due to the implementation of construction activities. As Figure 3.1 displays, there are contributing factors for the produced additional transportation volumes related to the construction process. These factors have to be considered for designing a valuable prognosis model. Therefore, these influential parameters are in the scope of this study and are incorporated for designing the prognosis model. For a better understanding, the factors that are taken into account according to the scope of this thesis are given in red color in Figure 3.1. The effect of the population growth as well as the adverse weather condition on the generated transportation volumes related to the construction process is not in the field of this research's field.

First, in order for the designed model to be able to function properly, the relevant data need to be gathered from the involved interested parties (stakeholders). Concerning this procedure, the model of this study deals with the lack of communication between the construction project's stakeholders and the unfavorable condition of inefficient planning. More particularly, when inefficient planning is mentioned what is meant is detailed planning in terms of the project's construction logistics and mostly the transportation movements for the fulfillment of every construction activity. Hence, the model indirectly forces the involved and responsible parties to improve these two impediments for the avoidance of traffic congestion.

Furthermore, for designing the prognosis model, the implemented construction methods have to be considered since they influence the number of additional transportation flows on the road network. The selected construction method specifies the input data of the model and as a result, defines its output. Thus, the fact that the typology of structures plays a role in the derived number of vehicles for the realization of a project is included in the design process of this study's prognosis model.

Finally, due to the prediction of the traffic condition in the construction project's location, an opportunity is given to take beneficial precautionary measures for preserving uncontrollable traffic conditions on the examined road. Likewise, the most appropriate time slots regarding the project's road condition will be revealed and potential delays in the construction activities will be avoided as well as problems in the coordination of different construction processes.

## 3.2 Transportation of materials in construction phases

Reviewing the literature related to the realization of a construction project, it is observed that the construction phases are categorized, and every phase includes specific construction activities. Nevertheless, construction projects are influenced by different factors and differ in complexity level Winch (2010). Transportation of materials, which is part of construction logistics, is fundamental for the realization of a construction project and is mostly part of the pre-design phase.

### 3.2.1 Construction phases for the implementation of construction projects

Construction projects pass through characteristic life cycle phases, starting with their inception and closing with the project end and handover of the physical assets to the client (Lundin et al.,1995). According to Winch (2010), construction projects are dynamic with regard to the project life cycle. Also, the growth of the organization that constructs the project, the uncertainty level throughout the construction process, and the expertise of the involved stakeholders, can differ during the life cycle of the project.

In general, the life cycles of a project are divided into phases taking into account the transfer of main deliverables (e.g., going from requirements to design, construction activity to operational activity, and so forth) and the fields of expertise that are included in a project (e.g., contractors, subcontractors, architects, designers, and engineers) (Noktehdan et al., 2019).

The starting phase of a project includes the predesign approach, the feasibility study, and the concept design which are also the critical activities of the project (Liu et al. 2015; PMBOK 2013).

The next phase is characterized by preparing the details of the construction process and organizing the construction activities. The main steps are 1) a detailed design, 2) the tender process, 3) the selection of the proper contractors that will be responsible for carrying out specific tasks, and 4) the communication procedure. The aforementioned factors are some of the most crucial aspects of a successful construction process before the start of the construction activities (Liu et al. 2015).

The last phase of a project is concerned with reducing the risk and the uncertainty of the project based on risk assessment techniques, conducting the activities for completion and realization of the project and creating room for alterations to the existing situation of the project or potential changes.

According to this analysis, the understanding of how construction projects affect the traffic volumes on particular road networks is related to the predesign phase of the project since the requested insight into the additional transportation volumes due to the transportation of the building materials on site is included in this phase. Therefore, it is essential to research the fundamentals of the pre-design phase.

### 3.2.2 Pre-design phase of construction projects

Al-Reshaid et al. (2005) mention that the planning phase is sometimes referred to as the pre-design phase of a project. The steps of this phase are the following:

1) Budget estimate is the establishment of a budget for exclusively planning or the pre-design phase.

2) Preliminary scheduling, which includes the identification and monitoring of all pre-construction activities.

(3) Control program updating, which concerns the identification of a suitable reporting system.

These steps are sufficiently addressed by the relevant managers and consultants in their weekly or monthly reports and are being scrutinized for rectifications, improvements, and alterations, if any. The three aforementioned main steps of the predesign phase play a substantial role in safeguarding a productive and efficient pre-construction phase and handing over the deliverables on time (Al-Reshaid et al., 2005). Also, this belief is confirmed by all the contractors that have been interviewed for the conduction of this study.

Additionally, according to (Meredith et al., 1995) the conflicts-intensity relationship, is being modified from concept to completion of projects throughout the lifecycle of every project. In order to tackle future problems of the conflict-intensity relationship, a three-step sequential route is conducted during the pre-design phase (Al-Reshaid et al., 2005):

(1) Step No. 1: initial concept and scope of the work.

(2) Step No. 2: professional evaluation of the project-feasibility report.

(3) Step No. 3: appropriate data collection.

*The number of vehicles that are part of the construction logistics of the projects is incorporated into the third step of the pre-design phase* because the traffic volumes that are generated by the transportation of materials can be an obstacle to a smooth delivery process. The appropriate data collection in terms of used vehicles during the implementation of the construction activities requires an accurate record and as a result a scrupulous collection of the relevant data. Therefore, the literature study reveals that a way to control traffic congestion in an urban area is to manage the number of vehicles for transporting construction materials.

## 3.3 Construction logistics in construction projects

When construction projects are finished, it is observed that they can lead to an economically viable and sustainable urban area. Nonetheless, if the transport activities are not managed appropriately, they affect the surroundings negatively. (Balm et al., 2018) mentions that 15-20% of heavy goods vehicles in cities are from construction projects and 30-40% from light commercial vans. Therefore, the aspects of construction logistics that are meaningful for this study are researched in this section.

### 3.3.1 Characteristics of urban construction logistics

Construction logistics incorporates all measures for ensuring that equipment, material, and laborers are transported, safely and at the lowest cost, to the correct place at the right time (Quak et al., 2011). Also, construction logistics are related to the transport flows that are generated when constructing a project. This concerns not only the supply and removal of materials but also the transport flows of the personnel to and from the construction site. Within urban areas, no less than 30% of all transport movements are construction related. This indicates that the construction sector accounts for a huge share of the total number of transport movements in the cities (*Stadslogistiek - Bouwlogistiek Archieven*, n.d.).

Since the Netherlands aims to decrease greenhouse gas emissions in transport and mobility by sixty percent (60%) compared to 1990 until 2050 (Top Sector Logistiek, 2018), some useful ways have to be found in order to monitor and control all the aspects of construction logistics, also including the movement of the vehicles.

Firstly, the characteristics of construction work on transport movement to and from the construction site need to be addressed. Based on Balm et al., (2018), there are four specific characteristics of construction work so far:

1) The duration and the location of every construction project are unique. Moreover, every construction site needs its own logistics set-up.

Considering the aforementioned fact, transport movements have to be monitored and controlled for each project. Some construction sites will have enough space to store up their equipment and load and unload freight, while other construction projects will only have a restricted and limited number of square meters at their disposal.

2) Construction sites are materials' accommodations, and the building materials are delivered independently in each and every construction phase.

Since construction projects vary in terms of their design and purpose, different types and amounts of building materials are required. As a result, every construction project is built in another way. However, as has been already mentioned in Section 3.2.1, every construction project comprises the same construction phases.

3) Most construction activities are operated subsequently. Therefore, when a delay occurs, an overall delay in the construction project appears.

Hence, it is of great importance to deliver the building materials in the correct amounts and on time to the construction site. Furthermore, another crucial factor is the presence of laborers.

4) Every construction project involves different interested parties such as construction companies (involved contractors), suppliers, logistic companies, and regulatory bodies.

This indicates that there are different ways of working and managing the data in every project. Seeing that each construction project has different stakeholders and characteristics, the transportation volumes need to be managed in other ways in every construction project.

In conclusion, the four common characteristics of construction projects reflect the high complexity level of the construction sector, in particular, the management of the transportation volumes and meticulous planning. Consequently, the construction sector faces many challenges so as to provide or maintain livable cities and high quality of civilian life. Therefore, these challenges are researched and explained below.

### 3.3.2 Challenges in construction logistics

A high complexity level in a construction project reveals that the traffic volumes to and from the construction site are not effectively and thoroughly organized (Lu et al.,2015). In order to achieve an efficient and well-organized construction site, there are the following challenges that need to be tackled Balm et al., (2018):

1) Different objectives from the relevant interested parties. During the lifetime of a construction project the personnel, the equipment's utilization, and the delivery time of the building materials have to be taken into consideration. In consequence, it is important to follow adequate coordination between the key players so as to ensure a smooth construction process (De Bes et al., 2018). A few common problems related to poor coordination are an increase in $CO_2$ emissions, noise pollution, traffic nuisance, and public discomfort.

2) Poor coordination of logistics on the construction site. At present, the materials coming to the construction site are coordinated to a limited extent. For that reason, the overview of which material is needed and when is difficult. As a result, there is a delay in the use of the necessary materials. Thus, since a domino effect appears, the construction of the project is delayed, and extra urgent deliveries are needed.

3) Lack of proper planning, monitoring, and control on the construction site. As a result, there are possibilities of delivering broken materials or facing potential losses. Thus, partially filled trucks have to drive to and from the construction site once again.

4) Ineffective communication between the different stakeholders. A typical example is that because residents have fewer parking spaces at their disposal while the nearby companies do not want to experience any hindrance from the construction, the transport flows of the construction projects have to be managed.

Taking into consideration all of the above, it is concluded that the coordination, the planning, and the stakeholders' relationship and interest are the main challenges. The prognosis model can be used as a tool to improve communication between the stakeholders, provide insight into the traffic flows during the construction phases, and point out potentially needed alterations in the planning.

Lastly, an important factor is the impact of the building method on construction logistics since it influences all these main challenges differently. Therefore, research on this aspect has to be conducted.

### 3.3.3 Construction logistics in different building methods

One of the factors that have to be considered when comparing different construction methods is the accessibility of vehicles and personnel on and onto the site (Pasquire et al., 2005). The delivery of materials' quantities and vehicular accessibility to the site vary between traditional construction and prefabrication. Another significant difference regarding the impact of different construction methods on traffic condition of the project's road network is that different construction methods demand different types of vehicles for the implementation of the construction activities. The fact that different construction methods follow other ways of carrying out the construction activities results in different needs with regard to the quantity of the construction materials. As a consequence, the type of vehicles and their effect on the transportation flows of the road network in the construction project's location differ between the traditional construction method and the prefabrication. Therefore, since the selection of the building method affects the number and the type of needed vehicles for the transportation of construction materials and generates different number of vehicles for laborers' commuting, it has to be investigated.

Prefabrication is correlated with off-site manufacturing which refers to the implementation of prefabricated elements. The prefabricated elements are manufactured in a controlled environment where this manufacturing process reduces defective products as well as overall waste. In this case, there are fewer transportation movements and more available space on the construction site (Bogers et al., 2017). Prefabrication accelerates the construction of a building project and decreases the inconvenience for the local inhabitants. However, in comparison with the traditional construction method, prefabrication demands better cooperation and more detailed communication along the supply chain as well as high transparency level (Ufemat, 2008).

By following prefabrication, the delivery of materials on site results in less traffic congestion in big cities and connects demand and supply (Ufemat, 2008). London is a notable example because of projects' development that led to a 70% reduction in $C0_2$ emissions from the construction logistics on site (TfL, 2008).

Likewise, it is well known that the selected construction method influences the structural design of the project. Through the pre-design and design phase, the decisions of civil engineers, architects, and designers have a countless impact on logistics (Papaprokopiou, 2010). Therefore, a strategy for the delivery of construction materials and the required construction equipment as well as a risk analysis in the preliminary design of the construction site and the upcoming building is necessary.

Finally, in the conducted interviews for carrying out this study, the interviewees (contractors) of the construction companies mention that the construction materials with the biggest volumes are more capable to impede smooth construction logistics because their transportation on the construction site is rarely neglected in the corresponding records of a construction project.

Consequently, the prediction of the additional traffic volumes that are generated from the traditional construction method, the prefabrication, and the combination of them, is a fundamental requirement for the model of this thesis.

## 3.4 Stakeholders' analysis in construction projects

The decision-making process in construction projects is a distressing consideration for the involved actors because the construction projects need to be in harmony with the cultural, environmental, and socio-economical characteristics of the surroundings (Wideman, 2004). Moreover, project managers frequently have to deal with the controversial expectations of stakeholders that are critical for the project's success (Wang & Huang, 2006; Davis, 2014). Since the interactions and interrelationships between the stakeholders play an important role in construction processes, effective stakeholder management is a key factor in the implementation of a successful construction project. Therefore, this approach can also facilitate this study since it mostly deals with complex construction projects, that in most cases involve multiple stakeholders, and betters their communication. The following sections mention two core steps for accomplishing successful stakeholder management.

### 3.4.1 Stakeholders' identification in construction projects

Freeman (1984) specifies a stakeholder as "a person or a group of persons, who are influenced by or able to influence the project". In particular, the influence of the participants affects the construction project's performance and on-time delivery. Also, another influential factor is the degree of complexity of the construction project. According to Mikaelian et al. (2008), a high degree of complexity leads to a system that is subjected to uncertainties and that may lead to suboptimal performance or even a catastrophic failure if left unmanaged.

In order to achieve proper stakeholders' analysis and create a successful strategy for the completion of the construction project, stakeholders' mapping is an essential requirement. The identification of all the relevant stakeholders, their interests, objectives, and power are basic components for project management and delivering the construction project in good condition. Bryson (2004) states that by taking stakeholders' needs seriously, the project can benefit and avoid unfortunate delays. A basic proactive technique used for the identification of the involved interested parties in a construction project can be as simple as brainstorming about the potential stakeholders (Bryson, 2004). More specifically, the division of stakeholders is based on the role that they play in the construction project.

There are the following two categories:

1) Internal stakeholders: They are directly involved in the organizational decision-making process (e.g., clients, supply companies, employers, and employees)

2) External stakeholders: They are affected to a great extent by the decisions of the internal stakeholders (e.g., local inhabitants, the general public, and governmental bodies)

In construction, there is an emphasis on the relationship between the internal stakeholders because they are responsible for the procurement phase of the construction project and the management of the construction site, while the treatment of the external stakeholders is mostly the responsibility of public authorities via legislation and regulations. For a construction project that has an impact on the transportation movements in an urban area due to construction logistics, some of the main stakeholders that have to be taken into consideration for an efficient construction process are demonstrated in Table 3.1.

The identified stakeholders that are stated in Table 3.1 are involved in every construction project that is located in a densely populated urban area. Each of the referred stakeholders can influence the process toward the realization of a construction project.

Table 3.1: Involved stakeholders in a construction project that generates traffic in an urban area

| Stakeholders |
| --- |
| Municipality |
| Project developers/Contractors |
| Construction material suppliers |
| Logistics managers |
| Drivers |
| Local residents |
| Laborers |
| General public (pedestrians) |

In this study, the designed prognosis models and the evaluation of it, takes into consideration the above referred stakeholders in terms of their needs and objectives as well as their knowledge and experience respectively. More precisely, the project developers and contractors (that represent the responsible construction companies of the project) as well as logistic managers, are those who ought to gather the needed data regarding the number of vehicles for the transportation of the building materials, the delivery of the needed project's equipment as well as the commuting of the laborers in the construction site. Consequently, they can know the number of additional transportation movements related to the construction activities of the project. Having effective communication with the relevant municipality that is responsible for the traffic conditions of the respective urban area, potential uncontrollable traffic conditions can be avoided by using insightful tools, such as a transportation prognosis model. Additionally, the volume of the building project in terms of the quantities of construction materials and their supply plays a critical role in collecting and providing the required data about the number of vehicles. Likewise, the number of laborers who need to arrive at the construction site of the project. Lastly, since this study's prognosis model is designed and developed to prevent uncontrollable traffic flows by its prediction, favorably affects the local residents of the urban area as well as its drivers and pedestrians. Thus, every stakeholder that is mentioned in Table 3.1 affects and is affected by the prognosis model.

Regarding the cooperation and behavior of the stakeholders, it is proven that effective communication and transparency are important values for a productive relationship between the stakeholders (Karlsen, 2002). In particular, some of the most common unfavorable results because of the miscommunication between the interested parties of a construction project, are an inefficient project planning and the likelihood of lacking transportation data related to the implementation of a construction process are. Taking into consideration that an inefficient project planning is strongly correlated with difficulties for managing effectively the project's construction logistics and is also partly responsible for adding transportation flows in the road that leads to the construction site of the project (Figure 3.1), it has to be avoided or effectively addressed.

To conclude, in accordance with the objective of the current study, the correct identification of the stakeholders is an extremely significant step for following successful stakeholders' management.

### 3.4.2 Stakeholders' behavior in construction project

Yang et al. (2009) identify assessing the behavior of stakeholders and creating correct strategies are also crucial factors. Also, the stakeholders' behavior sets out the stakeholders' influence on project outcomes (Nguyen et al., 2009).

The stakeholders' behavior is determined by their power, interest, and attitude level. The meaning of the level of the stakeholders' power, interest, and attitude is explained below (Rajeev et al., 2014):

- Power level: The stakeholders have a significant impact or control over the others.
- Interest level: A concern or interest in the implementation of the project.
- Attitude level: A tendency to react positively or negatively towards specific ideas, people, or conditions.

After the stakeholders mapping, a method needs to be followed since is required for dealing with uncertainties and potential problems in construction projects. The remedy consists of two core elements that are dealing with the gathering of the right information and with the analysis of useful decision-making (De Bruijn & Leijten, 2017).

By focusing on the scope of this thesis, in construction projects that are built in highly densely populated urban areas and influence the transportation flow, there is a lack of useful tools for monitoring the influence of extra traffic volumes in the road network. As a result, this deficiency of data leads to a larger possible ground for potential conflicts between the stakeholders. Therefore, due to the fact that is revealed from the literature review that large scale projects bear more ground for conflicts between stakeholders, and it is also observed a deficiency of data related to construction traffic, a rational conclusion is that the designed prognosis model of this study can have a key role for an efficient stakeholders' management.

Finally, it is worth mentioning that a predictive model about the extra traffic volumes that are generated from different construction methods is useful for all interested parties. The regulatory bodies avoid the extra social cost and complaints regarding public discomfort, local inhabitants and drivers stay away from noise pollution and daily delays and contractors prevent accessibility issues for the transportation of materials and construction equipment from and into the construction site. Lastly, communication between the interested parties can be improved through this model due to its contribution to better stakeholders' collaboration.

Based on this topic of the literature review, Chapter 4 describes the usability of the prognosis model in the scope of different users that are involved stakeholders of a construction project as well. Furthermore, the reasons for improving stakeholders' communication are explained in detail due to the contribution of the designed prognosis model to the improvement of their communication on the construction logistics topic. Also, Chapter 5 elaborates more on stakeholders' interest in a specific case study related to a complex urban area to provide a clearer understanding of the abovementioned aspects.

## 3.5 Model type & characteristics

The process of modeling has been widely used in the past years due to the need for a decision-making process in an upgraded society that provides access to a vast amount of information. With the aim to select the correct way or data for the achievement of a goal, many tools have been developed. The main objective of all the tools is to make an accurate prediction (Kuhn et al., 2013). Geisser (1979) defines predictive modeling as "the process by which a model is created or chosen to try to best predict the probability of an outcome.". In order to design the model of this thesis, one core step is to define the type of the model and more precisely, to follow the characteristics of transportation modeling.

### 3.5.1 Extrapolation-interpolation type of model

There are two types of modeling considering the cause and the goal of the model. The general terms of these two types are the extrapolation type of modeling and the interpolation type of modeling.

Extrapolation suggests calculating approximately an unknown value with the goal of expanding an already known sequence of values or facts. By extrapolation, a conclusion is made out of not explicitly existing information. To extrapolate is "to project, extend, or expand (known data or experiences) into an area not known or experienced so as to arrive at the knowledge of the unknown area by inferences based on an assumed continuity, correspondence, or other parallelism between it and what is known" (Gove & Merriam-Webster 1986).

Interpolation is used to calculate missing data. Another reason for selecting the interpolation type of method is to estimate the examined value based on already known values. More precisely, interpolation means defining a value from the already recognized values in a given data set. The most common model that follows the interpolation principle is the regression model which is a quantitative method to assess the relationship between a dependent variable and the independent one (Poole et al., 1971).

Concerning the aforementioned reasons, extrapolation is the suitable way to predict a factor based on a set of known past values and reliable estimations. Moreover, besides that extrapolation plays a major role in forecasting, it can also be connected to building a model based on estimations and probabilities, and not on specific data that there is no room for approximation.

For this study, the prognosis model is designed based on the extrapolation type of modeling and is developed by following specific estimations, assumptions, and simple predefined rules.

### 3.5.2 Key steps for predictive modeling based on extrapolation

Extrapolation is similar to an educated guess or hypothesis. When you make an extrapolation, you take facts and observations about a present or known situation and use them to predict what might eventually happen (Brezinski et al., 2020).

The extrapolation model has been a choice for prediction in many fields, such as ecology, medicine, *and transport*. The common ground in these different study fields is the basic rules of creating a model.

More precisely, according to Kuhn et al., (2013), "the foundation of an effective predictive model is laid with intuition and deep knowledge of the problem context, which are entirely vital for driving decisions about model development". Furthermore, a prior understanding has to be summarized in a conceptual model that will represent the main variables and the constraints of the model and how the model would be evaluated (Miller et al., 2004).

Also, a crucial step is the determination of the objectives that, in every model, are the main fundamentals together with the defined formula of the prediction model. For the implementation of the predictive model, a vital step is the selection of the relative data and the selection of modeling tools in order to accomplish the visualization of the chosen scenarios (Stillman et al., 2017).

The use of simulations can contribute to the design of several models, especially when a related reference to reality is analyzed (Bracke et al., 2015). In such cases, the starting point is the selection of a real condition, and the next step is a mathematical description of the situation which is made so as to achieve further investigation with the support of models.

Based on the core characteristics of modeling, in order to design the prognosis model of this study, one of the design steps would be to define the variables and the constraints of the model, and the mathematical formula that serves its objective. Furthermore, the selection of the more suitable software for this prognosis model is another significant step in order to design and develop a model that serves its purpose. The following section focuses on transportation models and their meaning.

### 3.5.3 Transportation modeling

Transportation models are tools that facilitate effective urban planning because they indicate the way that the transport system is expected to perform in the future. The development and application of a transportation model is a means for accessing transportation infrastructure options. Thus, transportation modeling is a strong tool for reliable urban and transport what-if analysis, and scenario planning (Stopher et al., 1975).

Transportation modeling enhances transportation planning. In order to create a functional transportation network, the transportation planner should simulate future network performance. The simulation reveals whether the transportation system is sufficient regarding the pre-established performance criteria (Werner, 2020). Additionally, based on logical thinking, since transportation models facilitate a better performance of transportation networks, are more needed in densely populated areas in which the transportation volumes are larger, and urban planning has bigger complexity and faces more challenges.

More specifically, in order to investigate how transportation volumes fluctuate over time, a traffic model needs to be created. The traffic models are mathematical models that examine road traffic based on specific data (Mahmud et al., 2016). For creating the traffic model, the main quantity that is being modeled is the traffic flow which is the number of vehicles such as heavy loads (e.g., trucks, cranes) and light loads (e.g., private cars, motorbikes) (Maerivoet, 2005). To examine the traffic conditions through traffic models the driver's travel behavior has to be taken into account. There are traffic models that try to simulate the behavior of the drivers while others take into account the average driver's behavior providing a macroscopic approach. In this study, the influence on drivers' behavior in traffic conditions is not considered.

Moreover, traffic stimulation is essential since makes it feasible to study models based on quantitative and qualitative treatment and produce an appealing and clear visual demonstration of the final output. There are two different types of traffic stimulation: either discrete event simulation or continuous-time simulation. Discrete event simulation models are stochastic (with random components) and dynamic (time is a variable). On the other hand, continuous time stimulation can resolve the inadequacy of discrete event simulation where the model is necessary to have input, state, and output trajectories within a time interval (Chapra et al., 2006). Therefore, the proper stimulation type for a model that aims to forecast the traffic load over time, is continuous-time stimulation.

At this point, it has to be mentioned that by reviewing the relevant literature regarding traffic models, it is observed that the introduced traffic models are quite difficult to be understood by the average reader with regard to the way of their design and development. Concerning the high complexity level of the problem that traffic models deal with, their complexity is reasonably expected. The present thesis targets designing a prognosis model for traffic loads that can be used without difficulty for its user. Since the user-friendliness of the prognosis model that this study aims to introduce is part of the model's requirements (Chapter 4), the already introduced traffic models are not used in the context of this thesis. Thus, the relevant literature review of these types of traffic models is not given in this section.

At last, nowadays simulation software is improved in a variety of several ways (Mahmud et al., 2016). With new developments in mathematics, engineering, and computing, simulation software programs are performing faster, becoming more detail-oriented, and they support more realistic cases (Nguyen, 2022). Thus, for the design of every model, including the model of this study, the software has to be selected. It is a truth generally acknowledged that nowadays there are several software programs with many abilities. For this reason, in order to design the predictive model, a chosen software is used. For the development of this study's prognosis model, the chosen software is MatLab.

# Chapter 4

# Design of the model

*This chapter elaborates on the design of the model that can potentially facilitate more efficient transportation management during the construction process of a construction project. This chapter responds mainly to the following sub-question:*

**Sub-question 4:** *What are the assumptions, the variables, the parameters, the coefficients, and the formula for the implementation of the transportation prognosis model?*

## 4.1 Introduction

The construction sector is often considered a cause for a large part of the negative influences on mobility in urban areas (Van Lier and Macharis, 2016; van Essen et al., 2019a) Furthermore, as mentioned in the previous chapter, traffic congestion is a regular occurrence in urban areas and can be analyzed and improved by traffic models. In order to predict the transportation movements of the examined road network during the realization of a construction project so as to better the conditions of the relevant urban area and take the appropriate precautionary measures to avoid traffic congestion, a transportation prognosis model is developed as a "tool". Additionally, another purpose of this "tool" is to predict the additional transportation volumes based on the selected construction method. Thus, this model facilitates transportation management.

To design the aforementioned prognosis model, first the requirements of the model are defined. Secondly, the input and the output of the model are decided and based on the main objective of the prognosis model, the variables are selected. Next, the formula, which is practically a mathematical expression of the model, is determined. In the next paragraphs, the elements and the whole process of the designed model are decomposed.

## 4.2 Requirements of the model

Ropohl (1999) determines well-formed requirements as a statement of the system's functionality that comply with the needs of the user. Traditionally, the identification of the requirements is the beginning step in order to develop a system or design a model (Thayer & Royce, 1990).

For the design of this model, the initial step is the definition of the model's requirements. In the very end, all the defined requirements have to be satisfied by the model in order to be considered a successful "tool" that serves its purpose.

The requirements of the prognosis model of this study have been determined based on the needs and wants of Gemeente Amsterdam after semi-structured exploratory interviews and consultation meetings with specialized experts. Additionally, after reviewing the relevant literature, which is stated in Chapter 3, the main issues of traffic congestion in complex urban areas and the complexity of mega construction projects in densely populated cities were disclosed and comprehended. Thus, the significant aspects that this model needs to serve were clarified so as to be a useful means of the traffic congestion's remedy.

Finally, aiming to design a generic prognosis model that can be adjusted in different urban areas, road networks, and construction projects, a system thinking approach was followed so as to identify the important requirements and hierarchy them.

The requirements of the prognosis model of this study are listed below as well as the justification for their selection. Likewise, the way these requirements are met by the model is explained.

1) *Accessibility of the examined road network.*

In particular, the road that leads to the location of the construction project has to be accessible not only for the delivery of construction materials, the required construction equipment and the laborers' commuting to the construction site, but also for the transportation movements of the public in the specific urban area. The prognosis model indicates if there will be potential difficulties in the transportation flow of this road. Also, it is a proactive and useful tool because these potential difficulties can be avoided by taking extra measures for the relevant experts and authorities. This requirement, which is satisfied by the model, is of great interest to all the stakeholders.

2) *Achievement of the desired/acceptable traffic level*.

The user of the model is the one that defines the acceptable level of traffic volumes in the specific road network as a threshold value. Any value below this threshold is considered acceptable. Exceeding the threshold means that the traffic volumes are above the desirable range. The threshold value is an input value and can be adjusted based on the needs of the examined road and the respective user. The Municipality as a regulatory body is the most interested party in retaining an acceptable and controllable traffic level.

3) *Identification of the most suitable time slots for the transportation of the building materials.*

The prognosis model reveals the traffic conditions of the examined road during the whole lifetime of the construction process. Identifying the specific time period that there will be an increase in the transportation volumes above the predefined level, the time slots in which the potential future delays will occur are revealed. Knowing this, the correct time slot for the transportation of the building materials is known. Thus, less waiting time for the transportation of the building materials on site is accomplished.

4) *Selection of the most appropriate construction method considering the generated transportation volumes*.

Since the prognosis model represents three different scenarios for three different construction methods, the traffic volumes that are produced from each construction method are examined. Therefore, the most suitable construction method for the avoidance of undesirable traffic volumes is indicated. Every construction method derives different transportation volumes due to the use of a different amount of vehicles. The main causes for this dissimilarity are the laborers' commuting on site and the different needed volumes of construction materials. To sum up, if the model can satisfy this requirement, the selected construction method can be validated as suitable or inappropriate considering the produced traffic volumes and the stakeholders' decision-making process will be more efficient.

5) *Insightful logistics information related to the planning of the construction project.*

One of the model's input variables is the number of vehicles during the lifetime of a construction project. The results of the model can be further analyzed in a potential expansion of the model to display the number of vehicles based on each construction phase. Likewise, this tool can enhance better communication between the stakeholders and be used for more convincing argumentation.

6) *Ability for the extension of the prognosis model which is friendly to the user.*

As has already been mentioned the design of the prognosis model is feasible by using the chosen software. The model of this study is designed in MatLab software that is linked with an external Microsoft Excel file. The use of these software programs makes easier the extension of the model and especially the connection between these two software tools provides a model that is friendly for the user since Microsoft Excel is broadly known. Chapters 4 and 5 mention the usability of the prognosis model and Chapter 7 elaborates more on the prognosis model's ability for further future expansion.

## 4.3 Initial assumptions for the design of the model

In the context of this study, in order to design the prognosis model some assumptions have to be made. These assumptions are made so as to define the initial rules and principles for the design of the prognosis model based on the extrapolation type of modeling. Another critical reason for making assumptions as a predesign step is to simplify the model due to the specific time framework of this thesis. Nevertheless, many additional variables can be included in a future version of the model and Chapter 7 recommends some of these variables.

The assumptions for the design of the prognosis model and an explanation of their usefulness, are mentioned below:

1) The drivers with their private cars who are related to the light loads of the road before the existence of construction activities will neither modify their travel choices nor change route in case of traffic congestion. *This assumption is conservative but determines the drivers' behavior and limits the prognosis model's input variables. Moreover, it is in favor of the worst-case scenario since the higher number of vehicles is concerned. The travel choice of the drivers involves route choice deviations that influence substantially their travel time. In this way, the travel time is considered the same for all the drivers and the parameter of the travel time is excluded from the prognosis model's design.*

2) The transportation volumes that the prognosis model can predict are during the working hours of each day of the construction project. For the working day, the working hours are examined. In particular, every hour of the working day from 7:00 am – 05:00 pm. The peak hours are considered from 07:00 am until 10:00 am and from 02:00 pm – 05:00 pm. *An assumption about time is required to define the time parameter of the model. For this study, the traffic volumes during working hours are examined, and a categorization between the peak and the non-peak hours is made by introducing factors in order to achieve an hourly traffic distribution for a better representation of reality.*

3) The trucks associated with a given origin-destination pair will follow just one predetermined route. Thus, one specific road will be researched. *By this assumption, the vehicles do not change their routes to avoid the traffic congestion. As a result, the prognosis model of this study examines only one route as an initial simplified version of the prognosis model. Furthermore, potential deviations in the travel time is not taken into consideration. Also, the traffic congestion of the surroundings is neglected and is not taken into account for this model.*

4) The vehicles, including the large trucks, that are determined as heavy loads, are equally distributed on the road along their route (e.g., three trucks following the same route will be equally separated). *This simplification indicates that the transportation flow will be examined in one lane and limits the scope of the designed prognosis model.*

5) The capacity of the road regarding the number of lanes is known and will be introduced as an input variable. *Defining the capacity value is complicated since capacity depends on many factors. Based on experts' opinion from Gemeente Amsterdam, measuring the capacity with simulation models is unreliable because in practice what is measured is simply what has already been modeled. Measuring capacity with loops or cameras is a more trustworthy way. Hence, accurate measurements for capacity are difficult to be achieved and thus the prognosis model considers the capacity value as a known one.*

By making the aforementioned assumptions, the model will follow the stated certain rules and the next important step is the definition of the input and output variables of the prognosis model.

## 4.4 Input and output of the model

According to Bossel (2018), modeling and simulations demand a well-explained input and output of the model as well as a formula that is associated with the model's objective. In this section, the input, the output, and the formula of the model are mentioned respectively. Moreover, the assumptions to design the prognosis model based on extrapolation modeling have already been stated and justified, and hence the way that the model works is further explained.

### 4.4.1 Input of the model

For the prognosis model to forecast the traffic volumes of the defined road, the traffic volumes are translated into the number of vehicles. Hence, the traffic loads on the road before the start of the construction process and also the number of vehicles that are going to be utilized for the transportation of building materials and the human labor's commuting, have to be known. The data will be inserted in a specific Excel file in which every Excel sheet includes the respective data. The use of an external Excel file creates a practical tool that is friendly to the user. However, the final results are visualized in the MatLab file through graphical representations. Table 4.1 includes a list and a description of the model's input variables.

Table 4.1: Input variables of the prognosis model

| **Input Variable** | **Description** |
|---|---|
| $l$ | Transportation load of the road (light loads, medium loads, heavy loads) before the construction process |
| $v_i$ | Additional transportation loads of vehicle type *i* related to the construction process |
| $w_i$ | Coefficient related to the type *i* of the vehicle |
| $c$ | Capacity of the examined road per lane |

More precisely, $l$ represents the number of the existing transportation loads of the road before the start of the construction project. The aforementioned volumes include all the light loads that are generated from the typical car as well as the medium and heavy loads that are derived from public transport and other vehicle types. These vehicles have already been classified into the typical passenger car and translated into transportation loads. In this manner, the input variable $l$ is a specific number that represents all the transportation loads in terms of vehicles before any construction process and is practically the summation of light, medium, and heavy loads by being classified.

In order to summate the additional transportation volumes from the implementation of the construction project, a classification of the different vehicle types have to be done. $W_i$ symbolizes a coefficient that will be multiplied by the additional transportation volumes from the construction process ($v_i$) concerning the vehicle type i. In this study, the classification of vehicles is based on PCE which is an abbreviation that stands for Passenger Car Equivalent (PCE). Passenger Car Equivalent (PCE) is a unit of measurement mostly used in determining the impact of the vehicle on the road network. The length, the turning radius, and the acceleration differ in every vehicle type. Since there are various PCE values in the literature, this study uses the values related to the impact on the road network in the Netherlands and particularly in highly dense urban areas (National Academies of Sciences, Engineering, and Medicine & Board, 2022). The $w_i$ values are introduced as parameters in order to achieve an accurate classification and they are inserted in the code of the Matlab file of the prognosis model.

The following table demonstrates the above-described classification.

Table 4.2: Identification of $w_i$ values

| **Categories** | **Vehicle type *i*** | **Value ($w_i$)** |
|---|---|---|
| Class 1 | Passenger car | 1 |
| Class 2 | Truck | 1.5 |
| Class 3 | Large truck | 2.3 |

Furthermore, the input variable $v_i$ concerns the transportation loads from classes 1, 2, or 3 that $w_i$ indicates (Table 4.2). In other terms, variable $v_i$ indicates the number of vehicles derived from construction activities. These transportation volumes are generated from the construction process either from laborers' commuting or from the transportation of building materials and necessary equipment for the relevant construction project. The values of this variable can be derived from the planner and the logistic manager of the relevant construction project. The number of vehicles is associated with the construction method of the project and this model involves three different scenarios that have already been explained in previous chapters with regard to the chosen construction method for the project's implementation. Since every construction project and each construction method generate different transportation movements, it is concluded that every case is also different. All the interviewees mentioned that the way of constructing a project depends on the project's characteristics and needs, the different interests of the involved stakeholders, etc. Considering the uniqueness of each case is important for the model's adaptability the variable $v_i$ to be introduced as an input variable.

At this point, it is important to mention the difficulty of knowing the exact values of variable $v_i$ due to the lack of accurate information about vehicles' movements associated with construction processes. More explicitly, a common finding from all the conducted interviews with contractors, project managers, and municipal experts is the lack of data and detailed records about the produced "construction traffic" during the realization of a construction project. As a result, the forecast of the additional traffic loads related to construction activities is more challenging. Therefore, the values of the vi variable can be altered by introducing a factor related to the construction phase and the construction methods. In this way, in case there is difficulty in having the exact values of the additional transportation loads due to the construction process, an approximation can be made since this factor is multiplied by the variable $v_i$ and provides increased or decreased values. Thus, the prognosis model can still estimate the traffic conditions in the selected examined road roughly. If the user of the prognosis model can be informed about the number of the used vehicle during the lifetime of the construction project can insert the values of the input variable $v_i$ in the external Microsoft Excel file and have the respective prediction. But if not, then an estimation of the total number of vehicles can be inserted as input variable $v_i$ and be differentiated by using the aforementioned factor according to the construction phase of the project.

An example for understanding the use of this factor, named as $f_{ij}$, is given in Chapter 5 since this "tactic" has been followed in order to evaluate the designed prognosis model of this study. At this point, it has to be mentioned that the construction phases of a project can be executed in parallel. Since the designed prognosis model of this study uses this simplification, a potential way to prevent an unreliable result is by introducing larger values to the relevant construction phases. For example, if the façade is constructed in parallel with finishing (that is usually the case), then a larger value of the factor $f_{ij}$ should be used.

At last, the capacity per lane of the examined road is considered as a known value for every road and is the input variable c. Since there are different approaches for expressing the capacity of a road, there are also different meanings of the various road capacities according to the purpose that they serve. In general, road capacity is the maximum potential capacity of a given road (Abelson et al., 2001). For the design of this prognosis model, the input variable c introduces the strategic capacity of the examined road. The strategic capacity is practically the real capacity, hence a value representing the actual maximum traffic volumes that the examined road can handle. Thus, the c value does not refer to a road under ideal traffic conditions but in realistic situations.

In aiding to maintain the highest level of service in the defined road, it is significant to note that this model aims to forecast the traffic conditions by taking into account the worst-case scenarios. Therefore, in cases where the origin of the road is a junction, the capacity that the prognosis model will use is the capacity of the junction since this is the worst-case scenario. In general, the capacity of a closed junction is preferred because it is more suitable to forecast the additional traffic loads and the situation of the examined road under unfavorable conditions. Furthermore, in cases where the used road for transporting the construction materials in the location of the construction project is not a single section but is divided into several sections, the capacity's input variable will be the lower capacity between the different sections of the examined road. Thus, the prediction of the worst-case scenario will be achieved as well.

It is significant to clarify that the selection of the input variables aims to provide *a flexible model that can be adjusted in potentially different cases*. When an effort is made to tackle a problem by using a simulation model, the model's flexibility is crucial. Therefore, the street data are chosen as an input variable allowing the model's functionality for different examined roads. Additionally, by introducing factors the limited accessibility of the needed data could be partially tackled since reliable estimations can be made.

After mentioning and explaining the input variables of the prognosis model, Figure 4.1 demonstrates where the input variables that concern the street data of the relevant examined road will be inserted in the external Excel file. Since *one of the prognosis model's requirements is to be user-friendly*, an Excel file that is linked with the Matlab file gives the user the opportunity of inserting the relevant data (input variables) into the respective Excel columns.

More specifically, the created Excel file clearly shows the model's user the way that needs to be filled in. In particular, the capacity of the examined road per lane is inserted in the first column of the Excel file and remains the same throughout the whole lifetime of the construction process of the building project. In the other columns, the light loads generated by passenger cars, the medium loads related to trucks' movements and the heavy loads produced by large trucks before the occurrence of the needed construction activities for the realization of the construction project are inserted respectively. Figure 4.1 represents these data correlated to the respective construction method by giving an example of one working day of the building project constructed by the traditional construction method. In a similar way of thinking, the input variable *l* that expresses the transportation loads of the road (light loads, medium loads, heavy loads) before the construction process of the project is filled for all working hours of the construction project in the indicated columns of the Excel file.

| | | | | | | |
|---|---|---|---|---|---|---|
| 1 | **Street data** | | | | | |
| 2 | | | | *Average traffic values/Hour* | | |
| 3 | Lane Capacity | Date | Hours | Light loads | Medium loads | Heavy loads |
| 4 | 1700 | 9/1/2022 | 7:00:00 AM | 1,226.139 | 2.98 | 4.32163005 |
| 5 | 1700 | 9/1/2022 | 8:00:00 AM | 808.870 | 4.12 | 6.97609779 |
| 6 | 1700 | 9/1/2022 | 9:00:00 AM | 1,080.764 | 6.12 | 5.84928711 |
| 7 | 1700 | 9/1/2022 | 10:00:00 AM | 908.055 | 3.33 | 8.43803142 |
| 8 | 1700 | 9/1/2022 | 11:00:00 AM | 712.113 | 2.72 | 7.53928185 |
| 9 | 1700 | 9/1/2022 | 12:00:00 PM | 656.541 | 2.07 | 10.1597887 |
| 10 | 1700 | 9/1/2022 | 1:00:00 PM | 701.958 | 4.09 | 5.84449583 |
| 11 | 1700 | 9/1/2022 | 2:00:00 PM | 662.225 | 4.12 | 7.92838955 |
| 12 | 1700 | 9/1/2022 | 3:00:00 PM | 1,001.311 | 4.10 | 2.98864303 |
| 13 | 1700 | 9/1/2022 | 4:00:00 PM | 1,195.558 | 1.77 | 7.39706561 |

Figure 4.1: Screenshot of the external Excel file with the excel sheet where the user can insert the input variables regarding the examined street data (example of the 1st day of the construction project)

As has already been mentioned, three classes of vehicles are considered to be used regarding the transportation needs of the construction project. Concerning the type of these vehicles, it has been assumed that the commuting of the laborers (construction personnel) happens with passenger cars (class 1). With regards to the transportation of construction materials and the delivery of the project's construction equipment, trucks (class 2) and large trucks (class 3) are used respectively. The aforementioned vehicles' types are considered for all the construction methods that the prognosis model of this study examines. Thus, for this prognosis model, three Excel sheets regarding the additional vehicles generated by the used construction method are provided in the external Excel file connected with the Matlab file; one Excel sheet for traditional construction method, one for prefabrication and one for "mixed" construction method. In every Excel sheet, the working hours of the whole duration of the construction project are included. In this way, the designed prognosis model can serve its purpose in case the construction project will be implemented by some of the above reffered construction methods.

Furthermore, a comparison can be achieved between these three construction methods in terms of their usage on the traffic flows of the examined road. In this way, the communication between the responsible municipality, the contractors and the logistic managers of the construction project about the used construction method and in general about produced transportation movements related to the construction process can be grounded on correct and well-structured argumentation.

Figure 4.2 demonstrates a Screenshot of the external Excel file with the excel sheets according to the selected construction method where the user can insert the input variables vi (transportation loads derived exclusively from the construction process) related to the relevant construction methods. For every construction method, an example of the used number of vehicles class 1, class 2 and class 3 of the construction project's first day is provided.

| | | | | | |
|---|---|---|---|---|---|
| 1 | Traditional | | | | |
| 2 | | | Number of Vehicles | | |
| 3 | Date | Hours | Class 1 | Class 2 | Class 3 |
| 4 | 9/1/2022 | 7:00:00 AM | 12 | 9 | 5 |
| 5 | 9/1/2022 | 8:00:00 AM | 50 | 23 | 5 |
| 6 | 9/1/2022 | 9:00:00 AM | 73 | 26 | 7 |
| 7 | 9/1/2022 | 10:00:00 AM | 22 | 9 | 19 |
| 8 | 9/1/2022 | 11:00:00 AM | 70 | 19 | 4 |
| 9 | 9/1/2022 | 12:00:00 PM | 49 | 4 | 17 |
| 10 | 9/1/2022 | 1:00:00 PM | 9 | 29 | 18 |
| 11 | 9/1/2022 | 2:00:00 PM | 61 | 7 | 3 |
| 12 | 9/1/2022 | 3:00:00 PM | 6 | 8 | 10 |
| 13 | 9/1/2022 | 4:00:00 PM | 12 | 6 | 18 |

| | | | | | |
|---|---|---|---|---|---|
| 1 | Prefabrication | | | | |
| 2 | | | Number of Vehicles | | |
| 3 | Date | Hours | Class 1 | Class 2 | Class 3 |
| 4 | 9/1/2022 | 7:00:00 AM | 37 | 1 | 12 |
| 5 | 9/1/2022 | 8:00:00 AM | 48 | 12 | 9 |
| 6 | 9/1/2022 | 9:00:00 AM | 29 | 12 | 2 |
| 7 | 9/1/2022 | 10:00:00 AM | 17 | 0 | 2 |
| 8 | 9/1/2022 | 11:00:00 AM | 57 | 12 | 12 |
| 9 | 9/1/2022 | 12:00:00 PM | 47 | 7 | 6 |
| 10 | 9/1/2022 | 1:00:00 PM | 34 | 1 | 14 |
| 11 | 9/1/2022 | 2:00:00 PM | 57 | 9 | 4 |
| 12 | 9/1/2022 | 3:00:00 PM | 3 | 19 | 6 |
| 13 | 9/1/2022 | 4:00:00 PM | 55 | 11 | 6 |

| | | | | | |
|---|---|---|---|---|---|
| 1 | Mixed | | | | |
| 2 | | | Number of Vehicles | | |
| 3 | Date | Hours | Class 1 | Class 2 | Class 3 |
| 4 | 9/1/2022 | 7:00:00 AM | 10 | 7 | 11 |
| 5 | 9/1/2022 | 8:00:00 AM | 26 | 14 | 0 |
| 6 | 9/1/2022 | 9:00:00 AM | 23 | 9 | 7 |
| 7 | 9/1/2022 | 10:00:00 AM | 1 | 16 | 14 |
| 8 | 9/1/2022 | 11:00:00 AM | 7 | 7 | 9 |
| 9 | 9/1/2022 | 12:00:00 PM | 24 | 10 | 8 |
| 10 | 9/1/2022 | 1:00:00 PM | 45 | 13 | 9 |
| 11 | 9/1/2022 | 2:00:00 PM | 44 | 8 | 8 |
| 12 | 9/1/2022 | 3:00:00 PM | 9 | 13 | 10 |
| 13 | 9/1/2022 | 4:00:00 PM | 26 | 15 | 15 |

Figure 4.2: Screenshot of the external Excel file with the excel sheets where the user can insert the input variables related to the construction methods (example of the 1st day of the construction project)

### 4.4.2 Formula of the model

The formula of the model is a mathematical expression that represents the main objective of the model.

The generic formula of the prognosis model of this study is the following:

$$R = \frac{l + \sum_{i=1}^{3}( w_i \times v_i )}{c}$$

where,

$R$ is the saturation rate that represents the traffic conditions of the examined road, $0 \leq R \leq 1$, and
$l$ is the transportation loads of the road before construction process,
$w_i$ is the coefficient for vehicle $i$ classification regarding PCE,

$v_i$ is the additional transportation loads of vehicle type $i$ generated by the construction process, and
$c$ is the capacity of the examined road per lane.

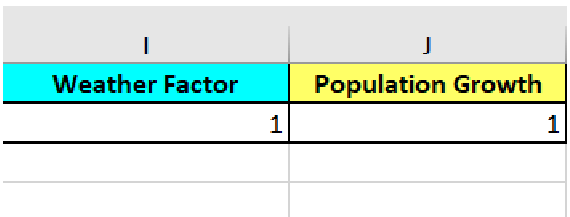
The input variables used in the prognosis model for this study are thoroughly discussed in Section 4.3.1.

More particularly, when $R = 0$ there are zero transportation movements which means the total absence of vehicles on the examined road, and when $R = 1$ reveals that the saturation is 100%. A 100 percent saturation rate shows that the traffic flow in terms of vehicles is the same as the capacity of the examined road. In this case, the road cannot handle any transportation movements since the capacity is totally exceeded.

In reality, traffic congestion is unmanageable even in $R$ values lower than one. According to this, an important parameter for the prognosis model is a threshold value $R_{th}$ which is determined by the user of the model (the one that inserts the input variables and "runs" the prognosis model) and reveals above which level the transportation volumes in terms of traffic conditions are undesirable or uncontrollable. More explicitly, the prognosis model introduces two thresholds; $R_{th1}$ that reveals the saturation rate in which the traffic flow starts to face problems and is lower, and $R_{th2}$ which indicates that the traffic flows cannot be managed. The room of the $R$ values between $R_{th1}$ and $R_{th2}$ discloses the need for taking precautionary measures in order to avoid unhandled traffic congestion. Furthermore, it is important to be mentioned that both $R$, $R_{th1}$, and $R_{th2}$ are expressed as percentage rates.

Finally, some other conditions that can be considered are the growth of the population since it affects the traffic level substantially as well as the weather conditions that change the speed of the drivers and increase the risk of road accidents' occurrence. To include the impact of the above factors on the transportation flows forecasted in the prognosis model, some parameters have to be inserted in the model's formula; $f_{\text{growth}}$ and $f_{\text{weather}}$. These factors can be calculated by transportation statistics of the road conditions in the examined road network and/or other effective research methods and be expressed as percentages.

Since the research of the aforementioned factors is not in the scope of this thesis, only the mathematical formula including these factors is given and Figure 4.3 displays the external Microsoft excel in which the weather factor and the population's growth factor are filled in.



| I | J |
|---|---|
| Weather Factor | Population Growth |
| 1 | 1 |

Figure 4.3: Screenshot from the external Excel file with the excel sheet named "Factors" where the user can insert the values of $f_{\text{growth}}$ and $f_{\text{weather}}$

The reason for including the abovementioned factors in the mathematical formula of the model is for designing a more detailed model that can also concern the population growth and the weather conditions in case these statistical finding are available to the user.

More specifically, the formula in this case is altered as follows:

$$R = \frac{f\text{weather} \times [(f\text{growth} \times l) + \sum_{i=1}^{3}(w_i \times v_i)]}{c}$$

where,

$R$ is the saturation rate that represents the traffic conditions of the examined road, $0 \leq R \leq 1$,

$l$, $w_i$, $v_i$, and $c$ are the input variables that are described in Section 4.3.1,

$f_{\text{growth}}$ is the population growth rate, and

$f_{\text{weather}}$ is weather impact on transportation flows expressed as rate.

It is apparent that the values of $f_{\text{growth}}$ and $f_{\text{weather}}$ can affect the traffic condition of the examined road. Nonetheless, the extent to which the population growth and the weather condition affect the traffic movements is proposed for future study (Section 7.3).

### 4.4.3 Output of the model

The output of the prognosis model is the saturation rate $R$ for the whole lifetime of the construction project. In particular, the saturation rate is calculated by the prognosis model for all the working hours of every working day over the lifetime of the construction project.

The Matlab code calculates and represents $R$ values in a graph where the x-axis is the number of working days divided by every hour during the lifetime of the construction project and y axis is the relevant saturation rate. Moreover, *three scenarios based on the three different construction methods are represented to compare their impact on the specific road*. The graphical representations also include the $R_{th1}$ and $R_{th2}$ value as well as the $R$ value.

In this way of the model's design, the prognosis model is capable of the following uses:

1) *The user can calculate the percentage of transportation volumes' increase due to construction traffic*. Since the graphical representations of the prognosis model show the saturation rate $R$ of the examined road without additional needed vehicles for the realization of the construction activities, a comparison can be achieved between the traffic conditions with and without the implementation of the project's construction process.

2) *The user gains insight into when and if precautionary or immediate measures need to be taken so as the traffic flows to be controllable*. More specifically, the user of the prognosis model can compare the traffic volumes related to different construction methods and understand if the construction process causes unwanted traffic conditions on the road that leads to the location of the construction project.

3) *The user can verify the impact of the selected construction methods on the road of the urban area in terms of additional traffic loads*. On this ground, another comparison can be made between the project's construction method taking into consideration the aspect of its transportation usage. The graphical representations reveal the construction process's impact on the traffic conditions in the road network related to the construction project's location and particularly toward the construction site of the project. Consequently, effective communication can be achieved on the ground of the most suitable construction method regarding the aforementioned effect.

Aside from the adaptability of the prognosis model regarding prediction in different defined roads that lead to the construction site, it should be mentioned that the use of the prognosis model is determined by its user. In particular, the users can be contractors, regulatory bodies such as municipalities, or logistic managers. Therefore, the prognosis model offers the opportunity for the fulfillment of each potential user's needs.

As is often the case when discussing fully functioning road networks in urban cities, municipalities have a strong interest since they are responsible for livable cities and citizens' quality of life. It has already been stated that *the prognosis model of this study can be used as a tool for proactive monitoring of the vehicles' movement along the construction process*. By knowing the potential problems of the defined road related to the transportation of materials and laborers' commuting, an effective strategy can be followed, and proper precautionary measures can be taken for managing properly the transportation flows of the examined road. For example, another day can be designated for the transportation of materials or another time slot so as possible delays to be avoided not only in construction activities but also in citizens' transportation movement. Moreover, since this model examines specifically the traffic movements associated with the construction activity, municipalities can gain a better insight into the most suitable construction method for the implementation of the construction project that generates fewer transportation movements. In this way, *the model can also be a means of persuasion by municipalities to the relevant contractors* when communicating along their collaboration.

Referring to a construction project, contractors are the most common and also powerful stakeholders that can influence the whole process in every construction phase. All the contractors that are responsible for construction projects located in public spaces have to deal with public authorities. In many cases, there is ground for conflict between these two stakeholders because their perspective differs. The contractors are mostly concerned about fewer changes in their planning and cost-effective implementation of the construction project while municipalities care about the public good and a smooth realization of the construction project on their land even by taking decisions that will delay or end the construction process. Thus, *the model can be used for contractors so as to achieve fewer future alterations in their planning* by being acquainted about probably delays in the building materials' transportation. Additionally, from the contractors' point of view, *the designed prognosis model can be utilized for convincing regulatory bodies* *that the construction project does not disturb the local living conditions* as well as the municipalities' reputation since future difficulties in transportation can be predicted and subsequently avoided.

Aiming to plan and organize building materials' and equipment's transportation as well as the arrival and departure time of the human force on the construction site, logistics managers can also take advantage of this prognosis model. *The prognosis model can be used as an indicator concerning the optimal time slots for the delivery of materials and equipment*. In this way, the logistics managers can define and outline the requirements that they have for the suppliers. Also, the logistic managers can use the model so as to check out the influence of their work in advance and have a generally satisfactory performance of the construction process.

At this point, it is worth mentioning that the prognosis model of this study aims to be a *generalized useful tool* for an efficient construction process and a well-functioning road that leads to the construction site. The examined road is a part of the local road network of the urban area; thus it can affect the whole road network of this urban area. Overall, concerning the above-referred model's benefits, it is understood that this model can be used for different reasons by each stakeholder but has a generally positive impact due to the model's main objective (the avoidance of traffic congestion) on the needs of the drivers, the inhabitants of the urban area, the laborers, and the general public. As a result, it is beneficial to all the involved parties, however, for different reasons. Additionally, *the prognosis model is an advantageous tool since it improves communication between the interested stakeholders with proven results regarding the construction project's impact on the traffic flows of the examined road*.

The output of the model is basically the model's results that are demonstrated through graphical representations. Every graph that is considered as output has different insightful results. An explanation of every graphical representation and its contribution to achieving the objective of the prognosis model is given for comprehending the prognosis model's output.

Firstly, with regard to the three construction methods, the first graph which is given below (Figure 4.4) represents the saturation rate $R$ for the working hours along the realization of the construction project. The legend of the graph displays its components according to the prognosis model's design.

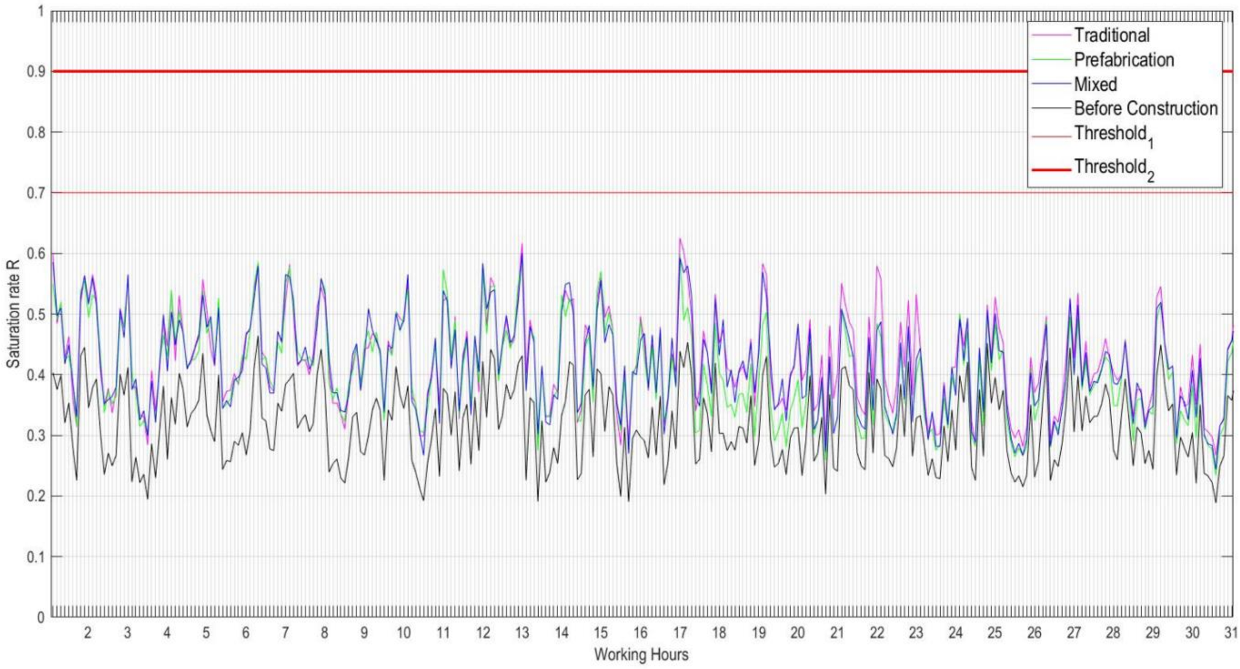



Figure 4.4: Saturation rate $R$ per working hours over the lifetime of the construction project for three different scenarios

This graph informs about the traffic movements of the examined road for every working hour and therefore indicates the exact time periods where the transportation of the building materials and required equipment will be possibly problematic and congested. In addition, a comparison of the traffic loads generated by the three selected construction methods can be made in order to determine which construction type is preferable from the perspective of transportation movement. Lastly, a conclusion can be made on the number of transportation volumes that are added to the current transportation volumes of the examined road.

In order to achieve a better understanding, an example based on random data is explained.

In the example's graph, the first working hour of the second day of the construction process has the following values:

$Y_1 = 0.2452$, where $Y_1 = R$ before construction

$Y_2 = 0.2764$, where $Y_2 = R$ related to traditional construction method

Thus, the calculated growth rate is:

$$\frac{Y_2 - Y_1}{Y_1} \times 100\% = \frac{0.2764 - 0.2452}{0.2452} \times 100\% \cong 12.74\%$$

This means that if the traditional construction method is selected, the traffic flows in the examined road network will be increased by 12.74% during the implementation of the construction project.

Secondly, the maximum $R$ value of each day is used to create the second plot (Figure 4.5) that shows the peak saturation rate per day over the lifetime of the construction project.

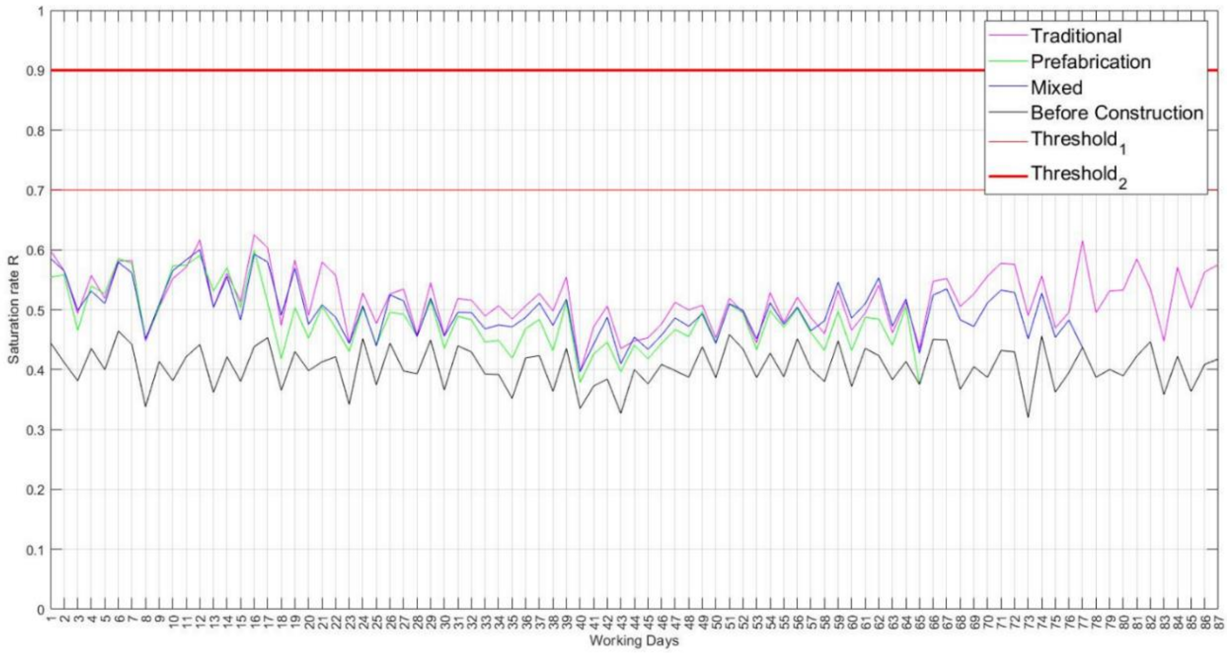



Figure 4.5: Peak daily saturation rate $R$ over the lifetime (working days) of the construction project for three different scenarios

This graphical representation is useful for the user of the model because reveals the most traffic congested hour of the working day. Hence, the conclusion is made easier and faster due to a clearly legible diagram. The peak saturation rate R of every working day of the project demonstrates the worst-case scenario which is an indicator of whether or not necessary measures ought to be taken. In this way, the needed information about the most congested working days as well as the most congested working hours is provided by the above presented graph.

Furthermore, the average $R$ value of each day is plotted in the third graph (Figure 4.6).

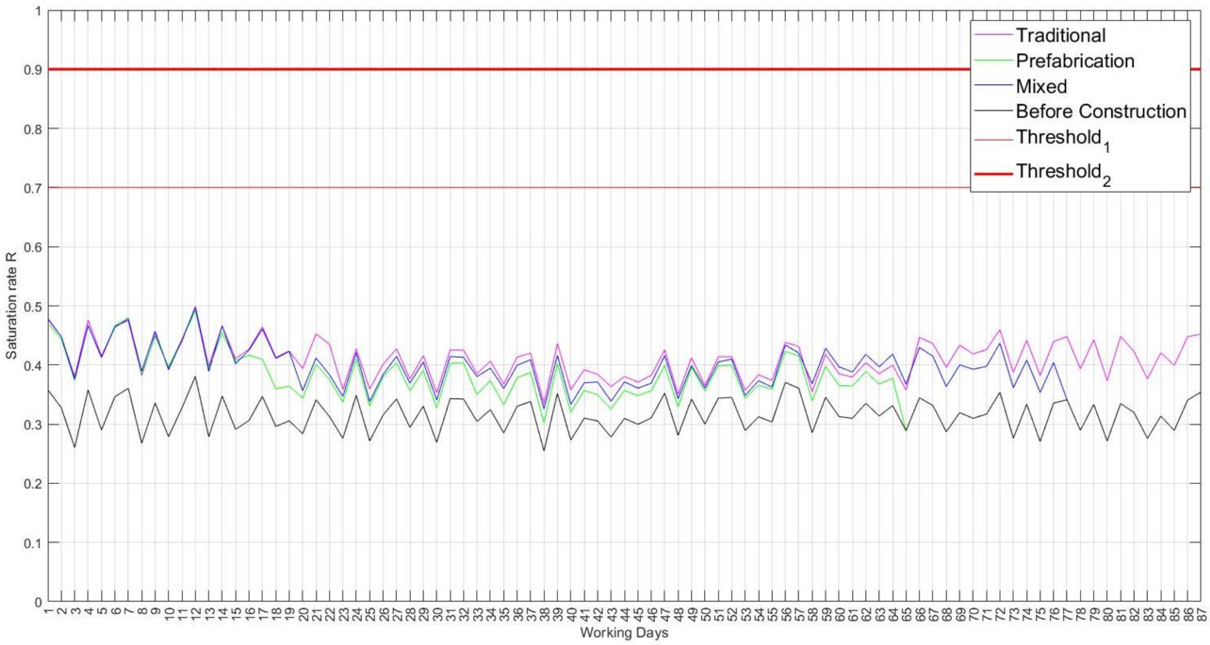



Figure 4.6: Average daily saturation rate $R$ over the lifetime (working days) of the construction project for 3 different scenarios

From the graph demonstrated in Figure 4.6, insight is gained into how smoothly the traffic loads are produced (the rate at which are produced) during the lifetime of the construction project. Moreover, a comparison can be made between the number of traffic loads that are produced during the different construction phases. The abovementioned results can stand as an indicator of the impact of the construction project, in correlation with its construction method, on the explored road.

Finally, a comparison with the $R_{th}$ values is a common point in all the graphical representations. Specifically, every graph shows what are the desirable and undesirable transportation movements by using as a reference the defined $R_{th}$ value. More explicitly, this comparison can lead to the following two cases:

1) If $R_{th2} > R$, then $R_{th2}$ - $R$ =$R_1$ where $R_1$ represents how much the value $R$ has room for increase until an uncontrollable level of traffic congestion appears.

2) If $R_{th2} < R$, then $R_{th2}$ - $R$ =$R_2$ where $R_2$ represents how much the value $R$ must be decreased for reaching a controllable traffic level.

Likewise, by summing the $R$ values of two construction methods, the question "what if two construction projects were implemented in parallel with the chosen construction methods?" could be answered. Hence, *not only a comparison in terms of traffic loads between the different construction methods for the implementation of the construction project can be achieved, but* *also an insight into the traffic conditions in the examined road during the construction process of two similar construction projects that will be constructed by different construction methods.*

Concerning what the model is capable of and designing a generic model, the prognosis model of this study offers multiple functions and can be adjusted according to the data's availability and the purpose that the model has to serve. At this point, it is worthy to remind that one of the model's requirements is its flexibility,

For a comprehensive overview of the aforementioned processes of the model's development, a flowchart (Figure 4.7) that demonstrates the flow of the data within the proposed prognosis model is displayed below. In particular, Figure 4.7 depicts the rational thinking and the followed process for connecting the external Excel file with the Matlab file. Following the system thinking that Figure 4.7 shows, the prognosis model's Matlab code is developed. The Matlab code is given in Appendix B.

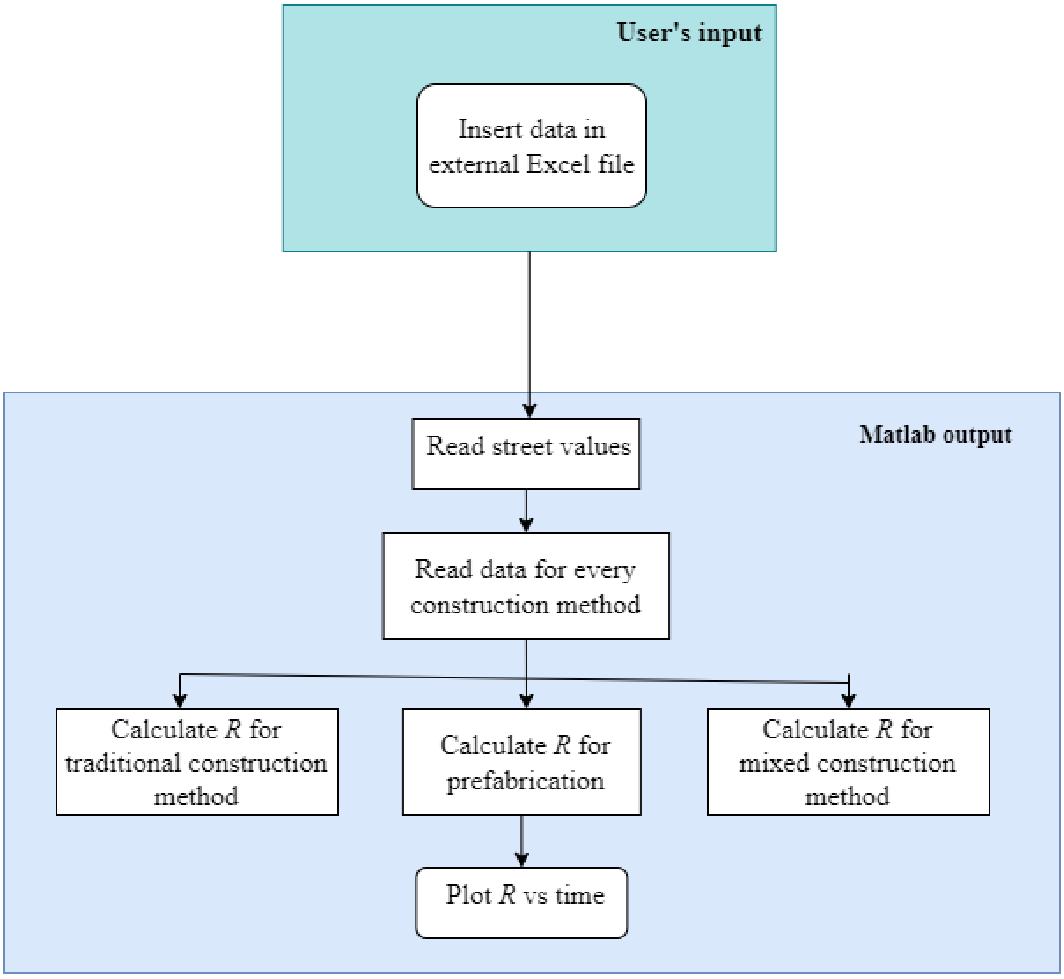



Figure 4.7: Data flowchart of the prognosis model

## 4.4 Conclusion & contribution of Chapter 4

This chapter targeted designing the prognosis model. The design steps were described, and the model's core elements were explained. In particular, the requirements of the model have been defined as well as the needed assumptions that assisted the model's design. Also, the core elements for the design of the prognosis model which are the input variables, the formula, and the output of the model were described and interpreted. In addition, the function of the model was explained by the use of an external Excel file connected with a Matlab file. Aiming to achieve a reliable and approximate forecast even in cases where there is a lack of specific data, a factor related to the construction method and the construction phase of the project can be introduced. Chapter 5 provides a thorough explanation about the aforementioned case.

The outcome of this chapter is the design of the prognosis model. A better understanding of the output of the prognosis model is achieved through graphical representations produced by using Matlab software. Additionally, every graph satisfies different objectives and serves the potential user's needs in another way. However, all the graphical representations uncover the additional transportation volumes of the three different construction methods so as the construction methods to be compared and their impact on the examined road to be discovered.

Moreover, since the potential users of this prognosis model are stakeholders with various points of view, the needs of each potential user that can be satisfied by this model were listed in Chapter 4. In this way, the usability of the model was underlined.

Finally, the flexibility of this simulation model as a predictive tool is outlined since the designed prognosis model can be adjusted in different cases (different examined roads) because introduces some road values as input variables.

At this point, it is worth mentioning that this chapter also explained thoroughly the design and development process of the prognosis model regarding the data's flow.

More precisely, the first step of the prognosis model's design process was to determine the requirements that this model aims to fulfill. Since the design and development of the model ought to be feasible during the limited time frame for the accomplishment of this study, it was crucial to point out some rational and simplified assumptions on the ground of the extrapolation type of modeling. To encapsulate, the above-described steps was the initial part of the decision-making process for the model's design.

On the ground of the relevant literature review, the main variables of the model were identified. In addition, the derived results from the semi-structured interviews with regard to what can and what cannot be modeled disclosed more clearly the prognosis model's input variables, the parameters that have to be considered, the mathematical formula and the output of the model. This decision was also made taking into consideration the data's availability for evaluating the designed model, but mostly its "fit for purpose" as a proactive tool for providing a broad view of the examined road's condition and improving the communication of the responsible stakeholders on the matter of construction traffic. As a result, it was assessed if the selection of the designed model's components satisfies the model's predefined requirements.

Establishing from the beginning the user-friendliness and the usability of the prognosis model of this study as important parts of the model's friendliness, the external Microsoft excel file was created and then examined based on the user's needs. Subsequently, using the Matlab software, the proper coding was implemented in order to produce the required output of the model through the graphical representations. At this point in the design and development of the prognosis model's process, the final graphs were evaluated. More thoroughly, it was checked if the graphical representations are informative enough as well as readable. In practice, the graphical representations' ability for providing better comprehension to the user about the outcome of the prognosis model.

For better comprehension, a flowchart that outlines the entire way of thinking about the design of the prognosis model of this study is presented in Figure 4.8.

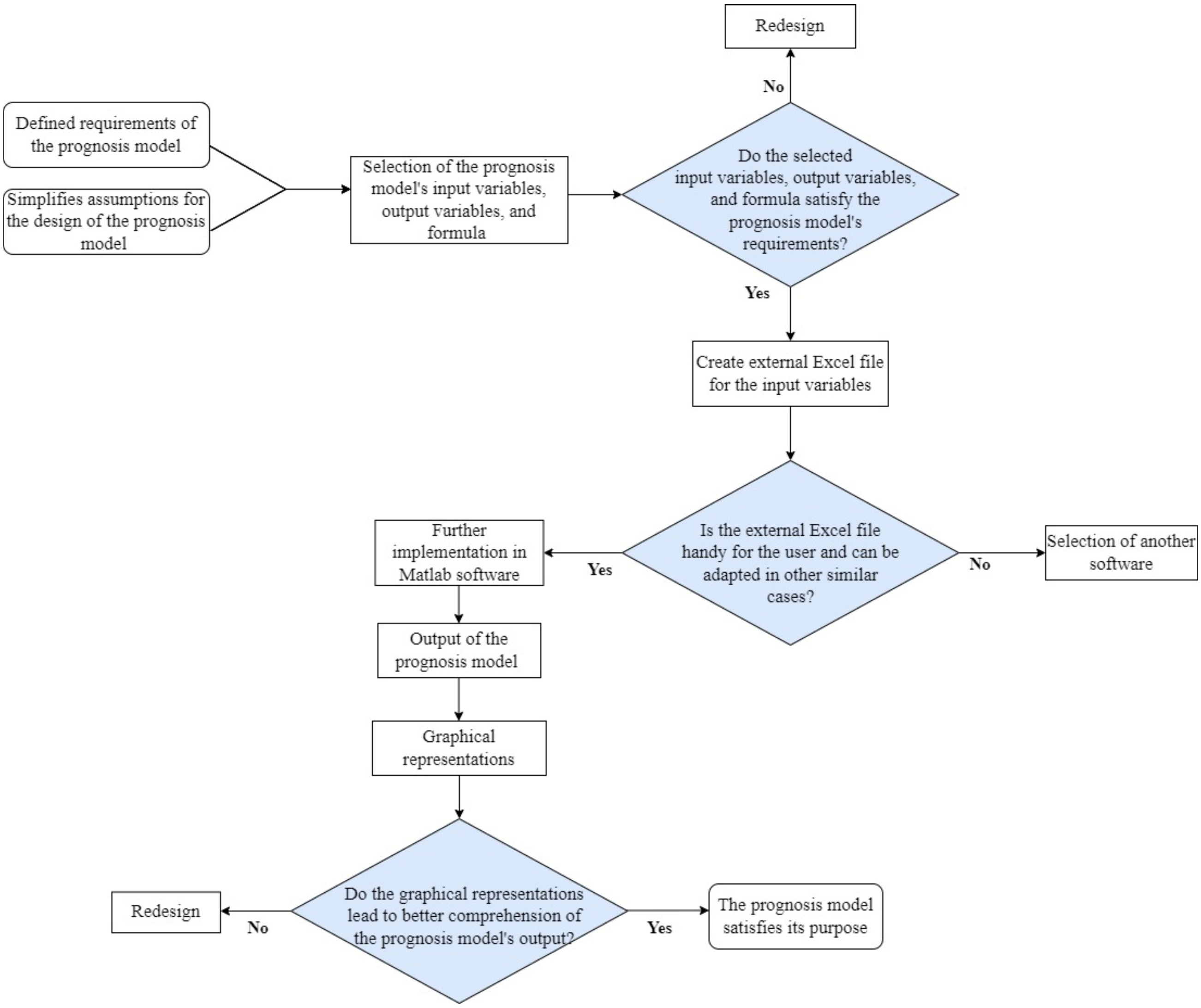



Figure 4.8: Flowchart of the prognosis model's design process

# Chapter 5

## Case study

*In this chapter, the case study is presented. The validation of the prognosis model of this study is carried out based on this chapter's described case study. The selection criteria for the chosen case are given in Section 5.1. In Section 5.2, general information about the project is given, and a more detailed explanation is provided from its subsections so as to achieve a better comprehension of the selected case study. Lastly, Section 5.3 elaborates on the data selection which is the important predecessor of the prognosis model's evaluation.*

### 5.1 Project selection

The project selection was grounded on the following main criteria:

1) The case should be a construction project, as this type of construction project is within the field of interest for the researcher and the public actor (Gemeente Amsterdam).

2) The case should bear characteristics in order to be suitable for validation of the prognosis model of this study.

3) The case should have a high degree of complexity and the impact of the designed prognosis model on the research field of this study has to have practical and academic value.

4) Access to project participants.

The selected case will function as a way to validate the designed prognosis model. In other words, the extent to which the prognosis model could potentially forecast the additional transportation movements generated by the construction process will be determined based on the chosen case. The selected project should have characteristics that are compatible with the purpose of the model. Moreover, since one of this model's goals is to improve the possible public discomfort by proactively acknowledging the occurrence of traffic congestion, the project should also be located in a complex urban area.

Likewise, since this study is realized in collaboration with Gemeente Amsterdam, the exploratory interviews for the final selection of this case study were conducted with experts from Gemeente Amsterdam. After the completion of the exploratory interviews, the proper project was determined which has all the above-mentioned appropriate characteristics. As previously stated, the exploratory interviews aimed to select a suitable project for the validation (both for quantitative and ex-ante evaluation) of the prognosis model while also establishing the context of this thesis. All the interviewees grounded their responses on the same project recognizing the difficulty that this project has regarding the availability of data. Therefore, since the process of data collection was challenging but is not the main objective of this thesis, was decided that is more important to choose a case that fulfills the listed selection criteria rather than a case with totally reliable and known data. The procedure of the data collection is thoroughly explained in Section 5.3.

The selected project is of great importance to Gemeente Amsterdam and is situated in a densely populated district of Amsterdam. Furthermore, this project is a joint venture of different construction companies and Gemeente Amsterdam. Apparently, the selected project constitutes a project that implies a multi-faceted challenge mostly for Gemeente Amsterdam but only for the involved contractors.

As a result, it can be argued that this project exhibits features that indicate an appropriate case so as to validate the designed prognosis model. However, the purpose of this study is to provide a generic prognosis model for traffic movements related to different construction methods. Therefore, the selected case involves different construction methods and appears similar to other potential cases in which the prognosis model can be used.

The needed information about the chosen case as well as a detailed description of its general and particular characteristics is mentioned in the following section.

## 5.2 Information about the project

The selected construction project concerns high-rise construction buildings that are part of the "Eleven Square" project. Eleven square aims to contribute to a wider transformation of ArenAPoort in Amsterdam. This development has a favorable effect and is beneficial to both the immediate surroundings and the area itself: the whole of Amsterdam including Amsterdam-Zuidoost. Also, this project is an area of 2.5 hectares that targets providing daily and living facilities and thus the urban dynamics of this area are strengthened. This construction project includes an addition of several hundred residences to assist the high demand for housing that Amsterdam faces at the moment. Figure A.1 (Appendix A) is an illustration of this construction project providing a visual comprehension of the final artifact.

Concerning the importance of this construction project from a process management point of view, Eleven Square is not only interesting because of its large scale and complex urban environment but also for the several involved stakeholders. More specifically, this project is a partnership between two construction companies; Ballast Nedam Development and AM Development. Eleven Square is also a development of OMC (Operation, Maintenance, and Construction). Thus, the contractors are not only responsible for the present performance of the construction project since the maintenance of the structural parts and the including systems of this project is their duty according to the contract type.

Finally, Gemeente Amsterdam, as a responsible party for the living conditions of the city of Amsterdam as well as a local authority and governmental body with corresponding power, shows a big interest in this case. Specifically, if this project faces problems during its implementation, there will be negative effects on many sectors of the city such as cost overruns, traffic congestion, safety hazards, etc. These effects trigger unwanted situations both for the realization of the construction project and the preservation of a pleasant way of living. In the context of this thesis, the major issue that needs to be tackled is the increase in traffic congestion during the implementation of a construction project with an emphasis on construction methods. Therefore, since the relative causes and consequences of traffic congestion have already been researched in Chapter 3 based on the relevant literature, this study researches the extra traffic movements that are derived from the three chosen different construction methods. Eleven square project is implemented by the use of different construction methods. The traditional construction method and prefabrication are used as building methods and are combined for some parts of the constructed buildings. More explicitly, one of the buildings is a high-rise structure in which the first floors are implemented by following traditional construction method while the other floor's synthesis leads to a high and totally prefabricated tower. For achieving a better understanding, Figure A.2 depicts the designed buildings after the construction project's completion. Considering the exploratory interviews with the contractors of this project, it was revealed that prefabrication is the preferred construction method for all the involved construction companies due to less cost associated with fewer personnel and thus lower salaries. Another reason for the preference for prefabrication is the lesser need for risk management because of the fewer safety hazards related to the lack of human force on the construction site.

At this point, it is worth mentioning that if the risk of a potential increase of many additional vehicles' movement will not be considered adequately controlled in the location of the construction project, the whole area will be affected as well as the construction project itself. Hence, the operator shall be required to take immediate response measures so as to avoid such damage. Because of the fact that the above case study is a mega project with high complexity level and several functionalities, it is crucial to receive a proactive treatment with suitable controls.

The following subsections analyze the characteristics of the urban area where the construction project is located as well as the examined road network and elaborate more on the construction site's description and the project's transportation needs respectively.

### 5.2.1 Characteristics of the urban area

Eleven Square is located at Amsterdam Bijlmer's center, next to Arena Boulevard. This specific urban area has a high complexity level due to its many different uses.

In particular, this area accommodates train and metro stations by being accessible to the general public. It is widely understood that in order to service inhabitants' needs, public transportation has to be provided in certain locations around the city which have a high need for transportation. Thus, it is apparent that there is a significant transportation need in this area because of its importance to the city and its high population level.

Moreover, this urban area is known as sports and entertainment destination of Amsterdam because of the two vast stadiums that are situated there, Ajax stadium and Ziggo Dome. The capacity of the stadiums evidences the large population in this area when music and sports events happen. Besides all the aforesaid services, the diversity of daily services, such as shopping centers, makes the area lively even outside of the peak hours. Another factor contributing to the area's dense population is the presence of several firms because of the large number of employees that work in these firms. Last but not least, large residential building blocks are also located in this urban area therefore there are many permanent residents that turn this district into a vibrant part of the city not only for cultural reasons.

Taking into account the above-described features, it is clear that a potential malfunction of this area could be disastrous for this district's facilities. To be more explanatory, it is necessary that the urban area will remain accessible in terms of transportation flow. Therefore, using the designed prognosis model as a proactive approach could be useful for this case.

Based on the existing conditions of this complex urban area, the following rational thought is made: there is a strong likelihood of an increase in the traffic congestion of the urban area since additional transportation movements related to construction activities are produced and thus another aggravating factor is added. Hence, this case has room for research and bears many characteristics that make this urban area critical for the protection of the general quality of life in Amsterdam's city.

### 5.2.2 Road network of the construction project's location

Difficulties in the implementation of a construction project are often correlated with the complexity of the location of the construction project. Regarding the characteristics of the case study's urban environment, a throughout explanation has been already cited in the previous subsection. One additional influential factor that must not be neglected is the characteristics of the road network of the examined urban area and especially the road that leads to the construction site. Therefore, the traffic policy of the city in which the project will be constructed sets out the characteristics of the road network which in turn has an impact on the traffic volumes. Since the chosen construction project is located in the city of Amsterdam, the traffic network policy which has been established by Gemeente Amsterdam determines the uses of the critical road network for this case study in terms of traffic flows generated by the construction project (Gemeente Amsterdam Klaas-Bindert de Haan, n.d.).

Formulating a traffic network policy for the city of Amsterdam aims to guarantee high accessibility levels to and in the city and limit the disadvantages of the large traffic flows. On the basis of this effort for providing efficiently functional urban mobility, the municipality of Amsterdam has incorporated in the traffic policy the creation of a hierarchy in the networks to limit the number of situations in which road users interfere with each other. On this ground, the Plus and Main networks are intended to introduce the hierarchy and structure into the complex network of roads and streets in the city. Another positive consequence of the system of Plus and Main networks is that offers road users continuous routes across city boundaries and divides different types of traffic in such a way that the traffic flow is enhanced, without road users getting in each other's way. The aforementioned categorization does not only concern the road network of the city but also the bicycle network as well as the public transport network.

A generic division between Plus and Main networks has been followed by the traffic policy applied in Amsterdam city, where in the Plus network the relevant modality is given; the bicycle, public transport, or car, active priority. With regard to the Main network the focus is more on maintaining sufficient capacity and quality related to functions and characteristics in the network.

More thoroughly, it has been pointed out that an intricate, cohesive network of high-quality, comfortable, contiguous, and safe bicycle routes is an important condition for further growth of bicycle use in Amsterdam where bicycle use has increased considerably in recent years. Therefore, the bicycle network within Amsterdam consists mostly of a coherent and intricate network of safe bicycle paths, bicycle lanes or bicycle streets where the inhabitants can cycle quickly, comfortably, and safely. Incorporating the hierarchy approach into the bicycle network, the traffic policy of Amsterdam city indicates that the Plus bicycle network facilitates a significant connection between city districts and with the regional bicycle routes to neighboring municipalities and the green and recreational areas around the city. This is subject to the need for cyclists to flow quickly at intersections and have sufficient space to pass each other. Moreover, a Plus bicycle network provides access to the residential and work areas in Amsterdam and consists of separate bicycle paths. The differences between Main bicycle network compared with Plus bicycle network are about the speed since cycling in plus bicycle networks is faster than the Main ones.

Considering public transport, is widely acknowledged that is a space-efficient and clean form of transport for large flows of people in the city. For the city of Amsterdam, public transport is a crucial factor for mobility due to its densely populated districts and the increasing tourism in the city. By targeting to keep city accessible to residents and visitors and concerning a potential future growth on this field, the improvement of public transport has been considered extremely important. For this reason, Gemeente Asmterdam as a road manager and manager of the local rail infrastructure is jointly responsible for the quality of the urban public transport network and thus the policy Plus and Main public network is followed. The Plus and the main public network differ because the Plus network provides fast and reliable routes in and through the city of Amsterdam while the Main network ensures reliable routes only through the city.

Since Amsterdam city's social and economic functioning is influenced by the performance of its road network, preserving an acceptable accessibility level for vehicles seems to be a necessity. Gemmente Amsterdam has identified that the accessibility of urban areas is maintained by concentrating car traffic as much as possible on a limited number of roads with good throughput quality. The Plus and the Main road network contribute to the separation of traffic and residential functions and promote road safety. It has been noticed that the better the traffic flow on the Plus and the Main road network is, the quieter the other roads are. In this way, traffic flows are not only handled effectively during the day or during regular peak periods, but also traffic congestion can be controlled in situations where parts of the road network are not available or when there is extra traffic due to events on the event locations in a district. Consequently, by following the hierarchical typification of the road network it is concluded that traffic movements can be managed more easily, and the goal of sustainable traffic safety can be achieved. More precisely, the Plus road network contains the main routes for freight transport, consists of roads with few other functions, and forms a closed network. In contrast, there is slightly lower traffic intensity in the Main road network in comparison with the roads of the Plus network. Likewise, the Main network is aimed at maintaining capacity and throughput quality appropriate to the function of the relevant part of the network.

All the above-mentioned characteristics are included in the traffic model VMA (Traffic Model Amsterdam) that Traffic and Public Space (V&OR) of the Municipality of Amsterdam uses for its traffic calculations. The VMA is an urban traffic model for the city of Amsterdam for strategic road and public transport studies. The basis for the model consists of research data from traffic surveys, traffic counts, characteristics of the road and public transport network and knowledge about spatial planning in terms of the number of inhabitants and jobs. These data are known for the past and the present, and estimations are used for future situations. An illustration of VMA model that depicts the type of networks in the researched area is given.

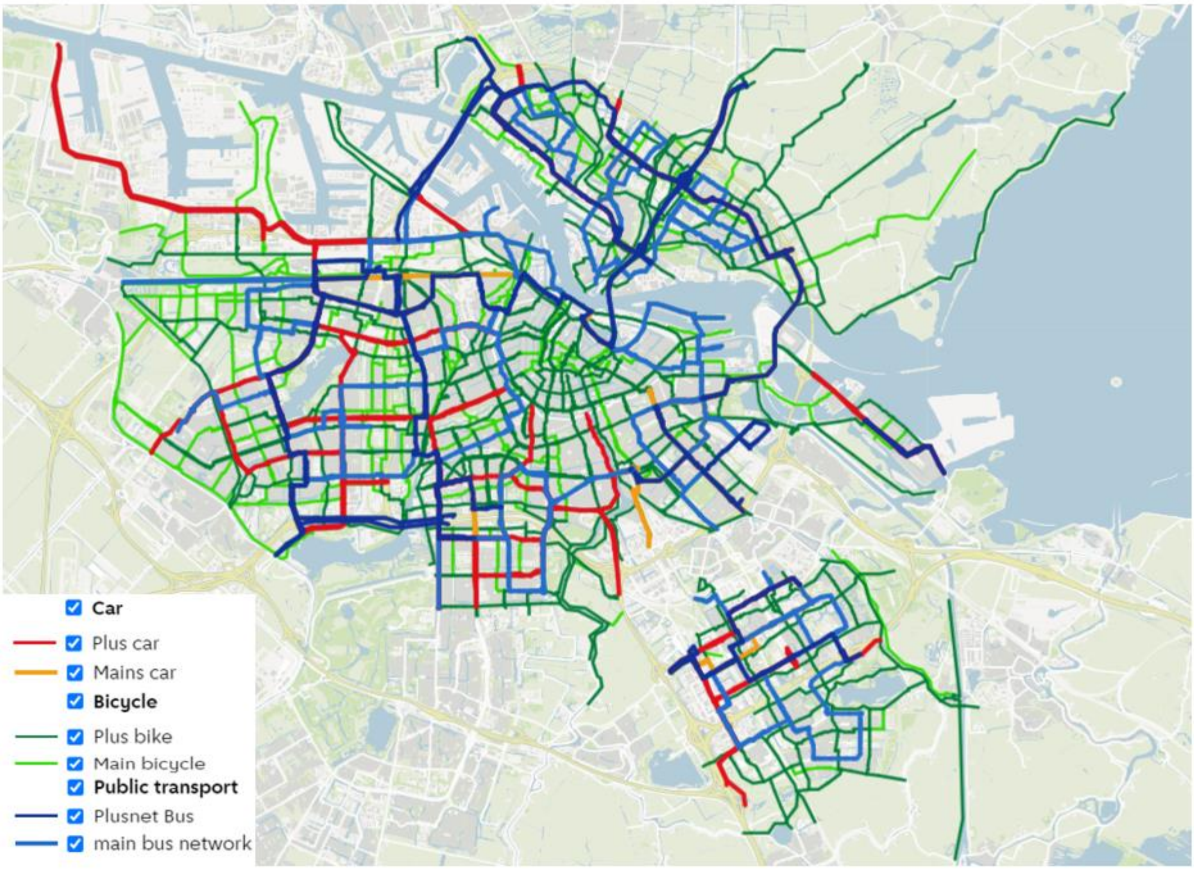



Figure 5.1: Cartographic representation of Plus and Main networks of the city of Amsterdam (Gemeente Amsterdam Klaas-Bindert de Haan, n.d.)

After explaining the traffic policy of Amsterdam city, the identification of the relevant road network related to this construction project las to be made as well as its categorization either as a plus or main network. In particular, the road that leads to the construction site is important due to its functionality as a connection between the location of the construction project and the external environment so as the building materials to be transported on site. In case these roads appear to have a high level of traffic congestion that cannot be managed in the required time period, delays will take place having a negative impact on the district's transportation flows and being an impediment to building materials' transportation that is vital for the construction process. In the case study of Eleven Square project this road is De Entrée. Regarding the traffic policy network, the fact that De Entrée has the use of Main road network indicates the provision of a robust capacity and fewer traffic flows compared to plus road networks.

Having an appreciable effect on the transportation volumes of De entrée street, Holterbergweg street has to be examined. The cause for taking into consideration Holterbergweg street's characteristics is that a countable number of vehicles that travels through Holterberweg street turn into De entrée street contributing to the traffic loads of the road that gives access to the construction site of the project. According to Amsterdam's city traffic policy, Hotterbergweg road is a plus network for bicycles, public transport and vehicles, and this is compelling proof of the large number of traffic loads on this road.

The following table summates the categories of the roads that need to be examined in accordance with the Traffic Policy of Gemeente Amsterdam.

Table 5.1: Holterbergweg and De Entee street based on Traffic Networks Policy for the city of Amsterdam

| **Categorization according to Traffic Networks Policy** | **Examined roads (junction)** | |
|---|---|---|
| | Holterbergweg | De entree |
| Plus road network | ✓ | - |
| Main road network | - | ✓ |
| Plus public transport network | ✓ | - |
| Main public transport network | - | - |
| Plus bicycle network | ✓ | - |
| Main bicycle network | - | - |

Finally, it is worth mentioning that the capacity value (the input variable c), which is inserted in the prognosis model for forecasting the traffic volumes produced by different construction methods along the construction process of Eleven Square project, is specified by the shaped junction of the two mentioned. The reason for introducing the capacity of the junction as the capacity of the examined road is to predict the transportation movements of the road in the worst-case scenario. A more detailed explanation of the capacity value is stated in subsection 4.4.1.

In order to comprehend better the critical road network, an illustration of the road network that leads to the construction site is demonstrated below with emphasizing on the relevant areas.

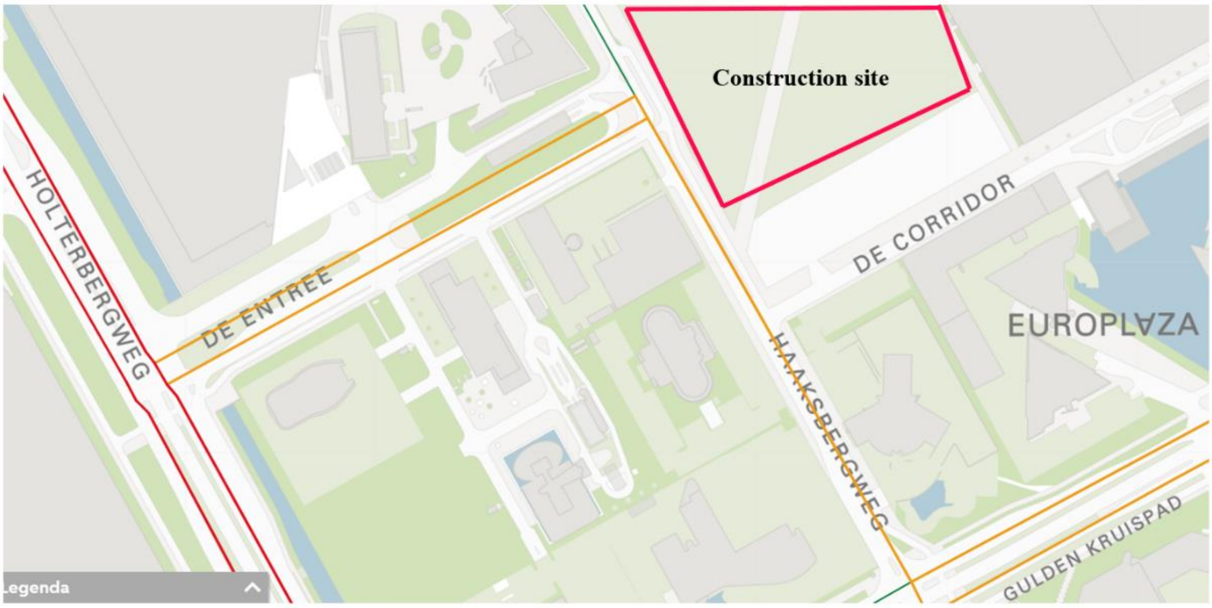



Figure 5.2: Cartographic representation of the construction site's location and the critical road network (Gemeente Amsterdam Klaas-Bindert de Haan, n.d.)

### 5.2.3 Description of the construction site & transportation needs

As is already explained, Eleven Square project includes three high-rise buildings with many utilities. Concerning the large volume of these structures, it is concluded that there is a high demand for building materials for this project. By acknowledging the considerable needed construction materials quantities, the derived conclusion is that many vehicles are needed for the transportation of the referred quantities. Also, for this large project to be efficiently constructed and by taking into consideration its nature as a time-driven and quality-driven project, possible delays have to be averted and the correct amount of building materials has to arrive on the construction site on time and without any damages. Therefore, in terms of a construction logistics point of view, this project is challenging because the transport flows have to be controlled in order to avoid difficulties in the implementation of construction activities and also the building materials' and personnel's transportation.

Furthermore, this project employs many laborers from different enterprises that have to be commuted to their workspace which is mainly the construction site. For the personnel's commuting specific roads are selected from Gemeente Amsterdam and assigned to the contractors as the only accessible routes for their employed laborers. This regulation was decided to be followed for the entrance and the egress gate towards the construction site and back to remain accessible for trucks and cranes that are used only for construction activities. Attempting to retain access to the above-mentioned road, some specific parking areas were chosen for the private vehicles of the employees of this construction project by Gemeente Amsterdam. Thus, the municipality endeavors to take efficient precautionary measures such as the specifically selected parking areas in order the traffic congestion on the road network of the urban area, in which the Eleven Square project is located, to be avoided.

Another important factor that has to be concerned is the transportation needs of the general public such as those of the local residents, the cyclists, and the construction personnel of the ArenAPoort area. The general public frequently arrives to work by driving private vehicles. Furthermore, this area has bicycle lanes, and many residents are used to cycling in this area. Also, the transportation movements inside the district have to be manageable because the public can be harmed by the atmospheric pollution from gas emissions and noise nuisance. As a result, potential resulting traffic congestion effects can impact adversely the public good.

Lastly, based on the general facilities of this urban area, the two worldwide known stadiums of Amsterdam's city furnish another compelling reason for a big need for fulfillment of transportation needs.

To sum up, considering the more thorough explanation of all the factors related to the transportation flows of this chosen case, the transportation needs of the construction project's location are several and undesirable traffic congestion will be harmful in various sectors. This statement was also affirmed by the interviewees that were the project managers of the companies responsible for the Eleven Square project. These interviews were conducted with "key" people (Mr. Richard de Jong who is the project manager of this project from Ballast Nedam, and Mr. Leon Prins who is the contractor of AM Development) of the project targeting to gain better insight into all the essential aspects of the project so as to achieve a better understanding of the issues that are part of the thesis scope. In particular, limited traffic congestion is a necessity for construction companies because possible delays in the transportation of the construction materials can cause an overall delay in the construction process and this is correlated with cost overruns.

Gemeente Amsterdam as the responsible municipal body for Amsterdam city is a lot more interested in preventing or reducing uncontrollable traffic flows due to the negative impact on the resident's life and the functionality level of the transportation network of this area and its surroundings. The aforementioned issue at stake is not purely financial for Gemeente Amsterdam but it is also a matter of principle based on its nature as a governmental body. In addition, the municipality's reputation can be easily damaged in case of adverse living conditions in ArenAPoort area.

By addressing the transportation needs of the location of the construction project, one can see the great importance of preserving an accessible road that leads to the construction site. Also, Traffic Network Policy of Gemeente Amsterdam which has been analyzed in the previous subsection, reveals the high transportation needs that the area of the construction project has to satisfy because of the categorization that has been chosen for this road network. Hence, retaining the accessibility of this road network is significant and this is also introduced as one of this thesis prognosis model's requirements.

More precisely with regard to the construction site's description, the construction site that is accessible through De Entrée Street can accommodate suitable and special equipment for the construction activities. On the construction site, not only the equipment for construction implementation is accommodated but also temporary offices are located on site only for facilitating the construction process because of laborers' immediate entrance and better ability for sufficient inspection on the construction site. Likewise, a better accessibility level on the construction site results in fewer safety hazards for the laborer and this is another essential reason for the use of these offices. Despite the large area of the construction site, not all the vehicles that transport the construction materials can remain inside the site. The condition of not remaining all the trucks and cranes for materials' transportation on the construction site would not only be inconvenient for the laborers in order to implement the construction activities correctly but would also have a negative impact on the project's planning in case of wanted optimization on desired time for the construction project's completion. The cause of this negative effect is the higher vehicle's remaining time on the construction site than is actually required for a time-driven construction project.

To conclude, with regard to the construction site's characteristics it is acknowledged that the construction site of Eleven Square project has to assist the construction activities by accommodating the proper equipment and following all the safety regulations. All the construction project's transportation needs, which are many considering the large scale of this project, have to be satisfied. Hence, the existence of traffic congestion to a problematic and uncontrollable extent can be disastrous for the project. Therefore, the designed prognosis model of this study can be validated with this construction project since it faces some potential issues that can be tackled by the use of this model.

## 5.3 Observed & estimated data

As per the discussions with the Project Manager of the case, who serves the interests of the municipality of Amsterdam, and the experts of Logistics and Transportation Department with whom the exploratory interviews for the selection of the case study were conducted, gathering data was a very challenging and difficult part in terms of data's availability and reliability. It has already been mentioned that Eleven Square is a construction project currently in progress and as a result, this does not ensure a high degree of precision for the numerical data. Moreover, as it has already been mentioned in Chapter 4, such data about transportation movements during the implementation of a construction project are not gathered regularly. However, reliable estimations are chosen as the strategy for dealing with the issue of not being totally aware of the relevant data.

In order to validate the prognosis model of this study, the selected input variables rely on known values for this construction project or other construction projects that appear considerable resemblance in their characteristics with those of the chosen construction project. Another way of gathering data is by making estimations based on partly known data, following rational thinking, and conducting consultation interviews and informative meetings with experts targeting to acknowledge accurate approximations for these values.

The first input variable that needs to be identified so as to be inserted in the external Microsoft excel file of the model, is the transportation loads of the examined road before the realization of any construction activity. According to the statistical records of Gemeente Amsterdam in the context of "Amsterdam's thermometer model", which uses the practical GIS method with information about the city's transportation logistics, the transportation loads of De Entree Street have been determined divided into three-time periods; daytime from 07:00-20:00, evening from 20:00-00:00, and night from 00:00-07:00. Regarding the vehicle type that produces transportation volumes, Gemeente Amsterdam classifies traffic loads into three categories; light, medium and heavy loads. In the researched case, the traffic loads that were selected to be inserted as input variable *l* are a summation of all the three aforementioned categories referred to the daytime.

More explicitly, the unit of measurement for the transportation loads which is the Average Weekday Daily Traffic, abbreviated as AWDT, has been calculated by Gemeente Amsterdam for the road network of the city of Amsterdam. As a final step, the average transportation loads per hour have been valued for all the periods of time and the vehicles' types (Gemeente Amsterdam Klaas-Bindert de Haan, n.d.-b). On this ground, the numerical data for the transportation loads of De Entrée Street without the implementation of the construction project are provided and the measurement unit is PCE/h. Another important point is that the vehicles' type has already been classified in this model having as a reference type of vehicle the passenger car.

In this context, the light, medium and heavy loads of De Entrée Street that are used for predicting the traffic congestion of this road by also taking into consideration the additional traffic loads generated by construction activities in relation to different construction methods, are introduced in the prognosis model. Thus, the *l* values that are used for this case study are known and highlighted in the following image.

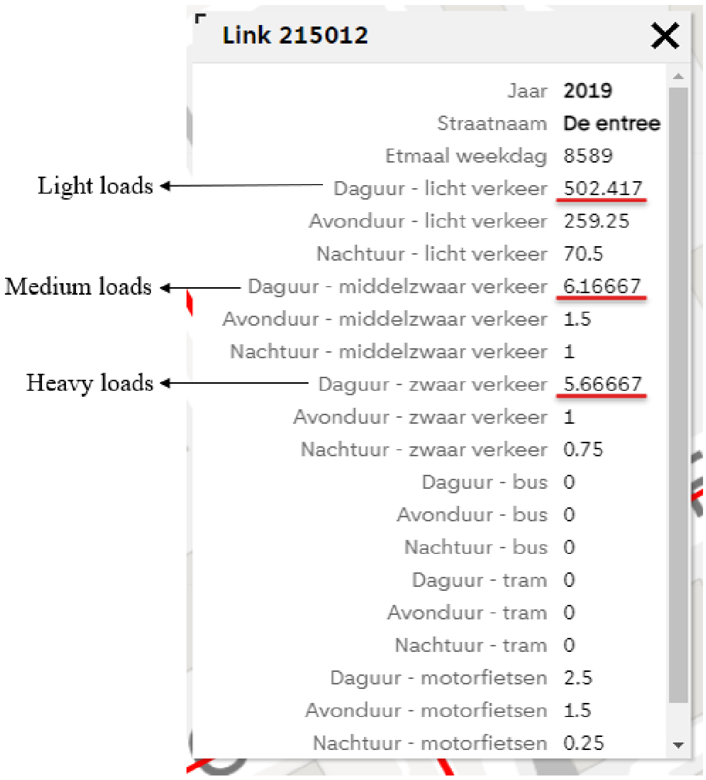



Figure 5.3: Values of the input variable l for the Eleven Square project (Gemeente Amsterdam Klaas-Bindert de Haan, n.d.-b)

On the busiest days of the week as well as the peak hours of the day, the transportation loads increase. Hence, due to this condition, the transportation volumes need to be differentiated by correction factors. According to the experts of Gemmente Amsterdam and the traffic numerical data of other urban areas with similar characteristics, the percentage increase of the traffic level during the morning peak hours (07:00-10:00) and the afternoon peak hours (14:00-18:00) is 18,3% and 18,8% respectively. In this designed prognosis model the peak hours are concerned from 07:00 -10:00 and from 14:00-17:00. An hourly traffic distribution is made based on these percentages and thus the input variable $l$ is increased. The aforementioned distribution in this case study has been made approximately based on the interviews' findings. Likewise, for the city of Amsterdam the days with the highest transportation needs are Tuesdays and Thursdays because the majority of the city's population works in person and not hybrid. High demand for transportation is also met on Fridays since there are many transportation movements after the end of the last working day of the week and also tourism is usually increased closer to the weekend in Amsterdam. For these reasons, a rise of 15% in traffic volumes is considered on Tuesdays, Thursdays and Fridays. Finally, since the light, medium and heavy loads of De Entrée Street are given as average values (Gemeente Amsterdam Klaas-Bindert de Haan, n.d.-b), an uncertainty of 5% is concerned in the relevant data.

Regarding the input variable c which refers to the capacity of the street, the capacity of the junction between Holterberweg and De entrée street is chosen. In general, the capacity of a junction with green traffic lights forecasts the traffic conditions of the relevant road in the worst case-scenario. With the aid of the traffic control program "COCON", that is used from the municipality of Amsterdam, the capacity of this intersections is defined. Specifically, the capacity for the direction Holtervergweg-De Entrée is 1700 vehicles per hour per lane.

In order to estimate the transportation movements derived from the construction process as precisely as possible, the three main transportation needs during the construction project are examined separately. Particularly, these transportation needs are the transportation of the construction materials regarding the construction project's volume, the laborers' commuting to the location of the project and the transportation of the required equipment. For the sake of ease of a multi-issue approach, *the traffic movements of construction materials' transportation* are calculated first, *the traffic movements of laborers' commuting* is also estimated, and *the traffic movements for the transportation of the essential equipment on the construction site* is determined as a last step. The summation of the aforementioned movements results in the total number of movements and produced vehicles related to the construction process.

In order to calculate *the number of vehicles for the transportation of materials*, the total volume of the construction project as well as the volume of a truck (class 2) and an articulated truck (class 3) have to be considered. For the case of the Eleven square project, the number of vehicles for the building materials' transportation is determined as:

$$Number\ of\ vehicles = \frac{Volume\ of\ the\ constuction\ project}{vehicle's\ volume}$$

In the examined case study, the total volume of the construction project is 965.615 cubic meters. A simplification that the total volume of the construction project is allocated equally to the trucks and the large trucks is made. With regard to the vehicle's volume, that is presented in the following table 5.2, the number of trucks' $N_2$ (class 2) and large trucks' $N_3$ (class 3) rides is calculated.

Table 5.2: Vehicles' volume

| Vehicle type | Length(m) | Width(m) | Height(m) | Total volume($m^{3}$) |
|---|---|---|---|---|
| Large Truck | 13,60 | 2,4 | 2,4 | 78 |
| Truck | 6,0 | 2,4 | 2,4 | 35 |

Thus,

$$\frac{Volume\ of\ the\ constuction\ project}{vehicle's\ volume} = \frac{482.807}{78} = 6.189\ rides\ of\ large\ trucks$$

$$\frac{Volume\ of\ the\ constuction\ project}{vehicle's\ volume} = \frac{482.807}{35} = 13.794\ rides\ of\ trucks$$

Conducting an exploratory interview with a head coordinator of environmental safety and construction logistics, it was stated that there is approximately 40% inefficient load factor in the construction sector, 12% waste from new materials related to the construction sector and 10% unforeseen transportation movements that have not been recorded during the implementation of a large construction project. All the aforementioned factors are also considered for the calculation of the vehicles' rides in the Eleven Square project.

Table 5.3: Additional transportation rides due to influential factors

| Extra influential factors | Number of transportation rides (vehicles class 2) | Number of transportation rides (vehicles class 3) |
|---|---|---|
| 40% inefficient load factor in the construction sector | 5.518 | 2.476 |
| 12% waste from new materials | 1.655 | 743 |
| 10% unforeseen transportation rides | 1.379 | 619 |
| | **22.346** | **10.027** |

Overall, the number of needed vehicles for the transportation of materials for the Eleven Square project is:

$N_2 = 2 \times 22.346 = 44.694$ number of vehicles class 2 to and from the construction site

$N_3 = 2 \times 10.027 = 20.054$ *number of vehicles class 3 to and from the construction site*

The above calculated numbers have to be divided by the total number of the working days and the total working hours of the working day. In the context of this thesis, for the validation of the prognosis model with the selected case study, one year is considered as the lifetime of the construction project (225 working days) and 07:00-17:00 are the daily working hours (10 working hours) and hence, these values will be divided with the number of the working days and the daily working hours which ware mentioned above.

Thus, concerning the transportation of the construction materials on site the total number of rides is:

$N_2 = 19{,}864$ *number of rides of vehicles class 2 per working hour*

$N_3 = 8{,}913$ *number of rides of vehicles class 3 per working hour*

To calculate *the vehicles' movements for the laborers' commuting* it is assumed that 1,5 employees per vehicle are transported to the construction site. This hypothesis is based on the following rational thinking:

1) Car sharing can be chosen as a travel choice by the laborers
2) Not every laborer has to be present at the construction site every working hour and every working day
3) Public transport is a travel option

Furthermore, the total number of employees of Eleven Square project is 600 employees. The aforesaid information was retrieved from contractors of the construction project. Usually, private passenger cars (class 1) are used for this purpose.

Thus,

$$total\ number\ of\ employees\ \div 1{,}5 = 600 \div 1{,}5 = 400 \text{ rides of vehicles class 1}$$

It is worth noting that for estimating the total number of vehicles in the worst-case scenario it is assumed that the employees leave the construction site by using the same road.

Thus,

$N_1 = (400 \times 2) \div 10 = 80$ *number of rides of vehicles class 1 per working hour*

Finally, *the transportation loads due to the delivery of the required equipment* for the implementation of the construction activities has to be examined and the required vehicles are categorized in Class 3.

Assuming that for every 25.000 cubic meters there is one subcontractor, and that the basic equipment is delivered during the working weeks (45 working weeks for 1 year) while the basic machinery is delivered during the working days (225 working days for 1 year), the way for calculating this number of rides is presented in Table 5.4.

Table 5.4: Total vehicles' rides for the delivery of the Eleven Square construction equipment

| | |
|---|---|
| Subcontractors every 25.000 $m^3$ | 1 |
| Total volume of the construction project | 96.5615 $m^3$ |
| Total number of subcontractors | **39** |
| | |
| **Basic equipment (39 times × 45 working weeks)** | |
| supply | 1.755 rides |
| disposal | 1.755 rides |
| total | **3.510 rides** |
| **Basic machinery (39 shifts × 225 working days)** | |
| supply | 8.775 rides |
| disposal | 8.775 rides |
| total | **17.550 rides** |

As a result, the estimated number of transportation movements for the delivery of the required equipment for the construction process of the Eleven Square project, is:

$$Number\ of\ rides\ for\ equipement'\ delivery = \ 21.060\ rides$$

Thus, the estimated number of rides for the delivery of the construction equipment per working hour during the total lifetime of the project is:

$N_3 = (21.060 \div 225) \div 10 = 9{,}36$ number of rides of vehicles class 3 per working hour

Since for designing this prognosis model the classification of vehicles is concerned, all the calculated number of rides that are considered equal to the number of vehicles and multiplied with the relevant PCE values that subsection 4.4.1 mentions. $N_1$, $N_2$ and $N_3$ values refer to the vehicles of class 1(private cars), the vehicles of class 2(trucks), and the vehicles of class 3 (large trucks) respectively.

The different amounts of transportation loads derived from the three different construction methods have been discussed and analyzed by experts, such as the contractors and the project managers of this project, through interviews. From these interviews, it was concluded that the calculated numbers $N1$, $N2$ and $N3$ differ in every construction phase.

In this study, the main four construction phases are examined: the substructure, the superstructure, the façade and the finishing. Also, in the context of this research, it is deemed that the construction phases are implemented separately, and the implementation of every construction phase lasts one month. This simplification is made in order to conduct this research in the timeframe of a master's thesis. In reality, the construction activities associated with different construction phases can be utilized in parallel.

In particular, on the ground of experts' knowledge and experience, a comparison of the total number of vehicles $N$ for the construction phases was made through interviews and the interviews' findings were generalized and quantified into factors.

Therefore, for differentiating the calculated values in the construction methods and construction phases that this study includes, the factor $f_{jk}$ is introduced.

Where,

j is about the construction method

k is about the construction phase

In this way, the final number of vehicles ($N$) related to the realization of the construction project will be multiplied by the factor $f_{\mathrm{jk}}$ to provide more accurate and reasonable results. In Chapter 4, the use of the factor $f_{\mathrm{jk}}$ is suggested to be introduced so as the outcome of the model to be given even by using roughly estimated data. This recommendation is given so as to employ the prognosis model in real-life situation where the construction phases are not strictly separated.

Table 5.5 demonstrates the $f_{\mathrm{jk}}$ values that have been decided under consultation meeting with logistics industry experts and contractors and have been approved and confirmed by experts from Gemeente Amsterdam. Also, it is noteworthy that each interviewee considered the same aspects for determining these values. These common aspects are the duration of a construction phase in comparison with the whole lifetime of the construction project, the ability to handle and store the construction materials and the requisite equipment for the implementation of each construction phase, and the number of the needed personnel so as to realize the appropriate construction activities.

Table 5.5: $f_{\mathrm{jk}}$ values related to construction methods and construction phases of Eleven Square project

| Construction method | Construction phase | $f_{jk}$ | $f_{jk}$ values |
|---|---|---|---|
| Traditional | Substructure | $f_{tsub}$ | 1 |
| | Superstructure | $f_{tsup}$ | 0,7 |
| | Façade | $f_{tf}$ | 0,6 |
| | Finishing | $f_{tfin}$ | 0,9 |
| | | | |
| Prefabrication | Substructure | $f_{tsub}$ | 0,95 |
| | Superstructure | $f_{tsup}$ | 0,5 |
| | Façade | $f_{tf}$ | 0,4 |
| | Finishing | $f_{tfin}$ | 0,45 |
| | | | |
| Mixed (40% traditional construction method & 60% prefabricated elements) | Substructure | $f_{tsub}$ | 0,975 |
| | Superstructure | $f_{tsup}$ | 0,6 |
| | Façade | $f_{tf}$ | 0,5 |
| | Finishing | $f_{tfin}$ | 0,675 |

Furthermore, another focal point from the conducted interviews is that not all the working hours produce the same amount of “construction traffic”. It has been observed from the contractors’ and logistic managers’ experience that there are particular time slots when the traffic related to construction activities is denser. Therefore, for the evaluation of this prognosis model, these numbers are increased based on the relevant factors about traffic distribution that are demonstrated in Figure 5.4.

| | A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|---|
| 1 | Hourly traffic Distribution | | Day of the Week Distribution | | Construction Traffic Distribution | | Construction Phases Distribution Traditional | |
| 2 | 7:00:00 AM | 1.166 | Monday | 1 | 7:00:00 AM | 1.7 | Substructure | 1 |
| 3 | 8:00:00 AM | 1.183 | Tuesday | 1.15 | 8:00:00 AM | 1.2 | Superstructure | 0.7 |
| 4 | 9:00:00 AM | 1.2 | Wednesday | 1 | 9:00:00 AM | 1.1 | Façade | 0.6 |
| 5 | 10:00:00 AM | 1 | Thursday | 1.15 | 10:00:00 AM | 1 | Finishing | 0.9 |
| 6 | 11:00:00 AM | 1 | Friday | 1.15 | 11:00:00 AM | 1 | Construction Phases Distribution Prefab | |
| 7 | 12:00:00 PM | 1 | | | 12:00:00 PM | 1 | Substructure | 0.95 |
| 8 | 1:00:00 PM | 1 | | | 1:00:00 PM | 1 | Superstructure | 0.5 |
| 9 | 2:00:00 PM | 1.18 | | | 2:00:00 PM | 1 | Façade | 0.4 |
| 10 | 3:00:00 PM | 1.188 | | | 3:00:00 PM | 1.1 | Finishing | 0.45 |
| 11 | 4:00:00 PM | 1.196 | | | 4:00:00 PM | 1.7 | Construction Phases Distribution Mixed | |
| 12 | | | | | | | Substructure | 0.975 |
| 13 | | | | | | | Superstructure | 0.6 |
| 14 | | | | | | | Façade | 0.5 |
| 15 | | | | | | | Finishing | 0.675 |

| I | J | K | L |
|---|---|---|---|
| Weather Factor | Population Growth | Threshold1 | Threshold2 |
| 1 | 1 | 0.7 | 0.9 |

Figure 5.4: Screenshot from the external excel file with the used factors for the selected case study

Moreover, for the city of Amsterdam, the experts of the Transportation Department have found out that the traffic flow starts to be lower and face undesirable changes in its flow when $R_{th1} = 0{,}7$. Likewise, in rigid traffic control $R_{th2} = 0{,}9$. In particular, above this value the traffic is uncontrollable and there is unmanageable stalled traffic. Hence, the introduced threshold values for the function of the prognosis model take the abovesaid values.

Lastly, the influence of the weather conditions and the population’s density are not examined since their impact on the traffic conditions could not be researched in the limited time frame of a master thesis. By determining the accordant values as 1, the Matlab code neglects the impact of these values on the output of the designed model.

According to the above-detailed description of the deemed parameters/factors, the used factors for the case study of Eleven Square Project that were inserted in the Excel sheet named as “Factors” of the external Microsoft Excel file of the designed prognosis model are represented in Figure 5.4.

## 5.4 Conclusion & contribution of Chapter 5

This chapter described the selected case study that had to deal with the selection of the proper data for the function of the model. Aiming to define the relevant data for the chosen case study, structured and semi-structured interviews were conducted with involved stakeholders (experienced contractors, logistic managers and experts from Gemeente Amsterdam) in the selected project. It was disclosed that traffic data in construction projects are not often monitored and recorded from the contractors (that act in accordance with the interest of their construction company) and the identification of the data is made by realistic and rational approximations. This tactic was also followed in Chapter 5. As a consequence, another ability, that is provided to the user of this model due to the way that the prognosis model of this study is designed, is utilized, and thus confirmed; the possibility of forecasting approximately the traffic movements during the construction project and acquiring broad and rough comprehension of the traffic conditions in the examined road. Based on this project and by following the aforementioned approach, the validation of the prognosis model presented in Chapter 4 is conducted by means of individual interviews and interpreting the model's results.

# Chapter 6

# Validation of the model

*In this chapter, this study's designed prognosis model is validated as the final part of this thesis. Firstly, Section 6.1 is an introduction to this chapter. In Section 6.2, the goal of the validation is explained, while Section 6.3 encompasses the validation of this study's designed model with the described case study of Chapter 5. Sub-section 6.3.1 represents the results of the prognosis model by inserting data referred to the case study and Section 6.4 contains experts' opinions in order for this model to be evaluated in another way, too. Finally, in Section 6.5 the robustness of the model is discussed. This chapter responds to the following sub-question:*

***Sub-question 5:*** *To what extent can the output of the transportation prognosis model facilitate the pre-design phase of a construction project concerning the additional transportation volumes along the construction processes and be used as a proactive measure (tool)?*

## 6.1 Introduction

The validation of the designed prognosis model is the last part of this research. A literature review and exploratory interviews (to establish the context of this research and acquire important quantitative data as well as qualitative insights) were conducted. The outcome of the desk research is the design of a prognosis model that can potentially assist the user of the model to forecast and thus control the traffic movements of an examined road (the road that leads to the project's construction site) during the implementation of a construction project.

Due to the limited time frame of this study and the impediment of gathering accurate and exact data, the actual implementation of the designed model is not feasible. Therefore, it is apparent that the evaluation of the model (which typically follows after the model's implementation) cannot be achieved. For this reason, the model has to be validated using an alternative way. An appropriate strategy for such cases is the formative evaluation. This denotes that a validation is conducted prior to the model's implementation (Verschuren & Hartog, 2005) (p.742).

## 6.2 Goal & context of the validation

The goal of the validation is to comprehend if the professionals would be agreeable to using the prognosis model in practice and if they are satisfied with the usability and the functionality of the model. As has been already mentioned in previous chapters, an important point of the rationale behind the designing of this model is to provide an interface that is friendly to the user. Furthermore, the outcome of the model and if the model satisfies the design requirements is an essential part of the evaluation process. Finally, it is substantial to interpret the results of the prognosis model as well as to test its robustness.

In addition, the context of the validation, which is practically the chosen means in order to accomplish the validation, has to be stated. The evaluation of the prognosis model is conducted on the ground of a single case study. The main criteria for the selection of this case study and the characteristics of this case are explained in Chapter 5. Also, the involved stakeholders in this construction project have already been mentioned, one of whom is Gemeente Amsterdam that is a highly influential party. Therefore, the main interviewees in the validation procedure are experts from Gemeente Amsterdam. The context and the way that the model is assessed by them are explained in Section 6.4.

Also, in order to test the prognosis model for providing acceptable results, comprehensible graphical representations, and to examine the fulfillment of the design requirements and the model's functionality in general, the quantified data of the chosen case study were inserted in the prognosis model's external Excel file and with the use of Matlab software were analyzed according to the prognosis model's objective. Since the use of specific accurate data related to the selected case study was not possible during this research, rational simplifications, and reliable estimations by interviewing experienced experts and researching similar case studies are followed as a suitable way to conduct the model's evaluation. On this basis, the used data being calculated in order to validate the designed model are described in Section 5.3.

With this type of validation, it is believed that the researcher is not able to conclude with sufficient certainty whether the designed prognosis model sufficiently works in practice. However, the validation can offer some preliminary findings with regard to if and how professionals can gain insight into the behavior of transportation movements during a construction project's implementation and evaluate the model's usability and handiness. Moreover, professionals' expectations of the future use of the model can be clarified and an interpretation of the model's final results can be made.

The following section elaborates on the aforementioned ways in order the model of this study to be validated.

## 6.3 Validation with the case study & Results

By verifying a designed model the main aim of the researcher is to ensure that the model is implemented with respect to it designed requirements and the main mode's objective (Carson, 2002).

For this study, approximate estimated data that has been calculated by following a system thinking approach and experts' knowledge were used in order to achieve the prognosis model's validation. The above referred simplified data are stated in Chapter 5 which describes the calculation process thoroughly. More specifically, as a first step for the prognosis model's use the qualified data had to be inserted in the external Microsoft excel file as it is demonstrated in Figure 5.4.

By executing the designed model in Matlab software, the following graphs are illustrated being the output of the prognosis model.

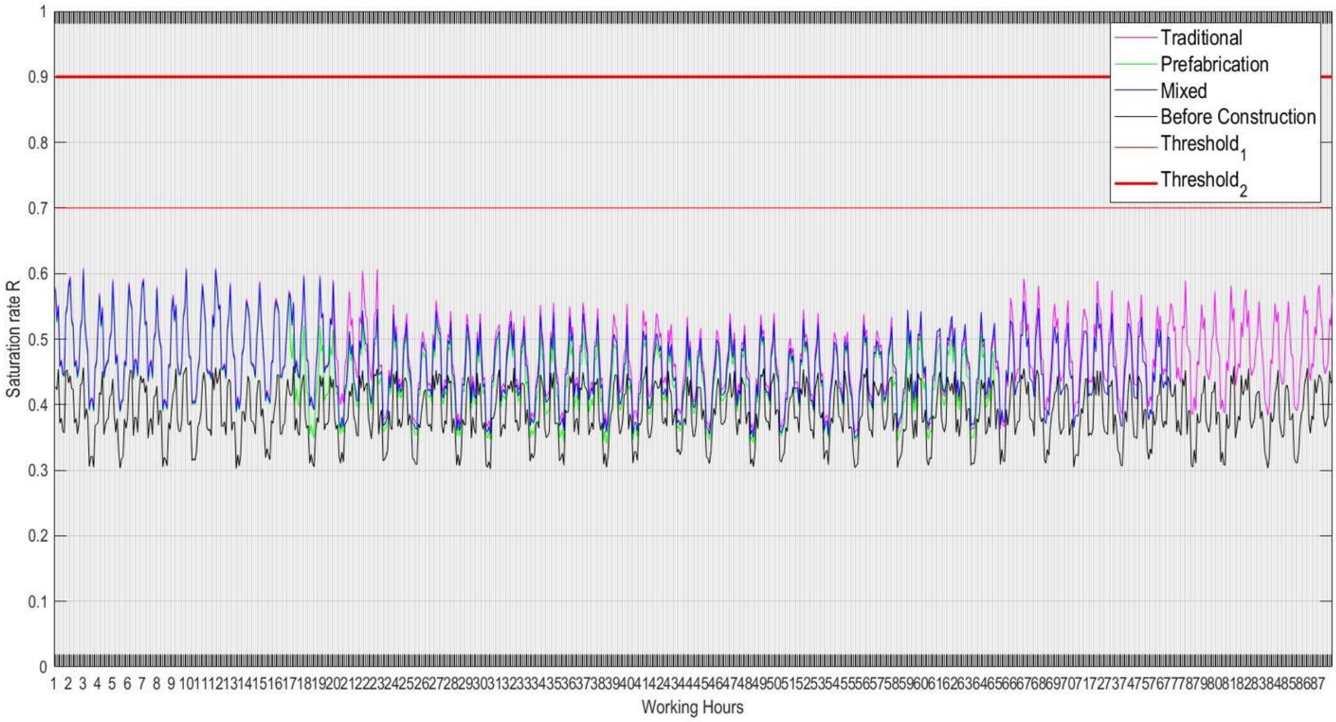



Figure 6.1: Saturation rate R per working hours over the lifetime of Eleven Square project for 3 different scenarios

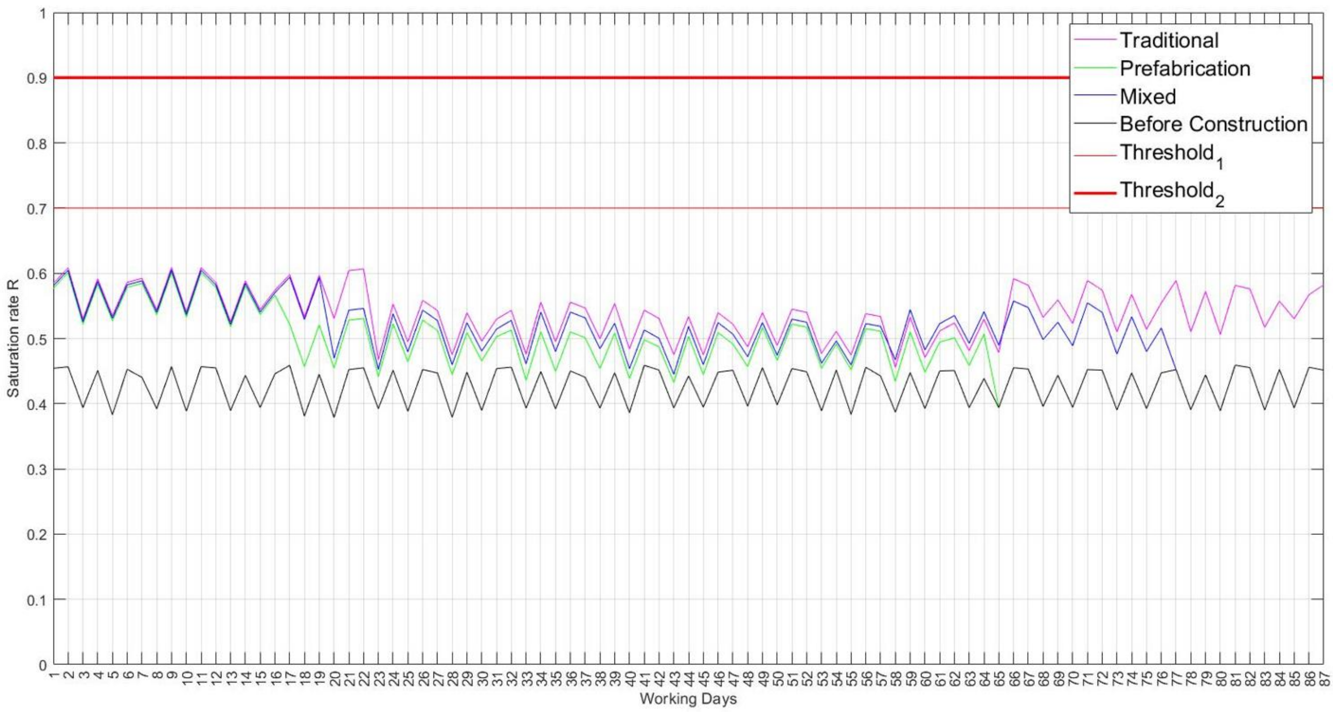



Figure 6.2: Peak daily saturation rate R over the lifetime (working hours) of Eleven Square project for 3 different scenarios

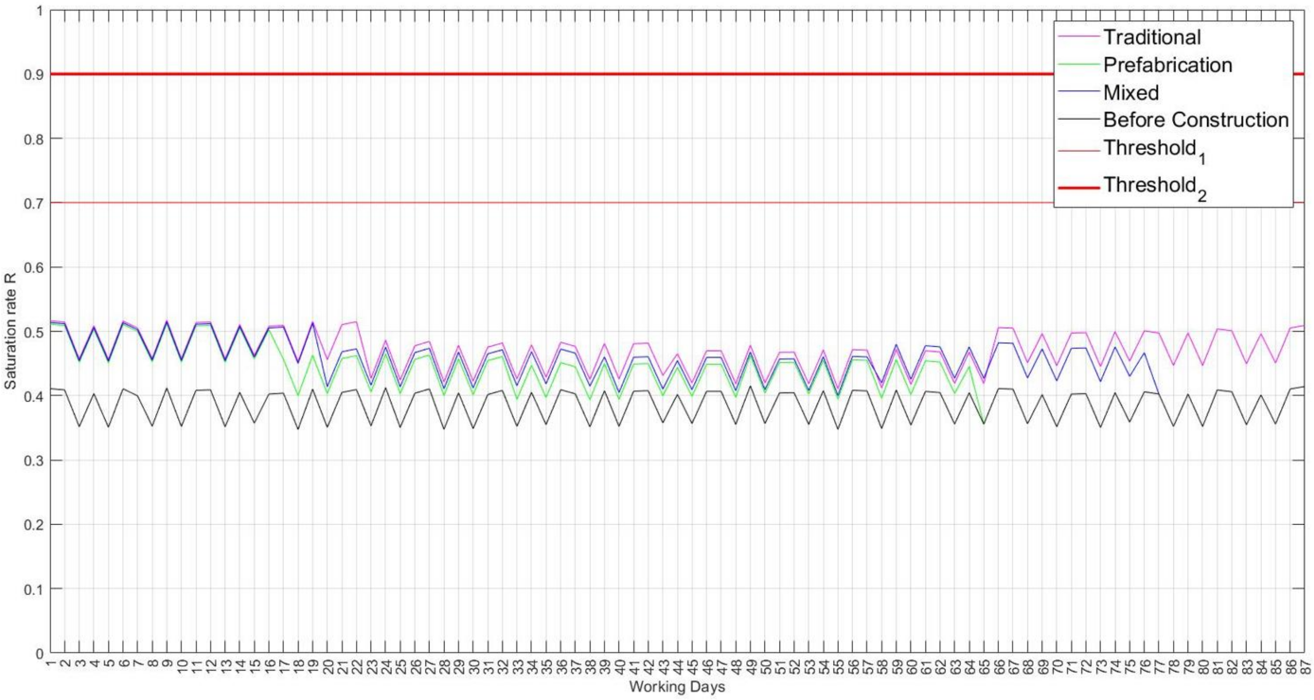



Figure 6.3: Average daily saturation rate R over the lifetime (working days) of the construction project for 3 different scenarios

The above figures are presented by executing the Matlab file of the model. Matlab programming language was utilized which is presented in Appendix B. In practice, if the user of the program clicks in the working hour or the working day wanting to be informed about its respective saturation rate *R* related to the traditional construction method, the prefabrication, or the mixed construction method (in the chosen case study the construction method is considered as a combination of 50% traditional construction method and 50% installed prefabricated elements), as well as the traffic movements without the implementation of construction activities, can retrieve the needed values from the relevant graphical representation. The advantages that each graph offers to the user of the model are explained in detail in Chapter 4.

After running the developed prognosis model with the use of simplified data, *the obtained results for the chosen case study* are mentioned below. More explicitly:

1) All the types of construction methods increase the transportation movements of the examined road which is a reasonable and apparent result.

2) The three researched construction methods do not produce the same amount of “construction traffic” and thus their contribution to increasing the traffic level differs. More precisely, traditional construction method increase the traffic flows more than prefabrication since the number of produced transportation movements is bigger during the implementation of construction project related to traditional building method. This situation is noticed in every construction phase. The second more impactful construction method in terms of traffic level’s increase is the “mixed” construction method and

prefabrication produces a lower number of transportation movements than all the other construction methods.

3) The traffic movements of the examined road during the project's implementation are increased differently in the project's construction phases. For the three construction methods, the results of the traffic movements' increase in the examined construction phases in comparison with the traffic condition before any construction process takes place, are different. Particularly, the largest percentage increase is observed during the implementation of the substructure. The increased traffic level of the other construction phases expressed as a percentage from the higher to the lower is noticed in the realization of construction activities during the finishing, the substructure, and the façade of the construction project correspondingly.

   For interpreting the results of the prognosis model, the saturation rates that are closer to the $R_{th}$ values are examined since the assessment of the more undesirable traffic conditions is the most critical.

   The aforementioned conclusions are made based on the following results:

   a) *Traditional construction method*

      - Substructure: Maximum increase level ≅ 33,56%
      - Superstructure: Maximum increase level ≅ 22,38%
      - Façade: Maximum increase level ≅ 21,01%
      - Finishing: Maximum increase level ≅ 26,47%

   b) *Prefabrication*

      - Substructure: Maximum increase level $R \cong 31{,}83\%$
      - Superstructure: Maximum increase level $R \cong 15{,}68\%$
      - Façade: Maximum increase level $R \cong 13{,}97\%$
      - Finishing: Maximum increase level $R \cong 12{,}34\%$

   c) *Mixed construction method*

      - Substructure: Maximum increase level $R \cong 32{,}67\%$
      - Superstructure: Maximum increase level $R \cong 19{,}03\%$

- Façade: Maximum increase level $R \cong 17{,}49\%$

- Finishing: Maximum increase level $R \cong 16{,}86\%$

4) The traffic conditions in the examined road are controllable. As the graphical representations reveal, the saturation rate of every working hour over the lifetime of the construction project does not exceed the lower threshold ($R_{th2}$).

5) The construction process of this project appears to be smooth in terms of construction logistics because the prognosis model's outcome does not disclose severe fluctuations of the saturation rate *R*.

The chosen points of the graph for calculating the above *R* values in order to test the prognosis model's output are demonstrated in Figure 6.4. A clear representation of the labels ("Data tip" in Matlab software) of the carefully chosen points is provided.

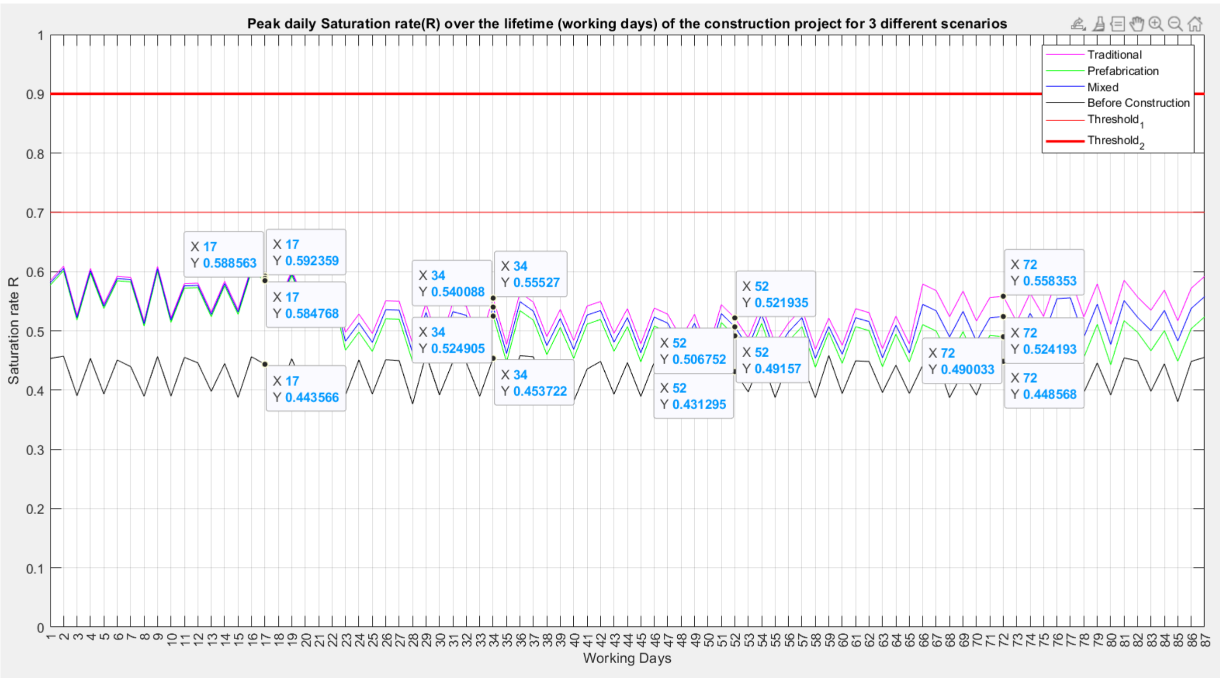



Figure 6.4: Prognosis model's critical results of Eleven Square project

At this point, it is worthwhile to discuss the prognosis model's functionality. The results of this case study are the outcome of the prognosis model's input data. In particular, due to the fact that the output of the model is a linear function of the input variable, the validity of the input data affects the reliability of the model's output. A more thorough explanatory analysis is provided in subsections 6.5.

## 6.4 Validation by experts’ opinion

Carson (2002) states that co-validation strategy in which the modeler and the model’s interested party cooperate in defining the design requirements of the model, can be proven efficient since not only the designed model can be developed in a desired timeframe but also a reliable outcome is feasible. This strategy is followed by the researcher (the modeler) and Gemeente Amsterdam as the interested party.

Interviewing professionals who work for the municipality of Amsterdam serves the purpose of this study which is to design a model that facilitates the transportation management of a highly populated urban area during a construction project’s implementation. To conduct broader research and comprehend the point of view of other interested parties rather than Gemeente Amsterdam, some of the interviewees were contractors and logistic managers.

The conducted interviews were semi-structured. At the beginning of the interviews, the context of this thesis was explained, and a more detailed description of the designed model’s objective was followed. To guarantee that the model’s reliability and usability would be validated by the conducted interviews, direct questions were asked. More particularly, the extent to which the designed prognosis model can facilitate transportation management in urban areas and how and if they can use prognosis model in practice were discussed. In addition, it was questioned if the designed model’s requirement for being “a handy tool” that is friendly for the user is met.

The main *findings based on the conducted interviews* are listed and interpreted below. These findings refer to the appropriate predecessors for potential use of the provided prognosis model of this study. Also, the level of the interviewees’ satisfaction regarding the functionality and the usability of the model is explained based on their answers.

1) Collaboration and frequent communication between the relevant municipality, the contractors, and the logistic managers

   Gemeente Amsterdam which is more interested in keeping controllable traffic levels for retaining desirable living conditions for the residents of Amsterdam, mentioned the high need of obtaining accurate information on the number of vehicles related to the implementation of the construction activities on site. In order to retrieve a reliable and realistic outcome the responsible contractors and logistic managers have to inform the municipality or any other potential user of the model about the exact data that are practically the input variables of the prognosis model. Great importance was given from all the interviewees to efficient and transparent communication in order to prevent undesirable traffic conditions. The aforementioned honest communication as well as the effective collaboration of these stakeholders is strongly correlated with the possibility of sudden changes in the planning of the construction problem. Hence, each change needs to be communicated with the other parties so as to be aware of the situation of the examined road by using the prognosis model. All the interviews mentioned that the designed prognosis model supports their efficient communication. They confirmed that the prognosis model aims to reveal through estimated forecasts the produced vehicles’ movements that are a potential ground for conflict between the involved interested parties.

2) Thorough planning

An interesting observation extracted from the conducted interviews is the pre-requisite of a thorough and informative planning of the construction project. All the interviewees believe that informative planning which mentions the number of needed vehicles and the required construction equipment in every construction phase of the project can prevent traffic problems. This was thought to be a catalyst. However, it was mentioned by the experts of Gemeente Amsterdam that it is rare to receive the above-described type of planning according to their work experience. Even if they ask contractors about this type of information there is a high likelihood of getting a negative response. Therefore, the use of the prognosis model in practice is challenging since the construction industry neglects this informative planning with regard to the number of the needed vehicles for the construction project's implementation.

3) Awareness of the needed resources

A focal point of the interviews was that the model's reliability is strongly dependent on the great need to know the resources related to the construction project. The building materials' quantities, the volume and the square meters of the construction site are crucial for calculating correctly the number of transportation rides. Very rough approximations lead to very rough final results and the reliability level of the prognosis model is decreased substantially.

4) Informative graphical representation as the model's final output

Positive feedback was received from all the interviews regarding the representation of the final graphs. It was stated that the rationale behind the design of the model is depicted in the final graphs. In particular, the interviewees were satisfied by the fact that the graphical representations are readable and informative. Also, it was confirmed that the three provided graphs offer the potential user a better overview of the model's objective. It was stated that the designed prognosis model facilitates the comparison between the different construction methods in terms of their impact on the urban area's traffic flows. Furthermore, the interviewees agreed about the use of the two threshold values since insight is gained into when and if precautionary measures have to be taken is essential and meets the prognosis model's requirements.

5) User-friendliness and flexibility of the model

As has been already explained in previous chapters, the objective of this prognosis model and its design requirements was utilized through exploratory semi-structured interviews with experts from Gemeente Amsterdam. During these interviews the need for an easy-to-use tool was highlighted. At that moment, it was concluded that the outcome of the prognosis model has to be provided even if the user of the model does not have knowledge of programming language and Matlab. On this ground, it was decided by the researcher to connect the Matlab file with an external Microsoft excel file in which the input variables can be inserted. The way that the prognosis model was designed satisfied all the interviewees since most of them want to use programs and models that are as easier and faster as possible. Additionally, the ability of the model to function with approximate factors in case there are roughly estimated data was positively commented through the interviews since all the interviewees believe that a high accuracy level of such data is difficult to be achieved in practice. Also, the designed model can be used in order the user of the model to gain insight into the traffic flows of another road since the prognosis model is strongly correlated with potential street data that can be easily adjusted in the respective excel sheet.

It is worth mentioning that the fact that the interviews paid more attention to the fact the model appeared to be handy and can calculate the needed information approximately was expected due to the lack of retrieving totally reliable information of the produced traffic movements associated with the construction process.

On the one hand, the contractors mentioned that the traffic congestion is not their greater responsibility while on the other hand municipality experts and logistic managers have the perception that contractors are mostly cost-driven and do not care for the public good. This is not a surprising outcome because the construction industry often copes with cost overruns and attempts to avoid them.

Finally, it was concluded that in order to accomplish a reliable prognosis model's functionality the involved stakeholders have to act as a whole through efficient communication and transparency in their shared essential information.

## 6.5 Discussion

Firstly, from the validation of the model by expert's opinion, it is proven that the co-validation of the prognosis model's development and design was valuable since the designed model can satisfy the use-friendliness and thus could potentially serve its purpose without constraints about the user's knowledge of modeling. Secondly, the designed prognosis model could enhance transportation management since it partially forecasts traffic movements even by rough approximations. However, proper attention has to be given by the construction project's stakeholders and the city's responsible municipality that is in charge of the project to the potential estimation and simplification in order to avoid wrong results.

Another important conclusion from the validation of the prognosis model is the model's contribution to the essential risk management of a construction project located in a dense urban area. Since the issues that the model aims to tackle are complex, even a small step toward the problem's remedy could be beneficial. Furthermore, efficient communication between the municipality, the contractors, and the logistic managers, that bear responsibility for the implementation of the construction project as well as the issues that can be postured by it, is one of the most important requirements for the model's reliability. In practice, this study's prognosis model cannot provide reliable results without reliable input data. As with every other model, the input-output relationship is strong and dependent. For that reason, it was decided to make a sensitivity analysis to show how the variables interact with each other.

More precisely, *sensitivity analysis* as part of the validation process aims to assess the impact of the input data on the model's outcome (Yin & McKay, 2018). On this ground, the influence of the input variables of this prognosis model in the model's final outcome is examined. As it has been stated, the output of the model is a linear function of the input variables and as a result, the validity of input data affects the reliability of the prognosis model's out.

Based on this case study, the uncertainty of each variable for carrying out the sensitivity analysis is decided considering the data resources and data type of the examined variable. The minimum and the maximum values of the examined variables as part of the sensitivity analysis are selected based on the experience and knowledge of the experts of Gemeente Amsterdam. The uncertainty level of the data that the transportation model of Gemeente Amsterdam provides is taken into consideration for determining the percentage of the examined input variables' uncertainty so as to reveal their impact on the prognosis model's output. Hence, the percentage of the uncertainty of the variables is chosen according to the uncertainty of their data.

As has already been explained in Chapter 4, the influence of population growth and weather conditions is not researched in this study. Therefore, the aforementioned factors are not included in the sensitivity analysis.

The following three main input variables are examined:

1) Sensitivity of $R$ to $c$

$$\frac{\partial R}{\partial c} = -\frac{l + \Sigma\,(\,w_i\;\times v_i\,)}{c^2}$$

Considering that the input variables ($l, w_i\;, v_i$) have fixed values it is proven that the output variable $R$ is influenced by the input variable c. More specifically, due to the fact that the partial derivative is negative, it is revealed that an increase of input variable c leads to a decrease in the output variable $R$.

In consideration of an important uncertainty level of the street capacity and the reliable estimation of its value that can be retrieved from "COCON" program, it was chosen to examine 20% uncertainty of input variable c ($\pm$ 10%). Figure 6.5 and Figure 6.6 demonstrate the prognosis model's graphical representations of which the following results are provided:

- 10% increase of $c$ → 9% decrease in $R$
- 10% decrease of $c$ → 11,1% increase in $R$

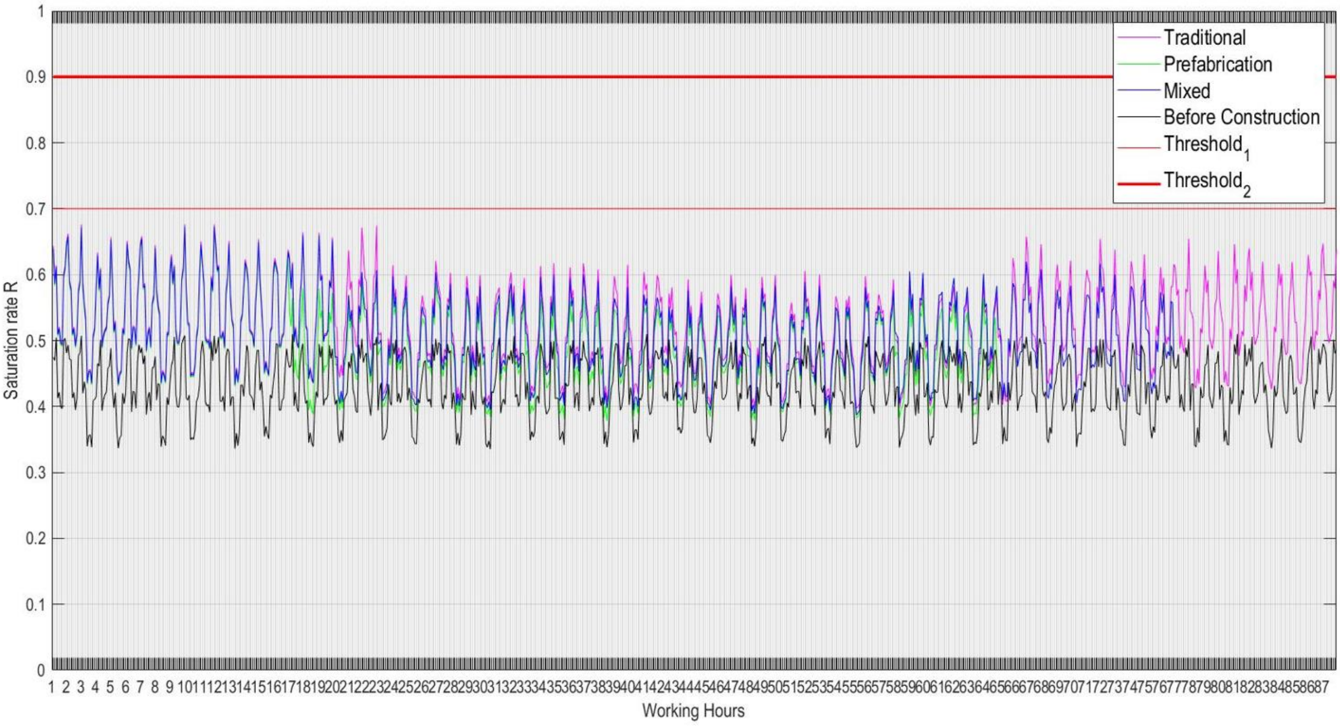



Figure 6.5: Saturation rate R per working hours of the lifetime of Eleven Square project for 3 different scenarios with a 10% decrease of the input variable c

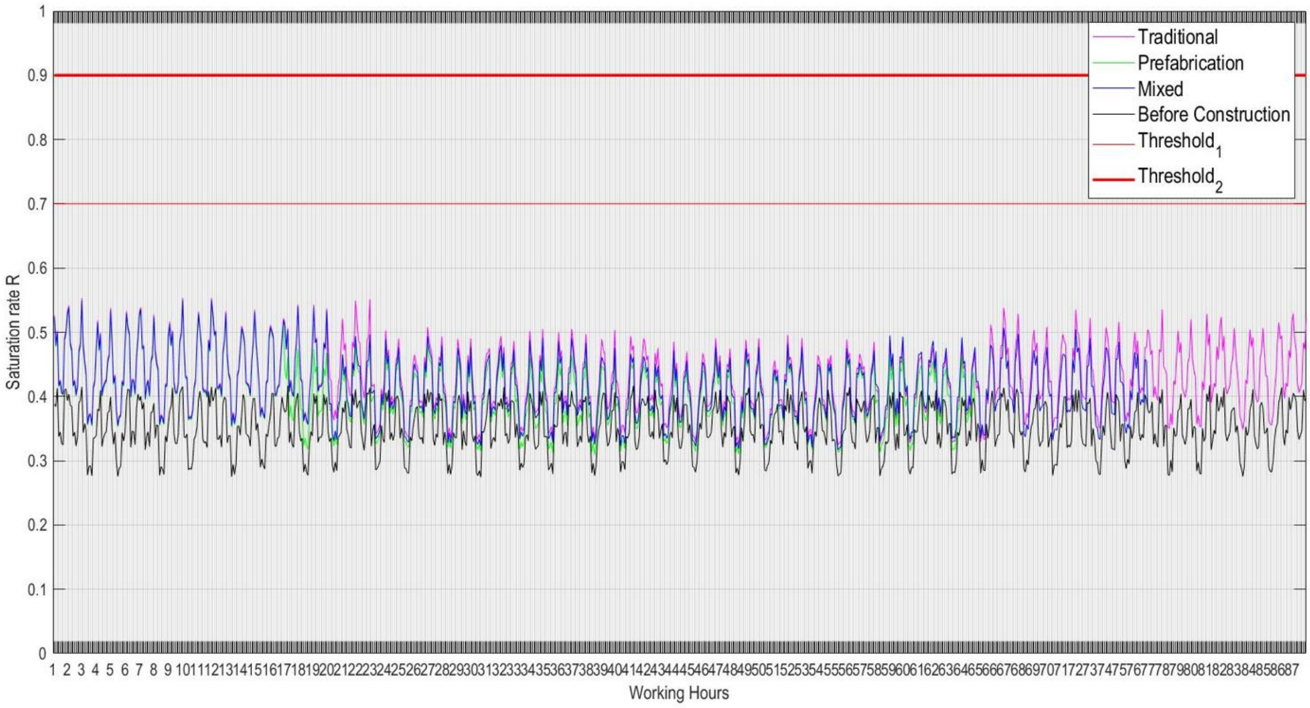



Figure 6.6: Saturation rate R per working hours of the lifetime of Eleven Square project for 3 different scenarios with a 10% increase of the input variable c

As expected, the capacity of the examined road has a significant impact on the saturation rate *R*. In real-life, the capacity of the road, that is how many transportation flows a road can handle, plays an important role in the occurrence of traffic congestion. This means that the model provides a reasonable outcome with regard to the interaction between these variables. If a road can handle larger traffic flows, then there are lower traffic levels. Nonetheless, a change in input variable c has the same effect in *R* regardless of the construction phase or construction method.

From this sensitivity analysis, it is disclosed that large attention has to be given to the reliability of input variable c since it affects the model's final output substantially.

2) Sensitivity of $R$ to $l$

$$\frac{\partial R}{\partial l} = \frac{1}{c}$$

The aforementioned differential equation reveals that the input variable $l$ affects $R$. However, if $v_i$ variable has higher value then $l$ has less impact on R. To examine the sensitivity of R due to $l$ , the formula's part $\Sigma\ (\ w_i\ \times v_i\ )$ has the same value as the selected case study (see Chapter 5).

Since the transportation flows of the road network of Amsterdam are provided by the traffic model of Amsterdam, an uncertainty of 10% of the input variable $l$ is applied ($\pm$ 5%).  The results are presented in Figure 6.7 and Figure 6.8 and given below:

- 5% increase of $l$ → 3,85% increase in $R$
- 5% decrease of $l$ → 4,2% decrease in $R$

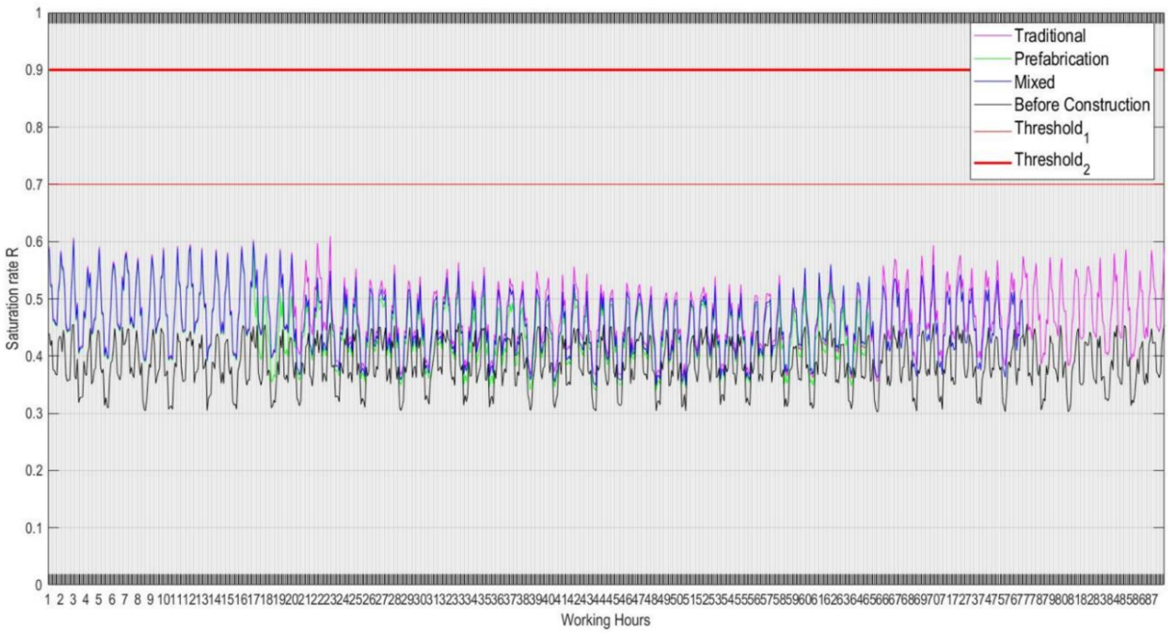



Figure 6.7: Saturation rate R per working hours of the lifetime of Eleven Square project for 3 different scenarios with a 5% increase of the input variable $l$

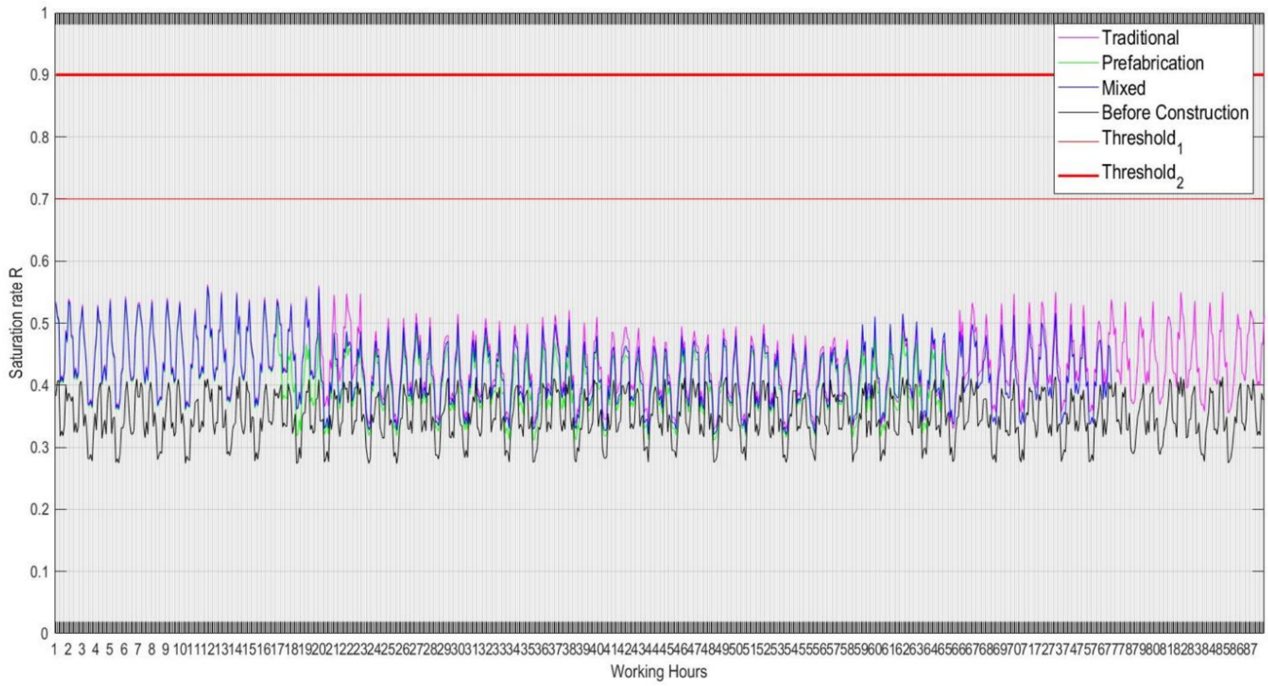



Figure 6.8: Saturation rate R per working hours of the lifetime of Eleven Square project for 3 different scenarios with a 5% decrease of the input variable $l$

This result implies that if the transportation movements of the road are slightly increased, the traffic conditions do not face any substantial change. Nonetheless, there is a small impact, and the two variables behave similarly; an increase of $l$ causes an increase of $R$ and a decrease of $l$ causes a decrease of $R$.

3) Sensitivity of $R$ to $v_i$

$$\frac{\partial R}{\partial v_i} = \frac{w_i}{c}$$

The influence of R value due to $v_i$ variable is not as much as the influence of the examined road's capacity but still is considerable for the prognosis model's results. If the road's capacity remains the same as well as the number of vehicle's movements without the realization of construction activity, the same behavior is observed between these to variable since the increase of R is equal to the increase of $v_i$.

For examining the sensitivity of $R$ to $v_i$, 20% uncertainty selected (±10%) for $v_i$ since rational estimations were made (see chapter 5) without being aware of the relevant exact data. In order to comprehend the impact of the additional transportation volumes on the examined road, the input variables $c$ and $l$ were used with respect to the chosen case study.

The results are demonstrated in Figure 6.8 and Figure 6.9.

- 10% increase of $v_i$ → 2,3% increase of $R$
- 10% decrease of $v_i$ → 2,3% decrease of $R$

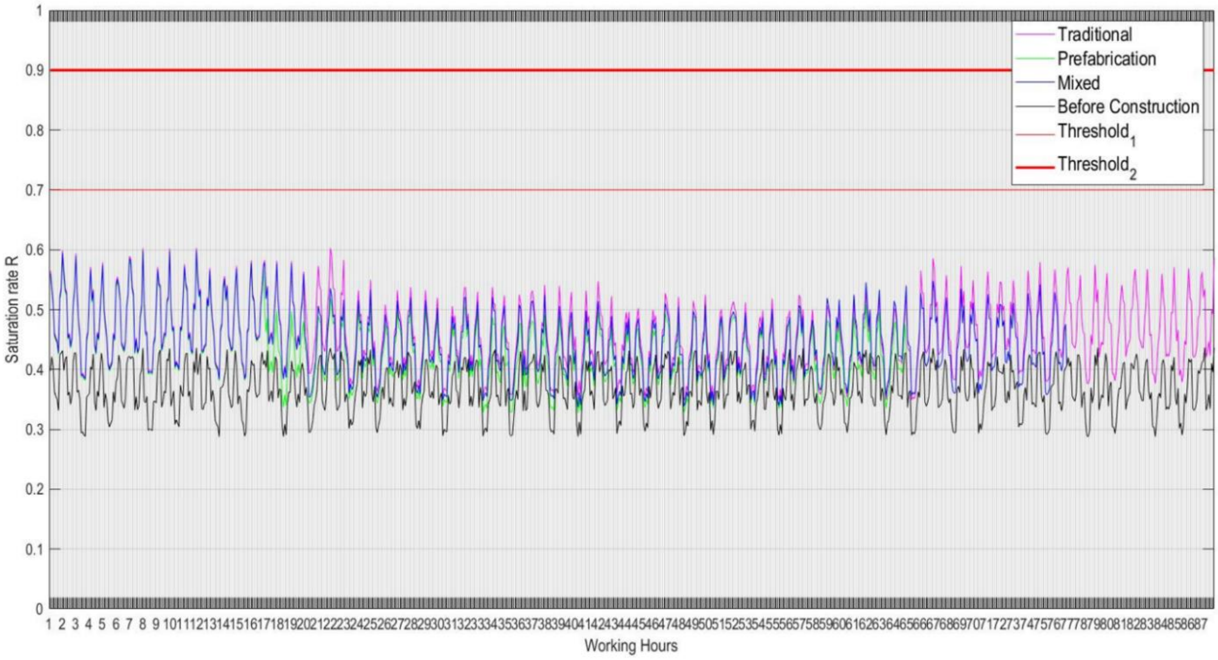



Figure 6.9: Saturation rate R per working hours of the lifetime of Eleven Square project for 3 different scenarios with 10% increase of input variable $l$

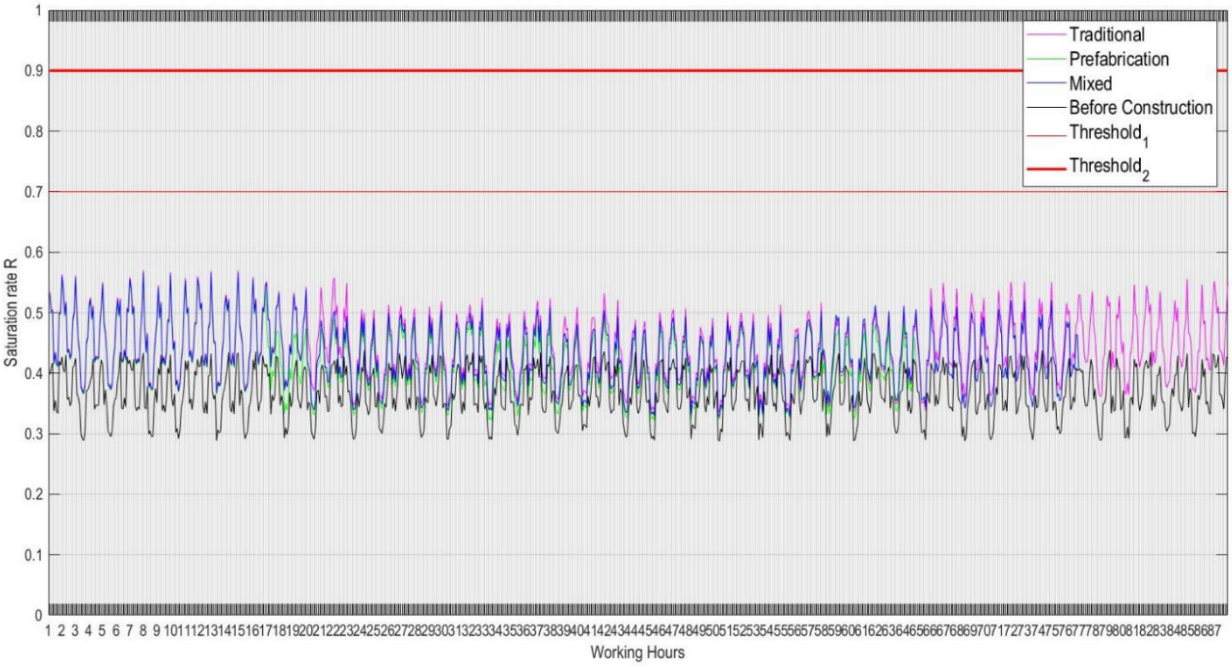



Figure 6.10: Saturation rate R per working hours of the lifetime of Eleven Square project for 3 different scenarios with 10% decrease of input variable $l$

It is worth mentioning that despite the value of $v_i$, $R$ is more sensitive to the transportation loads before the implementation of the construction project since it has a higher value. This is a rational conclusion about how much a road can be influenced by the construction process depending on the density of the road itself. However, if the construction project produces large number of vehicles due to its construction logistics, the traffic conditions of the road that leads to the construction site will be affected.

## 6.6 Conclusion & contribution of chapter 6

This chapter mentioned the validation process of the proposed prognosis model and was the last step of this research. The validation which was carried out based on a case study described in Chapter 5, targeted at accessing to what extent the designed model can facilitate the transportation management affected by construction logistics. Another aim of the validation process was to discover the willingness of the interviewees to use this model and their opinion about the flexibility of the model and its user-friendliness. In general, the interviewees were positive explaining that a model which can provide insight into the traffic flows during a construction project's implementation is promising. Additionally, a common point between all the interviewees was the need to have a model which can be used without being familiar with programming and related software.

However, the prognosis model's validation disclosed some constraints that affect the model's reliability and actual implementation. These constraints were taken into consideration in order to provide recommendations for the model's further improvement and future extension.

# Chapter 7

# Conclusions

*In this chapter, the main research question as well as the sub-questions are encompassed in Section 7.1. Furthermore, the limitations of this research are mentioned in Section 7.2, while Section 7.3 provides some recommendations for further research and the designed model's extension. Lastly, in Section 7.4 a reflection on the process of this research and the personal and practical lessons learned is given.*

## 7.1 Responding to research questions

At the beginning of this thesis, five sub-questions were formulated in order to gradually answer the main research question of this study which is how influential the construction process of a building is regarding the implemented construction method on transportation flows of the project's urban area. A response to the sub-questions and this thesis main research question is given below.

1. ***What are the characteristics and the main challenges of construction logistics for the realization of a construction project and why the pre-design phase is mostly related to the management of construction logistics? (Chapter 3)***

Reviewing the relevant literature, the characteristics and the challenges of construction logistics to the realization of a construction project were identified. From the literature study, it was disclosed that not much research has been done in the field of construction logistics. Nonetheless, all the relevant studies approach this field similarly and provide the same results and observations.

In particular, it has been observed that every relevant research highlights the uniqueness of each construction project and the need to be treated in a different way based on its characteristics. Specifically, every construction project has its own duration, needs a different set-up and involves different stakeholders. Also, regarding the construction materials of the project, these are delivered in every construction phase separately and are accommodated on the project's construction site. Another characteristic is the "domino effect" in the construction process because if one activity faces delay, the duration of the whole construction project will be affected.

Additionally, one of the main challenges in the field of construction logistics is related to the difficulty of efficient stakeholders' management since the involved interested parties have different perspectives and lack communication. Moreover, the inefficient coordination for handling and storage of the construction materials as well as the poor planning and monitoring of the construction project are usual, and the proper measures need to be taken in order to prevent the realization of a delayed or low-quality construction project.

Finally, the fact that different construction methods influence differently the construction logistics of a project was concluded. More specifically, prefabrication as a construction method produces fewer transportation flows than the conventional (traditional) construction method. Also, the pre-design phase is more subjected to a proactive approach to avoiding negative potential issues in construction logistics. The pre-design phase of a construction project involves the project's planning that can be detailed about the need for the project's construction logistics.

2. ***What are the causes and consequences of traffic congestion in urban areas? (Chapter 3)***

A review of the literature on the phenomenon of traffic congestion revealed that there are many contributing factors to creating traffic congestion as well as a wide spectrum of consequences.

Traffic congestion is a multi-faced issue caused by many factors such as insufficient road capacity and lack of investment in the infrastructure sector. In addition, the human factor influences the transportation movements of a road network due to the travel behavior of individuals and their travel choice in terms of the use of private vehicles or public transport. Also, the land-use patterns of the urban areas, the weather conditions, the population density, and the transportation flows related to logistics have a considerable impact on traffic.

Regarding traffic congestion's consequences, it was acknowledged that traffic congestion lowers the quality of life by harming living conditions. One main adverse consequence of stalled traffic is the social-cost overruns due to the occurrence of higher travel time for drivers. Furthermore, traffic has a substantial impact on noise and air pollution since it is a large contributor to the increase in $CO_2$ emission. At this moment it is worth mentioning, that particular attention is given to the traffic congestion's environmental impact in the Netherlands since the enhancement of sustainability and circularity are some of the main goals of the country. Additionally, another side effect of uncontrollable traffic is that can be an obstacle to realizing an efficient construction process of every project that is located in the congested road network.

3. ***What are the critical stakeholders and why does their behavior affect the logistics of a large construction project? (Chapter 3)***

Stakeholders' analysis and identification are crucial for a successful construction process. For this reason, it is critical for providing a high-quality construction project for the majority of the potential problems during the project's implementation to be prevented.

Furthermore, for realizing a construction project which is in harmony with its cultural and socio-economic environment, some precautionary measures have to be taken in order to avoid problematic influence on the project's location and surroundings.

For answering this sub-question, the conducted literature review was more focused on the internal stakeholders that can influence the construction process directly. The reason why the focus was kept on this was that a potential user of the designed prognosis model of this thesis can be an internal stakeholder who bears great interest in the construction project's general impact. As a result, it is concluded that the critical stakeholders are the municipality, the involved contractors, the material suppliers, and the logistic managers.

Potential conflicts between the interested parties, lack of communication, and totally different perceptions can negatively affect the construction process since they lead to delays and an unpleasant working environment which decreases personnel's performance. Additionally, the lack of communication causes ineffective handling and storage of the materials as well as misunderstandings related to planning and inadequate availability of the needed data.

4. ***What are the assumptions, the variables, the parameters, the coefficients, the extra influential factors, and the formula (which is the introduced mathematical expression for serving the model's objective) in order to design and develop the transportation prognosis model? (Chapter 4)***

The extrapolation type of modeling was considered appropriate in order to design and develop the transportation prognosis model of this study. On this ground, the design requirements and the assumptions and simplifications of this model are related to travel behavior, the distribution of vehicles, the examined time in terms of working hours, the predetermined examined route, and the availability of reliable street data.

The input variables of the prognosis model are the transportation loads of the examined road before the realization of the construction process, the number of vehicle's rides related to the construction process, the capacity of the examined road, and the Passenger Car Equivalent (PCE) values in order to achieve the proper classification for the types of vehicles. The output variable of the prognosis model is a graphical representation in which the x-axis presents the working hours over the construction project's lifetime and the y-axis the saturation rate described by the model's mathematical formula: $R = \frac{l+\sum_{i=1}^{3}( w_i \times v_i )}{c}$ (see subsection 4.4.2).

Additionally, the growth of the population and the weather conditions are considered as influential factors for the traffic flows of a road in general as well as for the extra transportation movements related to the implementation of a construction project. However, the designed prognosis model has the ability to consider the aforementioned factors, but their influence is not part of the scope of this thesis. A thorough description of the prognosis model's design and development is given in Chapter 4.

5. ***To what extent can the output of the transportation prognosis model facilitate the pre-design phase of a construction project concerning the additional transportation volumes along the construction processes and be used as a proactive measure (tool)? (Chapter 6)***

The prognosis model's validation was carried out based on a single case study and experts' opinion who can be the prognosis model's future users. According to the validation's results it was concluded that the prognosis model can facilitate the transportation management of the road network associated with the location of the construction project. Overall, according to the evaluation findings, this prognosis model can mostly be used as a proactive tool for gaining a broader insight into the traffic flows of the road influenced by the implementation of construction activities. Due to the fact traffic data related to construction methods are not available and part of the contractors' center of attention, this model can be a means of pressure for collecting this type of data.

Also, the development of the model by creating a connection between an external excel file and Matlab software satisfies the interviewees since most of them are not familiar with this programming language.

Finally, the use of this model can be proven beneficial for stakeholders' communication since the prognosis model's output can enhance their argumentation.

**Main research question**

***How much impact does the construction process of a building, considering the type of the construction method, have on the transportation movements of the urban area of the project?***

The evaluation of the model disclosed that the prognosis model can partially facilitate the transportation management of the road network related to the construction project's location by being applied as a proactive tool. To gain beneficial insights from the designed prognosis model and to use it as a proactive tool, the reliability of the input data must be ensured for preserving model's validity. For achieving the aforementioned goal, efficient communication between the different stakeholders to keep each other updated on potential changes in the project's planning and resources is crucial.

Furthermore, for the prognosis model's sensitivity analysis it was revealed that the transportation loads produced by the vehicles' movements due to construction activities influence the traffic conditions of the relevant road network. Particularly, different construction methods affect transportation movements differently. In this context, it was concluded that prefabrication produces fewer transportation movements during the construction project's implementation in comparison with the traditional construction method.

To conclude, *construction traffic partially impacts the urban area's road network negatively* but in order to specify to what extent can be harmful, further research must be conducted.

## 7.2 Limitations

Carrying out a sensitivity analysis in order to examine the interconnections of the model's variables and most particularly the extent that can be influenced by potential alterations of these values, it was revealed that the capacity of the road is critical for the occurrence of traffic congestion generally. Also, additional traffic loads derived from the implementation of a construction project located in this road network deteriorate further the phenomenon of traffic congestion. However, it is difficult to calculate the capacity of a road in practice since it can be affected by many factors. Thus, due to the fact that the designed prognosis model of this study introduces as an input variable the examined road's capacity which is difficult to be well-defined, *introducing the road's capacity as the model's input variable is a limitation itself*.

Moreover, the proposed linear mathematical formula of the model provides a strong relationship between the used variables. Therefore, *the model's validity depends on the reliability of the input data*. As a result, the stakeholders' efficient communication is required for the functionality of the model in order to use correct data.

Unfortunately, based on the literature review as well as the interviews' findings it was highlighted that in most cases, and especially for complex construction projects, there is a high possibility for different perceptions and conflicts among the involved interested parties. The selected input variables that have to be inserted in the external Excel file according to the way that the prognosis model has been designed and developed, can be defined only if there are relevant available data. The availability of the aforesaid data depends on the responsible stakeholders' willingness to gather this type of data. Therefore, *only with efficient collaboration between the involved stakeholders the use of this model is feasible.*

## 7.3 Recommendations

As already pointed out, the problem of managing construction traffic in densely populated urban areas and especially in road networks that are regularly suffering from unfavorable traffic conditions constitutes quite a challenge both for contractors and the responsible regulatory body. Regardless of the constant progress in the field of transportation modeling in order to manage transportation flows, the correlation between the construction industry and transportation management is newly introduced. This study was an endeavor to research -from an academic point of view- the impact of the construction process on the relevant examined road (the location of the construction project). Nonetheless, due to the limitations mentioned in subsection 7.3, there is room for further research and extension of the designed prognosis model.

The following recommendations are based on the observations during the analysis of the problem, the design process, and the evaluation process of the prognosis model.

1. The designed prognosis model considers population growth and weather conditions as influential parameters for the traffic flows of the examined road. However, it was out of this study's scope the determination of these factors. Therefore, it is recommended these factor to be numerically defined.

2. It is indicated from the literature review that transportation movements do not only affect the examined road but also its surroundings in terms of traffic flows. As a result, it would be valuable to observe the transportation flows of the surrounding roads related to the location of the construction project so as to examine to what extent influence the urban area's traffic flows.

3. In the context of this thesis, it was decided to examine only one predetermined route and thus, one road that leads to the construction site of the project. As Matlab software was chosen for its flexibility regarding the prognosis model's extension, more routes can be added and hence a more detailed and realistic outcome can be given.

4. From the validation process and specifically the semi-structured interviews with contractors, it was disclosed that construction companies are concerned about potential problems over the lifetime of a construction project when it comes to cost overruns. This means that if municipalities want to convince the responsible contractors about the negative impact of construction traffic on the project's location it will be more effective to translate possible delays of construction activities or inefficient construction logistics management into cost. Therefore, an extension of the model with potential what if scenarios for predicting the impact of construction traffic not only on traffic flows but also on cost could be useful.

5. Since traffic congestion has a substantial effect on atmospheric pollution and the Netherlands strives for a fully sustainable and resilient city by 2050, an extension of this prognosis model by connecting and quantifying the traffic flows with their respective $CO_2$ emissions is recommended.

6. A significant lack of transportation data was observed throughout the validation process. The contractors are not used to recording the number of the needed vehicles for the implementation of construction activities and mostly regulatory bodies have an interest in traffic control and thus public comfort. Therefore, a protocol that forces the contractors to submit the needed data can be proven useful so as to use the prognosis model and receive reliable results. Contractors should stop neglecting the need for more detailed planning that involves the number of vehicles along the project's construction.

## 7.4 Reflection

This thesis's journey has finally come to an end. It was a pleasant experience that taught me a lot both academically and personally. After focusing on this research for the last few months, it would be wise to take a step back and assess the procedure and the thesis' outcome.

**Procedure**

Looking back, I would say that my topic was pretty broad at first, which made it hard for me to choose where to start. Even though this step was completed efficiently, perhaps I should have been more proactive and more straightforward in asking for the needed data in order to limit the duration of this research. The lack of reliable exact data from the municipality in combination with unrecorded data in this field from the contractors in general, affected the time framework of my study negatively since I spent a fair amount of time trying to achieve reliable estimations. Also, the procedure of assessing data and making reliable estimations was more stressful since I was not used to using empirical data. As I follow a more practice-oriented mindset due to my degree in Civil Engineering, I prefer specific quantified data to work with.

Along with this, a preliminary study on the research field of construction logistics could have improved my performance on this topic in terms of a deeper understanding at the beginning of this thesis. Nonetheless, my engagement on this particular topic and my deep interest in it helped me to gain a lot of new knowledge and it was a pleasant and interesting procedure.

In general, during this research, I felt extremely proud of my flexibility since I had to tackle the lack of data and find ways to develop a “handy” model. Also, since I did not have programming skills and had little knowledge of Matlab software, I devoted very much time to learning and exploring the used software. However, with my commitment and will, I acquired this knowledge. As a result, I undoubtedly broaden and advance my skills in programming.

**Findings**

The findings indicated that the designed model has some potential as an initial rough model that can be further extended. What is not satisfying for me is the depth level of this study since it was conducted in the context of a master’s thesis. I would have been very happy to test the designed model by using reliable data in practice and comparing the model’s output with another already used model.

However, I am proud of the fact that I created a model that can be used by anyone without any special knowledge and is certainly user-friendly. Moreover, I enjoyed the interviews part since I had to be strategic so as to receive the needed information. During this journey, I met experts that inspired me and I have definitely improved my communication skills.

**Retrospective thinking and lessons learned**

One important lesson I gained is that if you already know that a process will be time-consuming and stressful, you have to be kind to yourself when feeling anxious and give the proper self-reward for everything that you have achieved until that point. At some point I was extremely stressed, and my productivity was affected negatively by my pessimistic approach. Nevertheless, the fact that I handled my stress levels was a big accomplishment for me.

The most important lesson that I gained during this research process but also along my whole academic journey at TU Delft is that I proved, first of all to myself, that I am a hard-working person who fights for her goals, no matter what, and I should be proud of this. Since I had to overcome some personal difficulties in my master’s academic years, I always reminded myself of my initial goal and the joy of gaining new knowledge. Therefore, this study helped me to realize once again that with proper support and efficient cooperation, personal continuous effort, patience, and persistence is feasible to fulfill your goals.

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# Appendix A

Figure A.1: Illustration of the Eleven Square project

Figure A.2: High rise buildings of Eleven Square project constructed by different construction methods

# Appendix B

In this appendix, the used Matlab code for designing the prognosis model of this study is given.

```
clear all;
close all;
format long;
clc;
%simplified version of the saturation model for one street with random
%loads and fixed capacity

street_info = xlsread('Input_data1.xlsx',1);
% capacity of the road
cap = street_info(1,1);

%reading the parameters of the model
parameters = xlsread('Input_data1.xlsx',5);
Rthreshold = parameters(1,11);
Rthreshold2 = parameters(1,12);
hour_traffic_factors = parameters(1:10,2);
day_factors = parameters(1:5,4);
hour_construction_factors = parameters(1:10,6);
construction_phase_factors = parameters(1:4,8);
weather_factor = parameters(1,8);


light_loads = street_info(:,4);
medium_loads = street_info(:,5);
heavy_loads = street_info(:,6);






traditional_trucks = xlsread('Input_data1.xlsx',2);
traditional_trucks = traditional_trucks(4:height(traditional_trucks),:);
prefab_trucks = xlsread('Input_data1.xlsx',3);
prefab_trucks = prefab_trucks(4:height(prefab_trucks),:);
mixed_trucks = xlsread('Input_data1.xlsx',4);
mixed_trucks = mixed_trucks(4:height(mixed_trucks),:);


R_trad = zeros(height(traditional_trucks),1);
R_prefab = zeros(height(prefab_trucks),1);
R_mixed = zeros(height(mixed_trucks),1);
R_without = zeros(height(traditional_trucks),1);
R_ref = zeros(height(traditional_trucks),1);
R_ref2 = zeros(height(traditional_trucks),1);


weights = [1 1.5 2.3]*1.1;
hour = 0; %it will rotate between 1 and 10
day = 4; %it will rotate between 1 and 5
for i = 1:height(light_loads)
    hour = hour+1;
```

```
    if hour == 11
        hour = 1;
        day = day + 1;
    end
    if day == 6
        day=1;
    end

    phase_factor_trad = parameters(traditional_trucks(i,5),8);




    R_ref(i) = Rthreshold;
    R_ref2(i) = Rthreshold2;
    R_without(i) = day_factors(day)*hour_traffic_factors(hour)*(light_loads(i) +
medium_loads(i) + heavy_loads(i))/cap;
    R_trad(i) = (day_factors(day)*hour_traffic_factors(hour)*(light_loads(i) + medium_loads(i)
+ heavy_loads(i)) +
phase_factor_trad*hour_construction_factors(hour)*(weights(1)*traditional_trucks(i,2) +
weights(2)*traditional_trucks(i,3) +weights(3)*traditional_trucks(i,4)))/cap;
    if i<length(prefab_trucks)
        phase_factor_prefab = parameters(prefab_trucks(i,5)+5,8);
        R_prefab(i) = (day_factors(day)*hour_traffic_factors(hour)*(light_loads(i) +
medium_loads(i) + heavy_loads(i)) +
phase_factor_prefab*hour_construction_factors(hour)*(weights(1)*prefab_trucks(i,2) +
weights(2)*prefab_trucks(i,3) +weights(3)*prefab_trucks(i,4)))/cap;
    else
         R_prefab(i) = R_without(i);
    end
    if i<length(mixed_trucks)
        phase_factor_mixed = parameters(mixed_trucks(i,5)+10,8);

        R_mixed(i) = (day_factors(day)*hour_traffic_factors(hour)*(light_loads(i) +
medium_loads(i) + heavy_loads(i)) +
phase_factor_mixed*hour_construction_factors(hour)*(weights(1)*mixed_trucks(i,2)+weights(2)*mix
ed_trucks(i,3) +weights(3)*mixed_trucks(i,4)))/cap;
    else
        R_mixed(i) = R_without(i);
    end

end


figure(1)
plot(R_trad,'m');
set(gca, 'FontName', 'Arial Narrow', 'FontSize',12)
set(0, 'DefaultLineLineWidth', 0.5);
set(gcf,'Position',[100 0 900 700])
set(gca,'linewidth',0.5);
grid on
hold on
plot(R_prefab,'g');
plot(R_mixed,'b');
plot(R_without, 'k');
plot(R_ref,'r')
plot(R_ref2,'r',LineWidth=2)
% title('Saturation rate(R) per working hours over the lifetime (working days) of the
```

```
construction project for 3 different scenarios');
ylabel('Saturation rate R');
xlabel('Working Hours');
ylim([0 1])
xlim([0 length(R_trad)]);
xticks(0:1:length(R_trad));
labels =  string(zeros(height(traditional_trucks),1));

for i=1:length((R_trad)/10)
    if mod(i,10)==1
        labels(i) = string(ceil(i/10));
    else
        labels(i) = "";
    end
end

xticklabels(string(labels));
xtickangle(0);
legend('Traditional','Prefabrication','Mixed','Before
Construction','Threshold_1','Threshold_2','FontSize',15);
```

```
%find peak values of each day and plot them
peaks_trad = zeros(length(R_trad)/10,1);
peaks_prefab = zeros(length(R_prefab)/10,1);
peaks_mixed = zeros(length(R_trad)/10,1);
peaks_wo = zeros(length(R_trad)/10,1);

trad_avg = zeros(length(R_trad)/10,1);
prefab_avg = zeros(length(R_prefab)/10,1);
mixed_avg = zeros(length(R_trad)/10,1);
wo_avg = zeros(length(R_trad)/10,1);

for i=1:length(R_trad)
    if R_trad(i) > peaks_trad(ceil(i/10))
        peaks_trad(ceil(i/10)) = R_trad(i);
    end
    trad_avg(ceil(i/10)) = trad_avg(ceil(i/10)) + R_trad(i)/10;
    if R_prefab(i) > peaks_prefab(ceil(i/10))
        peaks_prefab(ceil(i/10)) = R_prefab(i);
    end
    prefab_avg(ceil(i/10)) = prefab_avg(ceil(i/10)) + R_prefab(i)/10;
    if R_mixed(i) > peaks_mixed(ceil(i/10))
        peaks_mixed(ceil(i/10)) = R_mixed(i);
    end
    mixed_avg(ceil(i/10)) = mixed_avg(ceil(i/10)) + R_mixed(i)/10;
    if R_without(i) > peaks_wo(ceil(i/10))
        peaks_wo(ceil(i/10)) = R_without(i);
    end
    wo_avg(ceil(i/10)) = wo_avg(ceil(i/10)) + R_without(i)/10;
end


figure(2)
plot(peaks_trad,'m')
grid on
hold on
plot(peaks_prefab,'g')
plot(peaks_mixed,'b')
```

```
plot(peaks_wo,'k')
plot(R_ref(1:length(peaks_trad)),'r')
plot(R_ref2(1:length(peaks_trad)),'r',LineWidth=2)


% title('Peak daily Saturation rate(R) over the lifetime (working days) of the construction
project for 3 different scenarios');
ylabel('Saturation rate R');
xlabel('Working Days');
ylim([0 1])
xlim([1 length(peaks_trad)]);
xticks(0:1:length(peaks_trad));


legend('Traditional','Prefabrication','Mixed','Before
Construction','Threshold_1','Threshold_2','FontSize',15);
figure(3)

plot(trad_avg,'m')
grid on
hold on
plot(prefab_avg,'g')
plot(mixed_avg,'b')
plot(wo_avg,'k')
plot(R_ref(1:length(peaks_trad)),'r')
plot(R_ref2(1:length(peaks_trad)),'r',LineWidth=2)

% title('Average daily Saturation rate(R) over the lifetime (working days) of the construction
project for 3 different scenarios');
ylabel('Saturation rate R');
xlabel('Working Days');
ylim([0 1])
xlim([1 length(peaks_trad)]);
xticks(0:1:length(peaks_trad));
legend('Traditional','Prefabrication','Mixed','Before
Construction','Threshold_1','Threshold_2','FontSize',15);
```

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