Prospective Criminal Escape Routes

An Exploration of Fugitive Escape Route Decision-Making using a Dual-Process Approach

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An Exploration of Fugitive Escape Route Decision-Making
using a Dual-Process Approach

By

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An electronic version of this thesis is available at https://repository.tudelft.nl/.
Associated code and models are available at https://github.com/tomkempenaar/Model_Criminal_Escape_Routes.git

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Tom Kempenaar
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Executive Summary

The negatives effects of criminals are a threat to the Dutch society. In 2019, 15 percent of the Dutch citizens are victims of High Impact Crimes (HIC). Policy-makers have been mainly focused on disseminating information to businesses and individuals on how to protect themselves and their properties against crime and violence. However, an increased arrest rate is likely to have the largest impact on reducing the negative effects of HIC. Therefore, this research aims to explore the criminal escape route decision-making, to understand the choices made by criminals during their escape, resulting in a higher arrest rate. Since there is a lack data on escape routes, the modelling approach is used for this research. Therefore, a simulation model is developed to predict the prospective fugitive escape routes. The developed discrete-event model for criminal escape route decision-making within Rotterdam is developed based on both expert knowledge from the Dutch Police and the dual-process theory for criminal's decision-making developed by van Gelder. Analysis of the interviews held with the Dutch Police shows that, type of crime, location of crime, and time of crime are varied to explore the escape route decision-making of criminals. From the analysis of the model outcomes, we conclude that organized crime criminals prefer the bigger (S and N) roads to escape the spatial area. Whereas local criminals prefer smaller (S and collector) roads to escape the spatial area. Traffic density influences the destinations and road use of organized crime criminals in a more distributed use of smaller roads instead of the bigger S and N roads. The location of crime results in different behavior in terms of destination, road use, and choices. The acquired knowledge of this research can result in catching the criminals faster after the crime, due to improved knowledge on potential decisions a criminal could take. Further research should focus on low-level decision-making to give researchers more detailed insights in criminals escape route behaviour. However, additional research is necessary on how personal and micro-level spatial factors influences the criminal escape route decision-making. Also, further research should focus on developing a real-time simulation model for the Dutch Police to predict possible locations of the criminals during the fugitive escape. Therefore, implementing additional features (e.g., live traffic, traffic lights, and micro-level spatial characteristics) to increase the feasibility of the simulation model is recommended. However, additional research is needed on how the additional features influences the criminal escape route decision-making.

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1. Introduction

In this chapter, the main problem of this thesis research is described and the general steps for this research are given. First, a global introduction is given about the criminal system in the Netherlands. Second, a short overview of the existing research is given by means of a literature review. Following, the research design including knowledge gaps, scoping of this research, and research questions are presented. Lastly, the research flow of this research is visualized.

1.1. Problem Description

This section elaborates first on the general problem of this research. Thereafter, the problem from the perspective of decision makers and researchers are described.

1.1.1. Problem explanation: Criminality in the Netherlands

The negatives effects of criminals are a threat to the Dutch society. In 2019, 15 percent of the Dutch citizens are victims of High Impact Crimes (HIC) (Statistics Netherlands, 2020a). HIC are residential burglaries, robberies, and street robberies. Whereas mostly citizens are victims of those crimes. In recent years, the HIC number have been reduced significantly from 120.000 in the 90s to 40.000 in 2019 (Statistics Netherlands, 2020b). Even though, the Netherlands scores below Europe's average on HIC statistics (European Statistics, 2021) improvements can be made. In recent years, the priority of the police has shifted from HIC towards cyber crime and organized crime. However, in addition to the direct property losses of 150 million Euro's a year, victims can be traumatized by the unprovoked confrontation with the robbers. Therefore, it is imperative to reduce the negative effects of HIC. Policymakers have been mainly focused on disseminating information to businesses and individuals on how to protect themselves and their properties against crime and violence. Consequently, the HIC numbers decreased. However, the increased arrest rate is likely to have the largest impact on reducing the negative effects of HIC (Wan et al., 2012). Furthermore, only 25 percent of the criminal offenses in the Netherlands resulted in a suspect (Ministry of Justice & Security, 2020). The first moments after a HIC are imperative to catch the criminals. Getting the criminal caught in the act is the best way to close the case. However, most pursuits are abandoned, others end in crashes, injuries, and even fatalities (Cording et al., 2020).

1.1.2. Problem explanation: Research Perspective

Last decades, little attention has been given to the actual decision-making of criminals. According to Nagin (2007), this negligence to the decision-making of criminals averted attention that are fundamental to the understanding of crime. Furthermore, despite the negative impact of HIC criminals on the society little research have been conducted on fugitive escape route decision-making. Gaining knowledge about fugitive escape route decision-making can therefore result in strategy development of the police to find fugitives faster after a robbery. Nowadays, research on criminal decision-making is mainly focused on using, either the classical theory of crime by Becker (1968), or the theory of reasoned action by Fishbein & Azjen (1977). Both, theories assume a rational calculated criminal. However, in reality a criminal does not act fully based on rational calculations but do act impulsive based on emotions and external events. Improving the understanding of criminal behavior can potentially lead to lowering the negative effects of criminality.

1.2. Literature Review

In this section, the concepts, core definitions, and related work are given and examined to eventually identify knowledge gaps. First, the core definition of crime is discussed. Whereafter, literature on criminal decision-making is presented.

1.2.1. Criminality

Criminality is the aggregated consequence of criminal behavior of humans in different social-, and environmental conditions (Mehlkop & Graeff, 2010). Criminality generally do have a profound impact on the victim, his or her immediate environment and the sense of security (Shapland & Hall, 2007). Because the negative effects are notorious, various researchers, agencies, government institutions and nonprofit organizations are conducting research into all types of crime. Moreover, explaining and modelling fugitive escape behavior is a research area that has examined by multiple criminologists, socialists, policymakers, and the police since the first crime statistics were recorded (Malleson et al., 2010). Furthermore, there is a lack of data about prospective fugitive escape routes. Consequently, resulting in a lack of understanding about the criminals decision-making right after the criminal act, in more detail the lack of understanding in fugitives escape route decision-making. Modelling escape routes are the alternative to generate data of fugitive escape routes. However, fugitive escape route decision-making is a difficult phenomenon to model because of its inherent complexity; it is dependent on a multitude of human-human, human environment, and micro-interactions that ultimately lead to individual fugitive escape choices (Malleson et al., 2010).

1.2.2. Criminal Decision-Making

A number of psychological frameworks have been used to model criminal behavior. Two of the most used frameworks are reviewed here: (i) The economic theory of crime (Becker, 1968; Clarke & Cornish, 1985); and (ii) Theory of reasoned action (Fishbein & Ajzen, 1977).

The economic theory of crime

The economic theory of crime is a framework developed by Becker (1968) and is based on the cost-benefit analysis theory. This framework assumes a fully calculated actor; accordingly, decisions are made based on costs and benefits resulting from criminal acts (Becker, 1968). According to this theory, criminals try to maximize their advantages such as physical well-being or social recognition through criminal acts, while avoiding negative consequences at the same time. According to Becker (1968) the expected utility (EU) for the offence (S) can be calculated by the benefits (B) of the criminal act minus the probability of being caught (p) multiplied by the expected costs (C). The equation is as follows:

$$EU[S] = B - pC \qquad (1)$$

Following the equation, a crime is more likely to occur if the expected utility of a crime is positive, that is if the benefits are greater than the probability of costs multiplied by costs. The probability (p) differs depending on distinct factors, such as personal-, social-, situational-, and other factors (Mehlkop & Graeff, 2010). It is assumed that the costs that the criminals have to pay for this behavior are related to the degree of penalty for different offences. However, the degree of costs is uncertain and differ amongst individuals (Mehlkop & Graeff, 2010). The decisions are influenced by the knowledge of the legal system and by their own experiences with public prosecution. Different criminal behavior of different social classes therefore can be explained within a cost-benefit framework such as the above-described framework. Next, several examples of research focusing on the economic theory of crime are given: First, O'Grady et al. (2000) used the economic theory of crime to examine the illegal tobacco sales to youth. Second, Simpson et al. (2002) researched factors influencing the decision-making of corporate crime while implementing the economic theory of crime. Third, Clarke and Cornish (1985) developed a framework for modelling the effect of policy interventions on criminal decision-making which is related on the economic theory of crime.

The theory of Reasoned Action

Fishbein & Ajzen (1977) developed one of the most prominent theoretical frameworks to predict human behavior: 'Theory of Reasoned Action' (TORA). TORA is a framework about beliefs, attitudes, and intended behavior. Briefly summarized, an intention to engage in criminal acts is considered to be the best predictor whether a criminal engages specific behavior (Fishbein & Ajzen, 1977). Intentions are predicted in their turn by two variables. The first variable is a person's attitude towards an act. Does the criminal see his or her action in a positive or a negative way? The second variable is about the norms of a person about the act. Does the criminal see his or her action as something others think she or he should do or not? Moreover, according to Fishbein & Ajzen (1977), behavior can be expressed in the following equation:

$$BI = A_{act} + SN \qquad (2)$$

The behavior intention (BI), which can be any act, is a result of the sum of two variables: attitude towards the behavior involved (A_{act}) and the subjective norms (SN) towards the act. Resulting in the TORA to be uncompromisingly cognitive, and therefore holds only two variables (Tuck & Riley, 2014). Furthermore, the chosen act is the highest sum of BI, and therefore actors' calculated rationality is assumed. Next, a few examples of research focusing on the theory of reasoned action are given: First, Sulak et al. (2014) applied TORA to research domestic violence. Second, Gastil (2000) researched the intention to drive while intoxicated.

1.2.3. Discussion of both theories

Both theories are commonly used to model and predict criminal behavior. However, there is still much debate amongst researchers to what extent the theories are valid for predicting criminal behavior. Both theories are cognitive frameworks, with the assumption of a fully calculated actor according to the utilitarian perspective (van Gelder, 2013). However, Jacobs and Wright (2010) stated that criminals exhibit bounded rationality and tend to choose for an act that is satisfactory instead of the optimal. Furthermore, either the economic theory of crime and theory of reasoned action consider feelings and emotions as unrelated to the decision-making process (Svensson et al., 2017; van Gelder, 2013, 2017). However, several researchers claim otherwise (Cromwell et al., 1999; Mamayek et al., 2015; Shover, 1991; Svensson et al., 2017). Shover (1991) argued that moods can distort the criminal decision-making severely and make offenders unconcerned about risk. Furthermore, Cromwell et al. (1999) found that more than 20% of the interviewed offenders directly implicated their feelings as the primary motivation for their criminal behavior. Additionally, according to Svensson et al. (2017) moral beliefs cannot be added to both theories, which is one of the reasons both theories are heavily debated within criminology. Even more, risk seeking behavior results from persons with low-self control and are tempted by easy gratification and are not focused on long-term costs of their actions (Mamayek et al., 2015). Which cannot be captured within both theories. Subsequently, Daniel Kahneman (2011) authored a book, called Thinking, Fast and Slow, about his research of the human decision-making. In his research he stated that human are intuitive thinkers and that humans' choices deviate substantially from economic models. The approach taken in either TORA or economic theory does not fully capture findings from latest research about decision-making behavior as discussed above. Extending models of criminal decision making is likely to increase the explanatory scope of fugitive escape route decision-making.

1.2.4. Dual-Process Theory

Therefore, van Gelder (2013) proposed an alternative framework of criminal decision making based on dual-process theories in social psychology and related fields, such as behavioral economics and neuroscience. His proposed framework is strongly related to system thinking defined by Kahneman (2011) in his book Thinking, Fast and Slow. The most important insight from both researchers is that human's brain has two modus operandi. First, the most important and most used component, is the unconsciousness and fast way of thinking. This mode evaluates in a more intuitive way and responds to different situational characteristics, such as the temporal and spatial factors. Second, the consciousness and slow way of thinking. This mode is sensitive to considerations such as probabilities and calculated choices. Van Gelder (2013) distinguish both modes as the hot-, and cool mode. He proposed his framework in addition to the dual-process theory for law-abiding citizens and focuses on decision-making process for criminals. The notion of two systems that guide decision-making and information processing lends itself potentially well for researching and exploration of criminal behavior. According to Mamayek et al. (2015) risk-taking behavior such as crime is not solely due to cost benefit analysis nor is its people impulsive behavior but involves the operandi of both modes. Therefore, this research will take the dual-process framework developed by van Gelder (2013) as a basis for exploration of fugitive escape behavior.

1.3. Research Design

This section describes the design of this thesis research. First, the knowledge gaps following from the literature review are discussed. Whereafter, the scope of the research is defined. Lastly, the general research approach is viewed.

1.3.1. Knowledge Gaps

From literature review, the following knowledge gaps are identified:

- How should the prospective escape routes of criminals be modelled to improve the understanding of fugitive escape route decision-making.
- What influences the escape route decision-making of the criminals after a HIC, and what general rules and observations can be delineated from the chosen routes.

Next, to these knowledge gaps resulting from the literature review, the Dutch Police emphasizes the need to identify fugitive escape routes in real time. Improving the understanding of the fugitive escape route decision-making can result in a higher arrest rate of the criminals. Consequently, the Dutch Police and her interests and knowledge is involved throughout this entire research.

1.3.2. Research Scoping

Due to time constraints of this study, a demarcation of the research field is imperative to come to a challenging and relevant research question. This demarcation is two-fold: which types of crime, and what are the locations of the crimes, are considered. There are many types of crime from cyber crime to money laundering, from sexual harassment to drug crime. Because for each different type of crime, criminals do have different interests, goals, and reasoning, resulting in different behavior. Therefore, it is important to differentiate between these crimes. This research focuses on escape route decision making of criminals after they committed a High Impact Crime in an urbanized area. As aforementioned a HIC is a crime with a profound impact on the victims, resulting in residential burglaries, street robberies, thuds, liquidations etc. HIC are chosen because of the negative consequences for victims resulting from the violence of the HIC. This research focuses on the prospective escape routes of criminals, to develop a valid model a spatial scoping is imperative to increase the validity of this research. Therefore, the Rotterdam City District is chosen as the area of fugitive escape route exploration. Rotterdam is chosen because of its relatively high automobile friendliness, differentiation spatial characteristics, and surrounding highways and regional roads. Furthermore, Rotterdam can be seen as a city that is similar to the average city in Europe between 500 000 and 1 000 000 citizens, layout and characteristics are comparable to each other. Rotterdam is a city with more than 600 000 citizens, while having a harbor, airport, and highways connecting the surrounding area. Moreover, Rotterdam is rebuilt after bombing in the second world war, resulting in a modern designed spatial layout.

1.3.3. General Research Approach

The objective of this research is to provide policymakers and the Dutch Police with well-substantiated knowledge on fugitive escape route decision-making, therefore, a thorough identification and exploration of prospective fugitive escape routes is needed. However, there is the lack of data on fugitive escape routes and therefore data needs to be generated. Consequently, the most suitable type of approach is the modelling approach. As the definition states: a modelling approach is suited when there is a lack of understanding of the functioning of a socio-technical system. One can conclude that developing a model is imperative to predict and simulate the prospective the escape routes of criminals. Having the escape routes of criminals result in the analysis of the escape route decision-making and therefore the understanding of criminal escape route behavior.

1.4. Research Questions

Combining the aforementioned knowledge gaps from literature, Dutch Police, and scoping, the following main research question will be answered throughout this research:

What are the effects of the time-, the location-, and the type of crime on the criminal escape route decision-making after a High-Impact Crime using the dual-process theory?

To address the main research question, and the following sub questions (SQ) will be covered:

First, a literature review and experts' interviews will be held to select the factors influencing escape route decision-making of criminals. Hereafter, a conceptualization of the criminal escape route decision-making can be developed. This objective forms the first sub-question:

SQ1: Given the dual-process theory how to conceptualize the fugitive escape route decision-making of a criminal after a High-Impact Crime?

Second, an appropriate and valid model to simulate the escape route decision-making of criminals after a robbery in an urbanized area will be developed.

SQ2: How can the criminal escape route decision-making be simulated given the spatial-, temporal-, and situational factors?

Third, a number of experiments are set up to be able to analyze the outcome results. This sub-question will add societal value in reducing the crime numbers. The analysis of outcome results are imperative towards understanding of fugitive escape route decision-making within Rotterdam.

SQ3: What are the effects of time, location, and type of crime on the escape routes after a HIC in Rotterdam?

The goal of this research is to prospect fugitive escape routes and investigate the criminal escape routes to increase the understanding of the escape route decision-making and therefore to increase the arrest rate of the Dutch Police.

1.5. Research Methods per Sub Question

In this section, per sub question the research methodology is discussed and presented. In order to answer each sub questions, a series of different research methods, data requirements, and analysis tools are necessary. Next, all these elements for each sub question will be addressed. Figure 1.1 provides an overview of the methodology for each sub question in terms of a research flow diagram.

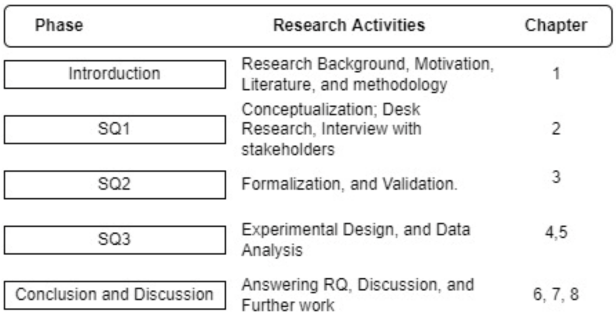

Figure 1.1: Research Flow Diagram

Sub question 1

For SQ1, qualitative data in the form of peer-reviewed literature related to criminal's decision-making during a fugitive escape considering the dual-process framework is needed. In collecting reliable (scientific) data a better insight on relevant factors influencing fugitives' decisions throughout a fugitive escape is possible. It is important to understand how criminals are influenced and what determines and influences their choices based on the dual-process framework during a fugitive escape. This literature data will be collected during desk research. The desk research consists of data collection using Scopus, TU Delft World Cat, and Web of Science. The tool Mendeley will be used to bookmark and order all the found literature. Additionally, interviewing experts (e.g., police officers from several police departments with different knowledge on different topics) results in knowledge which can contribute to answering the first sub-question. Therefore, conversations and semi-structured interviews are held with aforementioned experts. The guidance of these interviews is added to the appendix A. However, due to confidentially and social sensitivity of this subject, a fully transcript of the conducted interviews held with several police members working at different departments are not available to read, instead a summary will be given. The output of the first sub question is a table consisting of the found relevant personal-, temporal-, and situational factors related to criminal escape decision-making after a robbery based on the dual-process framework. This table is a conceptualization of the criminal escape-route decision-making.

Sub question 2

Having both the knowledge on how fugitives are influenced during the fugitive escape and how dual-process framework can be used, the abstract fugitive decision rules can be translated towards a formal model using the dual-process framework. More specifically, to better understand the decision making of fugitives, the literature and knowledge on robberies and chasing events will be synthesized into a formal model. Then a situation-based model that focusses on dual-process framework for fugitive escape behavior with specific offenses and locations will be developed. The output of sub question 2 is both a formal model and discrete-event model. This formal model is build using various conceptualization steps, such as pseudo-coding, model narratives, and flow diagrams. In conceptualizing the proposed socio-technical system *draw.io* will be utilized. The formal model will be build using the discrete-event system specification. Modelling psychological frameworks (e.g., dual-process) are not commonly applied in a discrete-event model, but has the potential (Brailsford & Schmidt, 2003). It was found to be very easily implemented, efficient, and effective (Brailsford & Schmidt, 2003). Therefore, the conceptual and formal models will be translated into a discrete-event model using a *Python Programming Language*. Lastly, validation steps will be conducted. Expert validation will be carried out, to validate the model. Therefore, several experts will be interviewed and asked to validate the model. The experts can be police officers, psychologists, criminologists, and (ex-) convicted criminals. However, due to time limitations and confidentiality reason, solely members of the Dutch Police are used as experts. The output of sub question 2 will be a validated discrete-event model, to explore fugitive escape routes after committing a burglary in an urban area.

Sub question 3

In order to address sub question 3, various simulation runs will be executed, therefore escapes routes from different robbery locations in Rotterdam City District will be generated. An experimental setup will be developed, whereas different sets of input variables are imperative to explore the influence of the type of criminal, time of crime, and location of crime. Different scenarios with different initial inputs variables are simulated to gather different outcome results. These outcome results will be analyzed using several diagrams, figures, and graphs. Libraries in Python are used to generate graphs, diagrams, heatmaps, histograms etc. to analyze the data. The output will be an analysis of all the outcome results of a HIC in Rotterdam to explore the escape route decision-making. Resulting in a higher understanding of the criminal escape route behavior after a HIC in Rotterdam.

2. Conceptualization of the Criminal Escape Route Decision-Making

This chapter gives insight in the current state of the criminal's decision-making in terms of route choice decision-making after a robbery in Rotterdam. Moreover, this chapter addresses the first sub-question posed in Chapter 1.4. First, the main concepts of the criminal escape route decision-making in a dual-process approach is discussed. Second, the fugitive escape route events of the criminals are explained. Third, the factors influencing the criminal route choice decision-making are explained in more detail, resulting in a conceptualization of criminal escape route decision-making. Last, the chapter ends with the short summary in answering the first sub-question.

2.1. Main Concepts of the Criminal Escape Behavior in a Dual-Process Approach

This chapter quantifies the main concepts of this research towards a dual-process approach. Previous studies and expert interviews are combined to obtain an operationalization of the escape route decision making of criminals after committing a robbery using the dual-process theory. First, the main concepts of the dual-process theory are described. Second, the main concepts of criminal escape route decision-making are described and operationalized using the dual-process theory.

2.1.1. General Introduction of Dual-Process Theory

Traditionally, criminal decision-making models, such as rational choice, deterrence models, and situational crime, hypothesize a reasoning actor who determines all the benefits against the costs to obtain a decision regarding their choices during the crime (Becker, 1968; Cornish & Clarke, 1986; van Gelder & de Vries, 2014). As aforementioned nowadays decision-making models are restricted to rational choice consideration, those have been challenged and limited in unrealistic portrayal of the criminal decision-making, therefore a few alternative decision-making models have been developed. This research uses the hot and cool model of criminal decision-making developed by van Gelder (2013). Van Gelder (2013) developed the hot and cool perspective of criminal decision-making not to argue against the idea of rationality but offer a more complete explanation and operationalization of the criminal decision-making. Direct ingrained reactions to different factors such as anger, panic, and fear are according to van Gelder (2013) mostly impossible to model as costs or benefits in the traditional theories; they are simply there. This hot and cool model offers a more complete explanation of the criminal behavior by considering the influence of affect and external factors, i.e., feelings, alongside with the rational consideration, i.e., cost and benefit analysis. The hot and cool model distinguishes either the cool, mostly cognitive, mode of information processing and the hot affective mode. The cool mode posits a criminal operating in accordance with the traditional assumptions underlying the rational choice and deterrence theories. Furthermore, the cool mode is not only responsible for weighting costs against the benefits, but also about the long-term consequences of the criminals. The hot mode posits a criminal operating in accordance with the information processing in a more intuitive way and is therefore largely unresponsive to the outcomes of probabilities. The hot mode, however, evaluates in a more intuitive way and the criminals responds to external factors, such as the temporal-, and spatial factors. Differentiating between the hot and cool mode of criminal decision-making is important because feelings and emotions operate according to a different logic than the cognitive probability estimates. According to Frijda (1988): "emotions know no probabilities. They do not weigh likelihoods. What they know, they know for sure." One can conclude that emotions can influence the outcome of the best choice, therefore criminals are likely to act differently, i.e., optimal probabilities, during an emotional state, such as panic or anger. Anger, consequently, can facilitate criminal action, while fear is likely to inhibit it (van Gelder, 2013). The theoretical idea of two different modus operandi can according to van Gelder (2013) elucidate the aforementioned fundamental issues to criminal decision-making that traditional theories have not been able to capture.

2.1.2. Escape Route Decision-making using the Dual-Process Theory

The notion of two systems that guide information processing and behavior lends itself well for studying and describing criminal decision making during the escape after committing a robbery. Next, the hot and cool perspective of criminal decision making is taken as the basis of the operationalization of criminal escape route decision-making after a robbery in Rotterdam. Criminals that committed a robbery are unpredictable and dangerous. This specialized form of criminal theft may target luxury shops, banks, companies, and humans to obtain valuable items in terms of money and/or products. The study of robberies by social scientists, criminologist, and police from the Netherlands have examined the phenomenon almost exclusively in terms of descriptive statistics about what happened and who did it (Cesar & Decker, 2017). Resulting in, no understanding at all about the criminal escape route decision-making. This lack of research limits the ability to operationalize the criminal escape route decision-making. There is research about the understanding of carjackers decisions, Cesar, and Decker (2017) conducted research to get an understanding of the carjacker's behavior relating to the hot and cool model approach. Research from criminologist depict those decision-making processes of robbers are aimed at addressing a pressing need for money to target a specific location to rob (Cesar & Decker, 2017). Additionally, HIC is associated with a high level of victim resistance, resulting in an influence of violence and fear (Topalli et al., 2003). To better understand the escape route decision-making of criminals after a HIC the literature and expert knowledge will be synthesized to eventually integrate a dual-process framework to the criminal decision-making in the escape route behavior. Due to confidentially and social sensitivity of this subject, a fully transcript of the conducted interviews held with several police members working at different departments are not available to read. Nevertheless, summaries of the interviews are added to the appendix A.

Type of Crimes

It is important to first know more about the background of the HIC. This section will describe the basics and general knowledge of HIC in the Netherlands. All the knowledge is obtained from interviews summarized in appendix A. The police stated that a distinction between two types of criminals has to be made to either the local and smaller criminals or criminals that are member of national and international criminal organizations. First, the smaller traditional street criminals who focus on liquid assets and cash. Stolen cash and liquid assets can generate considerable income for the criminals. Those criminals are mostly in a need for fast and easy money. Therefore, these criminals try to obtain as much money and/or liquid assets as possible with as little effort as possible. Consequently, the criminals target houses, smaller shops, jewelers, and citizens. The possible sentences are relatively low and therefore the criminals are not taking the full risk. Furthermore, these criminals mostly originate from the same region as the location of the HIC. Therefore, from now on these criminals will be called the ‘local’ criminals. Second, the police distinguished the bigger and more dangerous criminals. These criminals are mostly member of a criminal organization focusing on bigger targets. These targets consist of bigger shops, and banks, but also on liquidation of important people. These organizations do prepare their robbery carefully, they observe the area and target, to bigger the chance of a successful crime. Possible sentences are relatively high compared to the local crimes, mostly the goal is reached with the use of aggression and violence (e.g., gun violence). Therefore, these criminals are willing to take bigger risks to escape from the police. Because these criminals are mostly members of the organized crime they are called “organized crime” criminals. Now there is a distinction between the criminal type and their criminal act. Next, relating to the preparedness of the criminals a distinction between the vehicle type can be made according to the police. First, the local criminals are as aforementioned less prepared. Both, the local criminals, and organized crime criminals do use a stolen car to escape the crime location. However, they first, start to escape the crime scene with a small and flexible vehicle (e.g., scooter, bike, running, etc.) to their parked stolen vehicle. This vehicle is according to the police generally parked 2 a 3 block from the crime scene. The stolen car however differs a bit between the type of criminal. Whereas the local criminal steals a car shortly before the crime, the criminal uses this stolen car to escape the crime location. Therefore, the stolen car remains relatively visible to the police. Differently is that the organized crime steals a car months before the crime, after stealing the car the criminals copy another car’s license plate with the same characteristics to remain unnoticed to the police. Therefore, it is harder for the police to notice these stolen cars. To conclude, in Table 2:1 a short summary of distinction between these types of criminals are shown. Based on conversations held with the Police one can conclude that both the local-, and organized crime escape route behavior can be distinguished. According to the Police level of preparedness, level of risk, and level of local knowledge are the biggest reasons of this different behavior.

Table 2:1: Local Crime versus Organized Crime

	Local Crime	Organized Crime
Examples of Crime	Shop Robbery, Burglary, Restaurant Robbery	Thud, Liquidation, Bank Robbery
Goal of Crime	Cigarettes, Cell Phones, Jewelry, Cash	Big Amount of Cash, Valuable assets, Murder
Level of preparedness	Not – Prepared	Prepared
Origin of Criminal	Local criminals	Criminals from abroad
Type of Vehicle	Stolen car with same license plate	Stolen car with copied license plate
Level of risk	Low	High

The Four Quadrant Framework

As aforementioned the dual process theory revolve around the idea that criminals take decisions on two qualitatively different modes of mental processing. The police stated that criminals do act differently based on one important external factor, namely being chased by the police or not. According to the police the criminals not being chased drives based on choices that are in the long term to the best outcomes results. Considering the dual-process theory, one can conclude that this behavior results in a cool system modus operandi. Furthermore, criminals being chased by the police do act differently resulting in unpredictable driving influenced by spatial and external factors. Considering the dual-process, on can conclude that this behavior results in a hot system.

Table 2:2: The Four Quadrants

	Organized Crime		Local Crime	
Cool System	Organized-Cool	Predictable Behavior	Local-Cool	Predictable Behavior
Hot System	Organized-Hot	Unpredictable Behavior	Local-Hot	Unpredictable Behavior

Previously, the boundaries for the criminals and their resulting criminal acts are set for this study. The types of crimes are divided into two different categories. First, the local criminals, which do have a greater understanding of the local area but are less prepared. Second, the organized crime criminals, which do have a less understanding of the local area but are more prepared to escape the crime location. Furthermore, the mental states of the criminals are based on the hot and cool mode. Whereas, being chased by the police is assumed to be the only predictor to in being either the hot-, or cool mode of decision-making. All the above combined, results in a framework visualized in Table 2:2. For the purpose of clarity, the 4 quadrants are called hereafter either, organized-cool, organized-hot, local-cool, or local-hot.

2.2. A Fugitive Escape Route Event

In order to understand escape route decision-making, it is important to get familiar with the escape route procedure of the criminals. Thus, the general process of a robbery and the escape is discussed first. Hereafter, the escape route destinations of the criminal are discussed.

2.2.1. High-Impact Crime Locations

As aforementioned in Section 2.1.2 there are two different types of criminals resulting in different types of HIC. However, the general steps the criminals take to reach their objectives (a HIC) are similar. A HIC is a robbery of specific target, what this target exactly is and where it is, is depending on several factors. However, reasoning of targets is out of this research scope and will not be explained next. Moreover, the entire process before a HIC is out of this scope and will not be mentioned. After choosing a target and the preparation of the target, the criminal commits the HIC. As aforementioned in Section 2.1.2 the criminal uses mostly 2 different vehicles, one to escape the crime scene as fast as possible and one to escape the city area unnoticed to the police. The first vehicle is a fast and flexible vehicle for the first 2 or 3 blocks, this vehicle is mostly seen at the crime scene and therefore the criminal uses a second car to remain unnoticed. Because of scoping this research focuses on the escape route decision-making with the second car. It is unknown to the police what the exact location is of the second vehicle, moreover, is it unknown what behavior they show during the first run. All the above combined resulted in the scoping of the escape with only the second vehicle.

2.2.2. Fugitive Escape Route Process

As aforementioned, the criminals committing a HIC can be distinguished into two different criminals, with both different escape route behavior. Both, the local criminals, and organized crime criminals try to remain unnoticed towards the police. Depending on time, location, and type of crime this is likely to happen. If they commit the robbery during the day in a shop area the chance of being caught is higher relative to a burglary in an empty house in a business area during the night. The criminal gets noticed by the police if a citizen or the police caught or sees the criminal in his act. Combining this with the knowledge obtained in Section 2.1.2 the two types of criminals do act in the hot mode or the cool mode, resulting in different route choice decision-making. According to conversations held with the Police being disturbed in their escape (read: being chased) results in panicking and ad hoc and short-term decisions-based on local and external factors. This behavior can be seen as the hot system developed by van Gelder (2013). Vice versa not being chased results in behavior relating to the cool system (van Gelder, 2013). Therefore, the criminal decides based on the long-term outcomes of the opportunities, he can act based on his pre-determined plan and takes the plan the fits the highest benefits. The exact operationalization will be explained in further detail later on in Section 2.3.

2.2.3. Escape Route Destinations

Once, the criminals start their escape, they aim to reach the escape destinations. The exact location of the criminal’s destination is depending on several factors. As mentioned before this research focuses on Rotterdam and will not focus on the reasoning of the escape route destination outside of Rotterdam. According to the police the ultimate goal is to reach the hiding place, meeting place, or other pre-arranged location. For both the organized crime and local criminal the exact location is different. The local criminals mostly meet somewhere just outside the city to divide the stolen goods and to return home afterwards. The local criminals prefer to avoid highways and therefore take regional roads, the criminals assumes that they can stay unnoticed while driving on the regional roads. Therefore, the destination of the criminal is at the end of regional roads leaving Rotterdam. On the other hand, the organized crime criminals aim to travel long distances as quickly as possible to pre-arranged locations that can even sometimes be abroad. Therefore, the destination of the criminal is assumed to be at the end of highways leaving Rotterdam. Because of scoping this research does not focus on the exact location of the destination, therefore the goal of the criminal is to reach the boundary of the spatial scope of this research.

In this section the process of a fugitive escape event is discussed from crime location to destination of the criminal. To summarize, Figure 2.1 visualizes these steps of the process for both the organized crime and local crime.

Figure 2.1: Process of a Fugitive Escape

2.3. Conceptualization of factors influencing Decision-Making of Criminals

From now on this chapter focuses on the decision-making of the criminals in terms of their route choices. This section elaborates on the factors influencing the route choices of the criminals while driving in their second vehicle, which is a fast and stolen car, to their destination to escape the area. Because of time constraints and lack of knowledge the driving with the first vehicle is left out of the model. It is unknown to the police what the exact location is of the second vehicle, however the estimation of location is known by the Police Until now the route choice decision-making of the two different types of criminals in an either hot or cool mode is a black box. In this section, the black box will be explained and operationalized in terms of general rules and decisions. This black box is encoded towards an operationalization based on the expert knowledge of the Dutch National Police. According to the Dutch National Police there are a few factors influencing the behavior of criminals during their fugitive escape event. The Police stated that the factors influencing the criminal behavior, can be categorized into 3 different categories, namely spatial-, temporal-, and situational factors. First, as aforementioned, the factor of being chased by the police is an important factor that results in different behavior. Additionally, the type of the criminal is an important factor resulting in different behavior. Both factors can be seen as situational factors depending on the situation of the crime. Second, the characteristics of the spatial area are important. To be more specific the driving speed of the roads, the number of lanes, and road categories are important. Third, the temporal factors, such as driving distance over time, and traffic density of the roads. Depending on the time of crime the criminal gets influenced by the temporal factors. Next, the resulting behavior based on the aforementioned factors per quadrant is described.

2.3.1. Organized Crime in the Cool Mode

The criminal in this quadrant is in cool mode and from the organized crime. The criminal is not being chased by the police, resulting in predicted driving to their pre-planned destination based on the cool mode. Once the organized-cool criminal dumped their first vehicle and jumped into their second car, they drive as fast as possible to their destination. The criminals do have a pre planned destination at the end of highways leaving the spatial scope of Rotterdam, because of no disturbance during their escape the criminals do head to their pre-planned destination using their pre planned route. Additionally, the criminal prefers faster roads (km/h), and therefore roads with a shorter travel time. The time of the crime influences the travel time by the traffic density. By driving to the highways, the organized crime criminal is able to drive fast and for longer distances. All the above results in the following, criminals drive the predetermined fastest route towards their pre-planned destination. Van Gelder (2013) mentioned in his framework that the criminal decision-making based on the cool mode results in calculated behavior and therefore chooses the optimal outcome as behavior. One can conclude that this predictable driving can be seen as behavior within the cool mode, whereas the criminal takes the fastest route to the pre-planned destination. It is assumed that the chosen fastest route is the decision with the highest benefits and lowest costs, and therefore relates to the cool mode.

2.3.2. Organized Crime in the Hot Mode

The organized crime criminal in this quadrant has the mental state within the hot-mode. Being in the hot mode results in different driving behavior compared to the organized-cool. According to Police the hot mode is whether the criminal is chased by the police or not. Since the criminal is not known with the surroundings of the area, leading to only understanding of the bigger roads and therefore he is more likely to take those bigger and faster roads. The criminal does not use his predetermined route but does act based on ad-hoc decision. During the chase and being in the hot mode the criminal determines every intersection his routing behavior. First, the number of lanes are important for the criminal. The criminals prefer 2 or more lanes over 1 lane, therefore are they more likely to overtake other cars. Second, the criminals prefer high speed over low-speed road segments. Third, the criminal avoids blind alleys. Furthermore, while driving on regional and highway roads the criminals drive as fast as possible to the nearest highway to escape the city center as fast as possible. While driving on the highway and regional roads, the criminal is known with the directions and therefore he drives with the shortest route to the destination node. Van Gelder (2013) mentioned in his framework that behavior resulting in ad-hoc and short-term decisions based on panicking and emotions can be seen as behavior within the hot system. One can conclude that the aforementioned behavior can be seen as decision-making within the hot mode.

2.3.3. Local Crime in the Cool Mode

The criminal in this quadrant is a criminal originating from the local area without being chased by the Police, resulting in predictable driving based on the cool-mode. Once the criminal dumped there first vehicle and jumped into their second car, they drive as fast as possible to their destination. However, the criminals try to avoid bigger roads, according to the Police the criminal believes he will be less conspicuous. The criminals drive the predetermined fastest compensated by the road category route towards the destination. The pre planned destination is at the end of regional roads leaving the spatial scope of Rotterdam. Van Gelder (2013) mentioned in his framework that the criminal decision-making based on the cool mode results in rational behavior and therefore chooses the optimal outcome as behavior. One can conclude that this predictable driving can be seen as behavior within the cool mode, whereas the criminal takes the fastest route to the pre planned destination. Based on interviews held with the Police, it is assumed that the shortest route is the decision with the highest benefits and lowest costs, and therefore relates to the cool mode.

2.3.4. Local Crime in the Hot Mode

The criminal in this quadrant is compared to Local-Cool criminal in the hot mode. Being in the hot mode results in unpredictable driving behavior. According to Police, the hot mode is whereas the criminal is chased by the police and therefore the criminal is panicking. The local criminal has a greater understanding of the local area; therefore, they know all the smaller and bigger roads. During the decision-making process, the criminals use this greater understanding. Similar to the organized-cool criminals they do not use their predetermined route but do act based on ad-hoc decisions. During the chase, the criminals determine every intersection their routing behavior. First, the criminals avoid blind alleys. Second, a distinction per road category can be made. Therefore, the criminals choose random driving on the smaller city roads. Driving random the criminals assume that the chance to escape are higher while driving predictable. Next, driving on bigger city roads, the number of lanes are important for the criminals, therefore they prefer the roads with more lanes. Third, while driving on regional roads the criminals avoid driving on the highway. Furthermore, while driving on the regional roads the criminals drive as fast as possible towards the nearest regional road to escape the spatial boundary. Van Gelder (2013) mentioned in his framework that behavior resulting in ad-hoc and short-term decisions based on panicking and emotions can be seen as behavior within the hot system. One can conclude that the aforementioned behavior can be seen as decision-making within the hot mode.

2.4. Summary of Conceptualization

In this chapter, the black box of escape route decision-making is encoded towards a more formal language to model the criminal escape route decision-making. Therefore, the different spatial-, temporal, and situational factors are motivated and explained. Based on the 4 quadrants described in chapter 2, the relation between the influencing factors and the quadrants are explained. All the factors and their relation to the 4 quadrants are summarized in Table 2:3.

Table 2:3: Factors Influencing Criminal Escape Route Decision-Making

	Organized-Cool	**Organized-Hot**	**Local-Cool**	**Local-Hot**
Situational Factors				
Type of Criminal	Organized	Organized	Local	Local
Mental State	Cool	Hot	Cool	Hot
Spatial Factors				
Allowed Speed	Higher Speed	Higher Speed	Higher Speed	Higher Speed
Number of Lanes	No influence	More Lanes	No influence	More Lanes
Road Category	No influence	No Influence	Smaller Roads	No Influence
Temporal Factors				
Travel Time	Less Time	Less Time	Less Time	Less Time
Traffic Density	Lower Density	Lower Density	No influence	No influence

3. Formalization of Criminal Escape Route Decision-Making

After identifying the fugitive escape event, criminal characteristics, and factors influencing the criminal escape route decision-making, this Chapter builds upon the previous chapter to develop a formal model in order to simulate the prospective escape routes of criminals. Until now the black box of criminal escape rout decision-making is explained in factors and the relations between those factors in a narrative form. Next, this narrative will be formalized into conceptual-, and formal models. First, the network generation is explained. Second, the criminal as entity with several attributes will be explained. Third, an elaboration on the formal rules of criminals' behavior are viewed. Lastly, the formal model's translation to a Discrete-Event model will be discussed.

3.1. Spatial Network

As discussed in Chapter 1.3.2, the spatial network consists of the city district of Rotterdam. Before the spatial graph can be generated it is imperative to know the characteristics and the factors that are used to define the graph, this is explained is next. Whereafter, the limitations and simplifications are described.

3.1.1. OSMNX

A network with all the spatial characteristics will be generated using the OSMNX module of Python. OSMNX is a Python package that is able to download spatial data, project, and visualize the urban networks (Boeing, 2017). Therefore, the spatial network of Rotterdam will be generated using the OSMNX package. As mentioned in chapter 3, there are factors relating to the network, that are imperative to add as attributes of the network graph. Therefore, the OMSNX takes the allowed speed, travel distance, travel time, road category, and number of lanes as attributes of the network. This network consists of nodes and edges, with the edges as streets and roads connecting the nodes as intersections of the spatial area. The attributes connected to the network graph are visualized in Table 3:1.

Table 3:1: Network Graph Attributes

Edge Attributes			
Origin Node	Integer	Node ID	Real Data
Destination Node	Integer	Node ID	Real Data
Length	Float	Meters	Real Data
Allowed Speed	Float	Km/h	Real Data
Travel Time	Float	Seconds	Real Data
Road Category	String	[Small City, Big City, Regional, Highway]	Real Data
Number of Lanes	Integer	-	Real Data
Road Category Factor	Float	-	Assumed
Traffic Density	Float	-	Assumed
Node Attributes			
Node ID	Integer	-	Real Data
Connecting Out Nodes	Integer	-	Real Data
Connecting In Nodes	Integer	-	Real Data
Geometry Location	Float	Longitude, Latitude	Real Data

Using OSMNX with adding the in visualized attributes a fully spatial model of Rotterdam can be generated. Nevertheless, to change the spatial OSMNX graph into a discrete-event Model it is imperative that sources, servers, and sinks are defined. First, sources are plausible starting nodes of the crime in the simulation. Based on interviews, one can conclude that criminals mostly use strategies that consist of intermodal transport choices. The first moments the criminal tries to escape the crime scene, he uses fast and flexible vehicle to a place with their next transport, a faster car. Because of time constraints and lack of knowledge the driving with the first vehicle is left out of the model. It is unknown to the police what the exact location is of the second vehicle. Therefore, the exact starting location are determined based on the location of the crime but also in a residential area, parking places. The experts stated that the distance of the first vehicle is mostly 2 or 3 blocks from the crime location. Therefore, the starting positions of the criminals are small city intersections in a distance between 750 and 1 000 m of the crime location. Second, all intersections in the scoped area of Rotterdam will be transferred from the nodes in a network graph into servers of a discrete-event model. All servers are connected by links, which represent the edges (roads) in the network. Third, sinks are the plausible end nodes of the criminal. Based on interviews held with the Police, the researcher assumed that the destination of the criminals differs for each type of criminal. First, the organized crime criminals mostly target faster highways to escape from the regional area. Second, local criminals use the regional roads to escape the area. For either the local and organized crime criminals the destinations are set to ending locations of possible regional- and highway roads. The possible destination nodes are visualized in Figure B.1.

3.1.2. Spatial Network Assumptions

To generate the network graph a few assumptions needed to be made, the research demarcations in section 1.3.2 are used as a starting point for this section. The spatial network assumptions are listed below:

- **Spatial Boundaries –** the assumed boundaries used are the city boundaries of Rotterdam. Rotterdam is chosen because of its relatively high automobile friendliness, differentiation spatial characteristics, and surrounding highways and regional roads. Rotterdam can be seen as an average European city with 500 000 and 1 000 000

- **Location of the Sink Nodes –** Based on the knowledge of the Police the destination nodes of the criminal are assumed to be tactical locations to leave the spatial region. According to the Dutch Police criminals from organized crime escape the area through the highway. Therefore, the highway end locations, North, East, South, and West (A13, A20, and A16) are used as plausible escape nodes. The criminals from local crime escape the area through the regional road, with avoiding highways. Therefore, regional roads to leave the region via North, East, South, and West. Exact location can be seen in Figure B.1.

- **Road Category Weight Factor** – Additionally, the Road Categories are established in numbers to quantify the Road Categories, which are visualized in Table 3:2. Therefore, weight factors of the attitude of criminals towards the different road categories are used. The weight factors are based on the expert knowledge of the interviewed Dutch Police.

Table 3:2: Road Category Weight Factor

Road Category	Factor
Small City	1.00
Big City	1.00
Regional	1.75
Highway	2.00

- **Traffic Density** – Based on the Road Category the traffic density is added to the edges, therefore real data of live traffic flows (e.g., Google Maps, Flits Meister, etc.) are used to quantify the traffic flow. The traffic density can be used to determine the new travel time compensated by traffic density during the simulation run. The traffic density factors are visualized in Table 3:3.

Table 3:3: Traffic Density Factor

Road Category	Factor
Small City	1.00
Big City	1.50
Regional	1.75
Highway	1.75

- **Road Category** – The researcher divided the different road types into only 4 different categories. This categorization (Table 3:4) is based on the type of road from the OSMNX road database, combined with the Dutch Road categorization Sustainable Safety Covenant (DVV) (Rijkswaterstaat, 2021).

Table 3:4: Road Type Categorization

Road Category	Road Type OSMNX	Road Type DVV
Small City	Living Streets, Residential, Unclassified	Collector Roads
Big City	Primary Roads, Tertiary Roads	S-Roads
Regional	Regional, Secondary, Trunk	N-Roads
Highway	Highway	A-Roads

3.2. Criminal Decision-Making

To prospect the fugitive escape routes of criminals after a robbery in Rotterdam, the most important component is the decision making of the criminal. In this section the decision-making of the criminals are described in more detail. First, the criminal and its attributes are described. Hereafter, the formal models of the criminals' decision-making are described.

3.2.1. Formalization of the Criminal

The criminal is the entity of the Discrete-Event model. The criminal is generated at a source and moves over links (roads) and servers (intersections) throughout the model towards the destination node (sink). The criminal is an entity in the model, which has several attributes that are important throughout the model runs and therefore determines the entities route choice decision-making. The attributes are viewed in Table 3:5 and can be distinguished into two different categories. First, the input parameters. The input parameters are the attributes of the criminal that are set before the start of the run and can not vary throughout the process. Second, the attributes, are the parameters that can change throughout the process, this attribute will be update every event.

Table 3:5: Criminals Attributes

Input Parameters:	
Type of Criminal	Organized or Local
Type of inner state	Hot-mode or Cool-mode
Location of Crime	Lon Lat place in Rotterdam
Starting Node	Node name of starting node
Time of Crime	Time of the day
Attributes:	
Previous Node	Node name of previous node
Nodes	List of node names
Road Type of edges	List of categories travelled edges
Speed of edges	List of speed travelled edges
Choices	List of taken decision at nodes
Destination Node	Node name of Destination (Sink)

3.2.2. Formalization of Decision-Making

After identifying the factors influencing the criminals' behavior in Section 2.3, the formalization of the criminals' decision-making will be illustrated in this section. Based on the input parameters the criminals' initial behavior can be determined. However, the factors described in Chapter 2 influences the behavior. Next, the formalization of each quadrant is discussed. The formalization is based on the gathered information in Chapter 2 from expert knowledge. Furthermore, formal flow charts are visualized to substantiate the operationalization of the criminals' behavior. At the end all the formal charts are programmed into python functions to determine the next destination of the criminal.

Organized Crime in the Cool Mode

The criminals in this quadrant are from the organized crime and acts within the cool mode, resulting in predicted driving from starting node to the destination node of the criminal. The destination node is determined before the start of the simulation run. Because the criminals are from the organized crime their goal is to escape the area through the highway sink nodes. However, the criminals do travel based on their pre-planned destination, this destination is based on uniform distribution of the possible highway end nodes. Furthermore, because the criminals act based on the cool mode, resulting in calculating behavior. The shortest route is assumed to be the decision that has the highest benefits and lowest costs. Therefore, the criminals choose the shortest route towards his destination. As aforementioned, the traffic density influences the travel time during rush hours, therefore Table 3:3 visualizes the assumed traffic density factor. To calculate the shortest path Dijkstra's algorithm is used. Dijkstra's' algorithm is an algorithm to find the shortest path in a graph using the edge attributes travel time compensated with the traffic density at the time of crime. Figure 3.1 visualizes the aforementioned decision-making in a formal flow-chart.

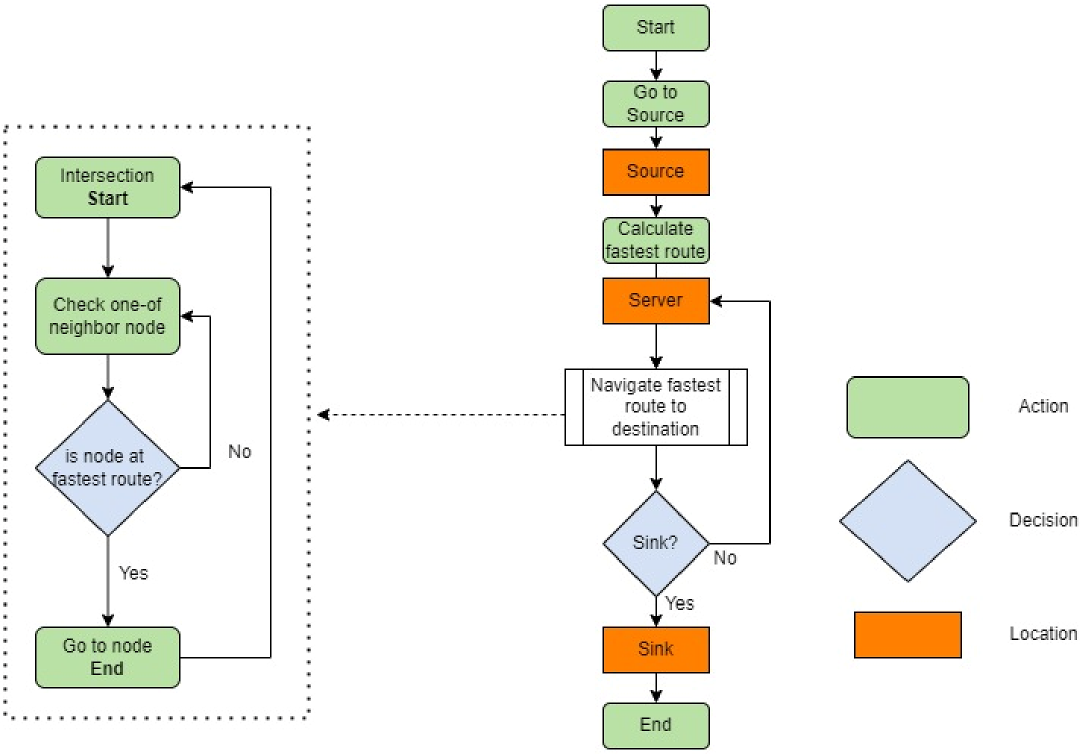

Figure 3.1: Formal Model Organized-Cool

Organized Crime in the Hot Mode

The criminals in this quadrant are from the organized crime and acts within the hot mode, resulting in unpredictable and dangerous driving from starting node to the destination node of the criminals. The criminals are chased by the Police and therefore act based on the hot mode, the criminals take ad-hoc and short-term decisions. At every intersection, the criminals take a decision based on the characteristics of the intersection. First, the criminals determine while driving on the small city and big city roads all the possible linking roads and adds a decision-number to the road. The decision number is based on the number of lanes and allowed speed of the possible connecting road, Table 3:6 visualizes the choice numbers. Additionally, the criminal takes the road with the highest choice number. Based on conversations held with the Police the choice numbers shown in Table 3:6 are determined, therefore more than one lane is preferred over speed, whereas higher speed is preferred over lower speed. Second, the criminals avoid blind alleys in all situations, therefore a blind alley will not be the next road. Third, if the criminals drive on a regional or highway road the criminals take the fastest route to the closest destination node that the criminals use to escape the area via the highway. All the above is visualized in Figure 3.2.

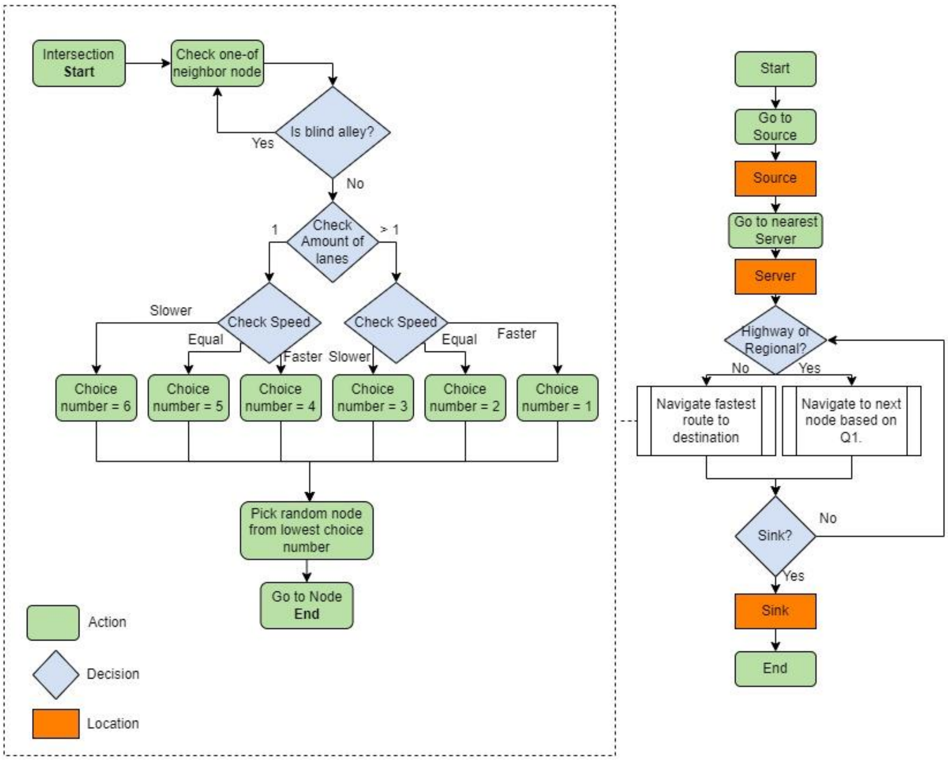

Figure 3.2: Formal Model Organized-Hot

Table 3:6: Choice Numbers for Organized-Hot

Choice Number	Number of Lanes	Allowed Speed
6	More than 1	Higher Speed
5	More than 1	Equal Speed
4	More than 1	Lower Speed
3	1	Higher Speed
2	1	Equal Speed
1	1	Lower Speed

Q3: Local Crime in the Cool Mode

The criminals in this quadrant are from the local crime and act within the cool mode, resulting in predicted driving from starting node to the destination node of the criminals. The destination node is determined before the start of the simulation run. Because the criminals are from the local crime and their goal is to escape the area through the regional sink nodes. However, the criminals do travel based on their pre-planned destination, this destination is based on uniform distribution of the possible highway end nodes. As aforementioned, the criminals have a great understanding of the local area and therefore the criminals avoid bigger roads and prefer smaller roads to reach the destination. Equal to the Organized-Cool criminal the criminals act based on calculating behavior and choose therefore the route with highest benefits and lowest costs, which is assumed to be the shortest route from the starting location to the destination node of the criminal. However, as aforementioned the shortest path is compensated by the quantification of the road category. This assumption has been made to model the preferences for a small city road over a big city road. To calculate the shortest path Dijkstra's algorithm is used. Dijkstra's' algorithm is an algorithm to find the shortest path in a graph, therefore the edge attributes travel time multiplied with the road type weight factor (Table 3:2) is used. Figure 3.3 visualizes the formal model, as aforementioned.

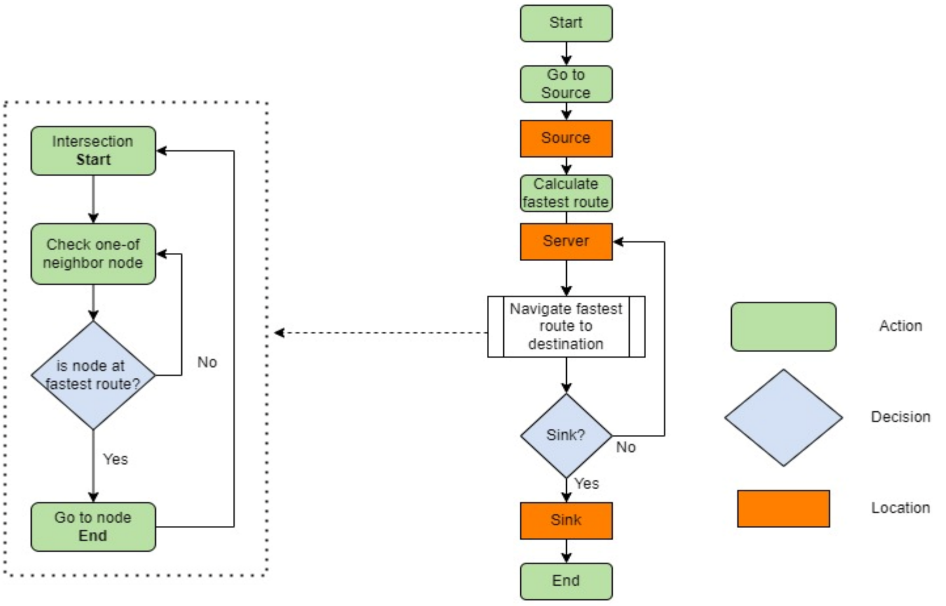

Figure 3.3: Formal Model Local-Cool

Q4: Organized Crime in the Hot Mode

The criminals in this quadrant are from the local crime and act within the hot mode, resulting in unpredictable and dangerous driving from starting node to the destination node of the criminals. The criminals are chased by the Police and therefore act based on the hot mode, therefore the criminals take ad-hoc and short-term decisions. At every intersection, the criminals take a short-term decision based on the characteristics of the intersection. The criminals determine based on the road category what decision they will make. While driving on a small city road or big city road, the criminals check all het connecting roads, if these are all small city or all big city roads the criminals decide randomly which roads they take, as aforementioned the criminals prefer driving randomly using small city and big city roads to loose the Police. If the criminals drive on a mix of big city and small city roads the criminals prefer roads with more lanes, and therefore roads with more lanes are randomly chosen as next road. Last, if the criminals drive on a regional or highway road, they take the fastest route to the closest destination node that the criminals use to escape the area via the regional roads. All the above is visualized in Figure 3.4.

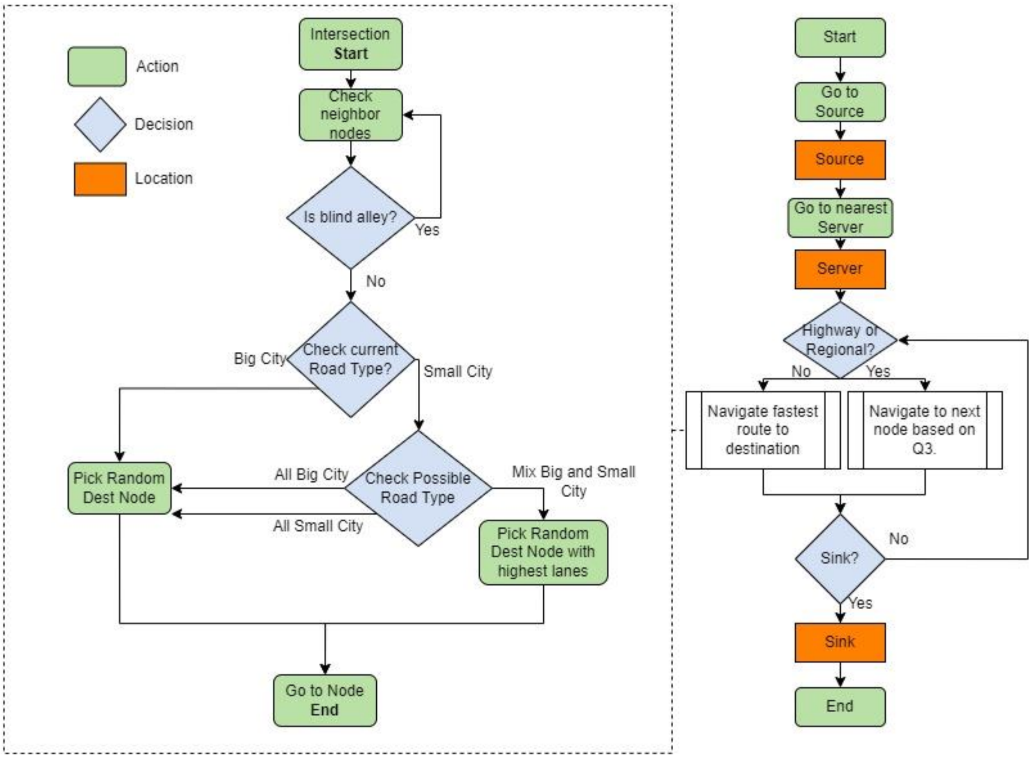

Figure 3.4: Formal Model Local-Hot

3.2.3. Criminal Assumptions

To model criminals' behavior a few general assumptions needed to be made, the identification of factors in section 2.3 and expert knowledge from the Dutch National Police are used as a starting point for this section. The criminal decision-making assumptions are listed below**:**

- **Determination of destination** – The destination of both the local and organized criminals in the cool mode are defined on a random uniform distribution over the possible destination nodes. This assumption is based on conversations held with the Police.
- **Road type quantification –** This is determined before the run, and all the criminals do quantify the road type exactly the same and will not vary throughout the simulation run. Due to time limitations the researcher chose for this simplification.
- **Inner state of the criminal** – During the entire run of the model, the criminal is assumed to stay in the same state of mind, either hot or cool. Due to time limitations and scoping the researcher chose for this simplification.
- **Organized-Cool criminal –** The criminal in this quadrant is assumed to take the shortest route from start location to the pre-determined destination. Therefore, the criminals calculates the shortest path based on travel time compensated by the traffic density at the time of crime. This assumption is based on conversations held with the Police.
- **Organized-Hot criminal –** The criminal is assumed to prefer driving over roads with multiple lanes instead of driving over faster roads. However, there is no difference between a road with 2 or 3 lanes. Furthermore, it is assumed that the criminal takes the fastest route while driving on regional or highway roads, this fastest route is calculated the same as the fastest route in organized-cool. The criminals take the fastest route since they are at known locations and have the possibility to drive fast. Therefore, the criminal takes the shortest route. Both assumptions are based on conversations held with the Police.
- **Local-Cool criminal –** The criminal in this quadrant is assumed to take the shortest route from start location to the pre-determined destination. Therefore, the criminals calculate the shortest path based on travel time compensated by weight factor of the road category. This assumption is based on conversations held with the Police.
- **Local-Hot criminal –** Driving on all small-, and big city intersections the criminals are assumed to take random decisions, therefore the next node is based on a uniform distributed choice over the possible nodes. Furthermore, it is assumed that the criminals take the fastest route while driving on regional or highway roads. The criminals take the fastest route since they are at road segments where it is possible to drive fast. Therefore, the criminal takes the shortest route. Both assumptions are based on conversations held with the Police.

- **Driving Speed –** The driving speed of the criminals are set to the travel time over the roads. The driving time is based on the time of the crime, resulting in a shorter travel time when traffic density is low and vice versa. However, criminals in the cool mode are aiming to drive with the flow to avoid being noticed by other road users, therefore their travel time is based on the maximum allowed speed. Whereas criminals in the hot mode are aiming to drive as fast as possible, resulting in travel time of the travel time based on the maximum speed during rush hours and 10% shorter travel time during low traffic density.

3.3. Discrete-Event Model

This section discusses the translation of the formal model into a discrete-event model. First, the main concepts on how the escape route decision-making is translated into a PyDsol model will be explained. Second, assumptions resulting from this translation are discussed.

3.3.1. PyDsol Library

In order to finalize the model to prospect fugitive escape routes, the implemented decision-making framework based on the four quadrants and the network graph are configured within the DSOL library in python (PyDsol). Isabelle van der Schillt developed PyDsol as a discrete-event object library based on the main concepts of DSOL in Java.

As aforementioned in Chapter 3.1, the network graph can be copied into a PyDsol model. Additionally, the decision-making framework of the criminals is added into PyDsol to determine the next connecting link of the servers.

The model is constructed as follows:

- The criminal is a subclass of the Entity class in PyDsol.
- The starting node of the criminal is a subclass of the Source class in PyDsol.
- The roads of Rotterdam are a subclass of the Link class in PyDsol.
- The intersections of Rotterdam are a subclass of the Server class in PyDsol. However, the inner working of the server in PyDsol is adapted, aiming to decide the next connecting link based on the previous described formal model.
- The destination nodes of the criminal are a subclass of the Sink class in PyDsol.

During the run the criminal will be created at a source, location of this source is explained in Section 3.1, this will be the starting point of the criminal. Additionally, a single source generates one entity per run. Depending on the crime location a single run consist of approximately 100 sources and therefore 100 entities. After generation, the criminal goes to the nearest server, every server has the capacity of infinity, therefore every server can handle an infinite number of criminals at the same time, besides the processing time will be 0. At this server, the decision-making framework will choose the next server of the criminal. After choosing the next server, the criminal enters the link connecting to the server, the time delay is the travel time of the criminal for that particular link. When the sink has been reached the criminal will be destroyed, since the criminal reached his goal. In appendix B the life spawn of the criminal is visualized (Figure B.2).

3.3.2. Model Assumptions

To change the network, and decision-making framework into a discrete-event simulation model, several assumptions are made. These model assumptions are listed below:

- **Server –** The construct server of discrete-event modelling is used differently in this model; therefore, capacity and processing time are not relevant to this model. First, the time a server needs to calculate the new destination is set to 0. It is assumed that a criminal needs zero time to think about his next decision. Second, the capacity of a server is set to infinity, to avoid queues when accidentally the criminals use the same server at the same time. The server can be seen as a node to determine the next destination.
- **Entity Creation** – The entity creation is based on one entity per source for 1 run. Therefore, the interarrival time is set to a large number, to avoid multiple entities for only one sources.
- **Length of link** – The length of the link is the travel time of the criminal in meters.
- **Speed of entity –** The speed of the entity is 1 m/s, therefore the time the criminal takes to travel over a link is the length of the link in seconds.
- **Exit output node –** The exit output node function in PyDsol is changed into the four quadrants decision-making functions, therefore the next link is determined by one of these functions.

3.4. Model Validation

To validate the fugitive escape route model, experts validate the first results. Because of lack of data, the validation with real data is not possible. Therefore, the police were asked if they thought the criminal's choices seem valid and plausible. Several runs with different combinations of input parameters are generated, the various outcomes were presented to the experts and assessed by them to validate the outcomes. How the expert validation is conducted is explained hereafter.

The validation process, consists of the following steps, additional information to these steps is added to the appendix C:

Step 1: General Outcome Experiments:

- First of all, the researcher explained both the idea of two types of criminals and two mental states of the criminal. Therefore, the 4 quadrants framework is mentioned in an implicit manner, to avoid bias.
- Second, the expert is asked to think like either an organized criminal or local criminal that is chased by the police or not.
- Third, based on the state and type of criminal the expert is asked to draw up the route he is probably going to take the destination.
- In the appendix C are examples of maps that are used to show the chosen routes.

Step 2: Destination choice:

- This step builds upon step 1; however, it tries to validate the destination choices.
- Again, the expert is asked to think like a criminal in one of the four quadrants. Next, the expert is asked what destination he would choose to escape the local area.
- In the appendix C are examples of maps that are used to show the chosen destinations by the expert.

Step 3: Assumption validation:

- This step builds upon the assumptions made by de researcher. The expert is asked about his opinion towards certain assumptions.
- Questions are asked to validate the reasoning behind the destination choices. (e.g., why is chosen for this destination?)
- Questions are asked about the preferences for multiple lanes and speed.

Step 4: Experiment validation

- The last step is to ask whether the generated experiments seems to be plausible.
- Therefore, single experiments are showed to the expert in order to ask if he agrees with the validity of that single experiment. Besides, t the expert is asked what type of criminal the expert think he is.
- Additionally, fake results are added to the shown experiments to see whether the expert is biased.
- In the appendix C, examples of the experiments are added.

Based on the expert validation, the developed discrete-event model can be seen as a validated model to prospect the fugitive escape routes of criminals after a robbery in Rotterdam. The expert stated: “The results are the physical results of my thinking about the fugitive escapes.”

3.5. Conclusion

This chapter concludes with a final discrete-event model to prospect the fugitive escape routes of criminals after a robbery in Rotterdam, answering sub-question 2. Moreover, this model is able to generate valid escape routes, which can be analyzed in the following chapters. To summarize, the discrete-event (PyDsol) model is generated from both the network graph of Rotterdam and the route choice decision-making framework of the criminals.

4. Experimental Design

Subsequently to the formulation and validation of the discrete-event model, to prospect fugitive escape routes, the experimental set up is discussed in this chapter. The experimental set up is how the model will be used in order to generate data that is needed for analysis. The chapter will start with a presentation of the different input parameters, and different outcome parameters, followed by the argumentation. Hereafter, chapter visualizes with the experimental design used to generate the data. This chapter ends with the substantiation of the number of runs.

4.1. Input-, and Output Parameters

Given the validated model to prospect the escape routes after a robbery in Rotterdam, it is important to distinguish what the important factors are to change in order to generate the outcome results. Therefore, a XLMR is visualized as Figure 4.1. A XLRM is a framework developed by Lempert et al. (2003), which underpins the design of the in Chapter 3 developed simulation model. X stands for the external factors ;these are the factors outside of control of the decision-makers. L stands for levers, which are in control of the decision-maker. R stands for the relations inside of the system, and lastly the M stands for the outcome metrices.

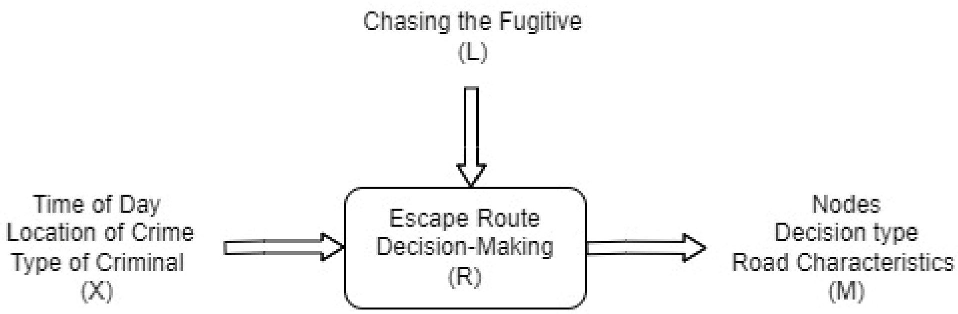

Figure 4.1: XLMR of the Model

Combining the XLMR and the model of this research, one can conclude that the researcher is able to change and control both the external factors (X) and levers (L) for generating outcome results. Chasing the fugitive is a call the Police can take, chasing the fugitive results being in the Hot mode for the criminal. Additionally, the time of the day, location of crime, and type of control is not controllable by the police, however for research purposes it is in control of the researcher. The time of the day results in either a high traffic density or low traffic density. Location of crime determines the start location of the criminal, all the locations in Rotterdam can be taken as crime location to determine the possible starting positions. Last, the type of criminal is either the organized crime or local criminal, both resulting in different escape route decision-making. The outcomes of interests (M) are used to analyze the performance of the model. Therefore, the route and their destination, in terms of passed nodes and edges, are stored as outcome. Additionally, road characteristics such as speed, road type, are stored to be analyzed. Last, the decision type can generate insight in on what terms the criminal determines his decision to take the next node.

4.2. Experimental Set Up

To compare the performance of the model, each of the components below are varied. The components are based on the previous described XLMR model and described independent variables. The motivation and implementation of each of the components are briefly discussed hereafter.

- **Quadrant of the decision-making framework**

The quadrant where the criminal is in is based on two factors. First, what the type of criminal is. Based on the knowledge about the crime the police is able to predict what type of criminal has committed the crime. Second, the police can determine the hot or cool state of the criminal, therefore the police is either chasing the criminal or not. Chasing the criminal results in a panicking criminal resulting in being in the hot mode. Varying the quadrant of the criminal results in different prospective escape routes, and therefor it is imperative to analyze the impact of the four quadrants. To conclude, every simulation run has criminals in one of the four quadrants.

- **Location of the Crime**

The location of the crime can be any location in the city. The location of the crime results in different starting positions of the criminal, every location generates his own set of sources, based on the in Section 3.1 explained function. The location of the crime can influence the route decision since every location has its own characteristics. In this research, three distinct locations with different characteristics are taken as location of the crime. First, the City Centre, this a street in Rotterdam within the Shopping Area Lijnbaan. The City Centre is an area with a relatively low road density connected to both living streets and S-roads. Second, the living area, this is a residential street within Crooswijk. The living area is an area with a high road density and mostly living streets and residential areas as road types. Third, the business area in the Waalhaven where a multitude of companies are based. The business area is relatively isolated location, mostly connected to S roads, and close to regional and highway roads. One can conclude that every simulation run has one of the three crime locations, with the locations visualized in Figure 4.2.

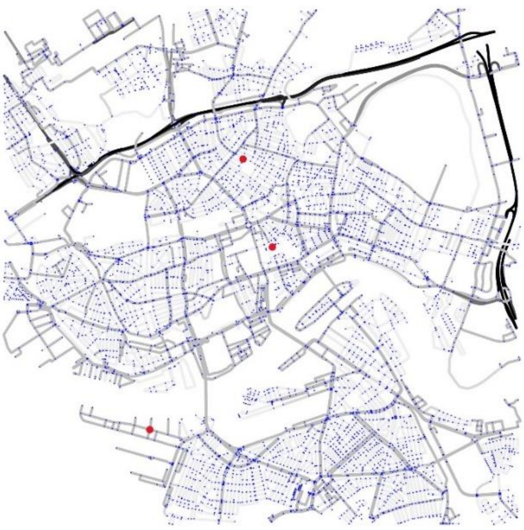

Figure 4.2: Crime Location Graph

- **Time of the Crime**

The time of the crime can be any time of the day. The model will distinguish between a low or high traffic density based on the time of the day. Therefore, the sets of possible time of crime will either be during the day when the traffic density is low, so at from late evening until early morning. Or when the traffic density is high, from early morning until late evening. One can conclude that every simulation run has either night or daytime, and therefore low or high traffic density. It should be noted that traffic density has no influence on the route choices for local criminals, see Section 2.3.

Based on the three components and the variation of these component the following experimental design can be developed, visualized in Table 4:1. The experiments are based on a full factorial design of the 3 components.

Table 4:1: Experimental Design

	Quadrant	Location	Time
1	Organized-Cool	City Centre	Night
2	Organized-Cool	Business Area	Night
3	Organized-Cool	Living Area	Night
4	Organized-Hot	City Centre	Night
5	Organized-Hot	Business Area	Night
6	Organized-Hot	Living Area	Night
7	Local-Cool	City Centre	Night/Day
8	Local-Cool	Business Area	Night/Day
9	Local-Cool	Living Area	Night/Day
10	Local-Hot	City Centre	Night/Day
11	Local-Hot	Business Area	Night/Day
12	Local-Hot	Living Area	Night/Day
13	Organized-Cool	City Centre	Day
14	Organized-Cool	Business Area	Day
15	Organized-Cool	Living Area	Day
16	Organized-Hot	City Centre	Day
17	Organized-Hot	Business Area	Day
18	Organized-Hot	Living Area	Day

Having the experimental design as discussed above, results can be generated. Therefore, the following data will be gathered and analyzed:

- **Used roads of the criminals** – Based on the knowledge which roads are used by the different criminals heatmaps of Rotterdam can be developed. Moreover, to see the behavior of the criminals over time the heatmaps over time are generated.
- **Destination of the criminals** – The destination of the criminals can be compared between the criminals in the hot-mode and for each location of the crime. Therefore, bar charts can be used to compare the outcome results.
- **Decisions of the criminals** – The Criminals take every intersection a new decision therefore all the decisions of the different criminals can be analyzed using bar charts.
- **Used road types of the criminals** – The different roads that are used during the escape, can ultimately say something about the preferences of criminals during the escape in Rotterdam. Therefore, the road categories per criminal for each location of crime are compared using bar charts.

4.3. Simulation Run

As described in Chapter 3.2 there is stochasticity inside the model coming from (pseudo) randomness in the decision-making processes of the criminal. This stochasticity can result in uncertainty in the outcomes; therefore, this section describes the influence of stochasticity and how to deal with it. Based on the sensitivity to stochasticity a certain number of simulations runs has to be executed. To see in what extent the model's outcomes are sensitive to stochasticity, boxplots from several random experiments are visualized in Figure 4.3, Figure 4.4, Figure 4.5, and Figure 4.6. Both the outcomes for road types and destinations are analyzed on the sensitivity of randomness. Because of time limitation only 2 different random set ups for each outcome parameter are chosen to analyze. First, the influence of randomness on the destination of both the local and organized criminals within the hot mode from the city center are visualized in Figure 4.3 and Figure 4.4. Based on the figures one can see that the results show few big outliers and therefore randomness does not influence the outcomes of destinations significantly. Second, the influence of randomness on the road type from both the local and organized criminals in the hot mode from living area are visualized in Figure 4.5 and Figure 4.6. Since there are no big outliers, one can conclude that the chosen road type is insignificant sensitive to randomness. Because of the insignificant sensitivity to stochasticity and time limitation 20 runs are conducted to dealt with the stochasticity in a valid way. However, conducting more runs would generate more reliable outcomes.

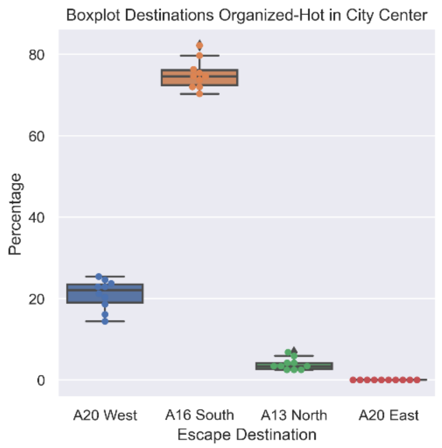

Figure 4.4: Boxplot Organized-Hot City Center

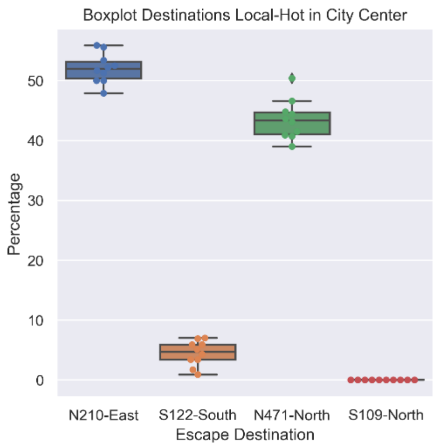

Figure 4.3: Boxplot Local-Hot City Center

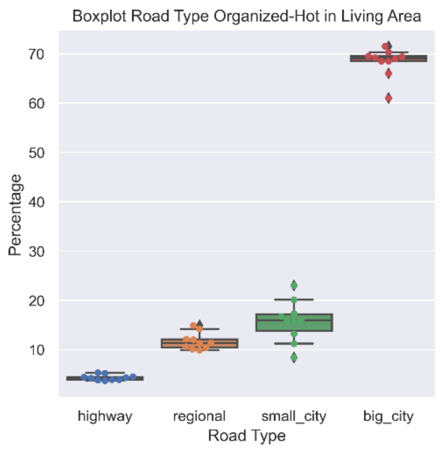

Figure 4.6: Boxplot Organized-Hot Living Area

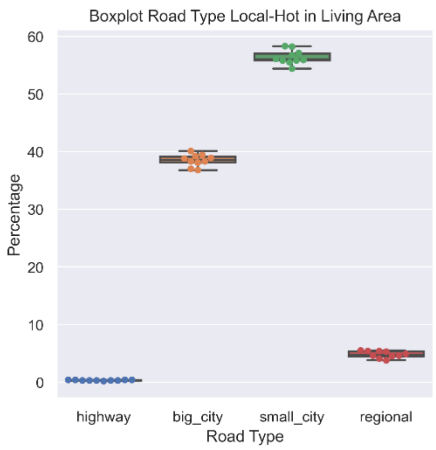

Figure 4.5: Boxplot Local-Hot Living Area

5. Results of the Escape Route Decision-Making

Subsequently to the experimental design in Chapter 4, the model outcome results are discussed next. The chapter will start with an analysis on the used roads during the fugitive escape event per quadrant. Hereafter, a more global perspective will be given about the destination of the criminals. Additionally, local decisions about the road characteristics and choices on a micro-level are shown. Last, the potential locations of the criminals over time are visualized. This chapter ends with a summary of the outcome analysis.

5.1. Escape Route Analysis

This section presents the results of the chosen routes of the criminals in each quadrant for all the three crime locations (city center, living area, and business area). To visualize, heatmaps are created to determine the critical road segments for each crime location.

Figure 5.2: Heatmap City Center

Figure 5.1: Heatmap Living Area

Figure 5.3: Heatmap Business Area

The organized-cool criminals' mostly used roads are visualized in Figure 5.1, Figure 5.2, and Figure 5.3. Based on the heatmaps the criminal prefers to take the S-roads within the city. S-roads are the most important roads of the city, which connects the city with the beltway (A16, A20, and A13). Furthermore, road segments part of the S113 and S112 to the North (A13) and road segments part of the S107 to the East (A16) are used within criminals from the city center, living area, and business area, therefore these roads can be seen as critical roads to escape the area.

The organized-hot criminals' mostly used roads are visualized in Figure 5.1, Figure 5.2, and Figure 5.3. Based on the heatmaps one can conclude that is not evident that the criminal takes just one route. The route choices of the criminal are more distributed over the area compared to the organized-cool criminals. Furthermore, the location of the crime has an influence on the mostly used roads, resulting in several critical locations. First, the S103 and S113 north with direction to the A13 highway is commonly used by the criminals from the business area. Second, the S107 with direction east to the A16 is mostly used by criminals from the city center. Third, the S113 with direction west to the A20 is mostly used for criminals from the living area.

The local-cool criminals' mostly used roads are visualized in Figure 5.1, Figure 5.2, and Figure 5.3. Based on the heatmaps one can conclude that the used roads are distributed and fragmented close to the crime location, resulting in the use of smaller roads. However, close to the destination the S roads are critical to the criminal to escape the area. Compared to the local criminals the S roads connecting the regional roads are more important. Moreover, location of criminal influences the resulting driving behavior. For both the criminal from the living area and city center the used roads are distributed, mostly all S roads connecting to the regional roads are critical. Whereas the road use for criminals from the business area is not distributed, resulting in the S103 and S107 as critical roads.

The local-hot criminals' mostly used roads are visualized in Figure 5.1, Figure 5.2, and Figure 5.3. Based on the heatmaps one can conclude that the used roads close to the crime location are distributed, resulting in the use of many different living streets and residential areas. However, close to the destination of the criminal the used roads are less distributed. Moreover, the location of the crime has a great influence on the used roads. First, the S107 with direction East and S112 with direction North are mostly used by the criminals from the city center. Second, the N471 with direction North is solely used by the criminal from the living area. Third, the S101 with direction South is solely used by the criminal from the business area.

All the critical roads with all the directions for each quadrant are summarized in the Table 5:1.

Table 5:1: Critical Roads of Experiments for each Direction

Quadrant	North	East	South	West
Organized-Cool	S112;S113;S103	S107		A20
Organized-Hot	S112			
Local-Cool	N471	S107	S103	
Local-Hot	S112;N471	S107	S101	

5.2. Escape Route Destinations

This section presents the results by the criminals' chosen destination. The analyses contain the destination nodes of both the local and organized crime criminals that are chased by the police. Criminals not being chased by the Police are left out of analysis, since the destination choice is set before the run and are assumed to be uniform distributed, as described in Section 3.2. First, criminal destinations during the normal hours are viewed. Second, the results of destination analysis for the criminals during rush hours are viewed.

Destination Analysis without High Traffic Density

Figure 5.5: Destination Graph Organized Crime

Figure 5.4: Destination Graph Local Crime

Concluding from the Figure 5.4 and Figure 5.5, one can see that the east roads A20 and N210 are not used as destinations to escape the area. Moreover, the destinations for Business Area are, 100%, A13 North and S112 South. Depending on the location of the crime the escape destination is reached, based on comparison with a roadmap of Rotterdam, the researcher concluded the following: The criminals use the destination roads that are fast and easy to reach. Therefore, the roads to the east are more difficult to reach, the criminals have to drive through smaller streets and for a longer distance. What should be noted is that the N210 East is not used as destination, however it is relatively close to the Crime Location. A reason for this is the fact that unpredictable behavior results in a bigger distance from the N210 East. All the above is summarized in Table 5:2.

Table 5:2: Distribution and Distance in Seconds to Destination

	Destination of Organized Crime							
Locations:	A16-South		A20-West		A20-East		A13-North	
City Centre	254 s	75.08%	339 s	21.01%	399 s	0.00%	396 s	3.88%
Living Area	363 s	15.39%	282 s	80.21%	347 s	0.00%	345 s	2.55%
Business Area	629 s	0.00%	613 s	0.00%	678 s	0.00%	603 s	100%
	Destination of Local Crime							
Locations:	S122-South		S109-North		N210-East		N471-North	
City Centre	395 s	4.45%	379 s	52.05%	287 s	0.00%	309 s	43.50%
Living Area	489 s	0.00%	392 s	5.83%	395 s	0.00%	257 s	94.17%
Business Area	230 s	100%	815 s	0.00%	663 s	0.00%	589 s	0.00%

Influence of Time at Destination Choices

Next, the influence of the time of the crime on the destination decision-making is discussed. Both types of criminals in the hot mode decide their destination during the run, therefore they are aiming to take the shortest route to the closest destination. The shortest route is corrected by the traffic density at the time of the HIC, however solely the organized crime criminal will be influenced by the traffic density. Therefore, the differences between the chosen destinations for the different locations and different traffic density of the organized crime criminals are visualized in Figure 5.6. As can be seen in this chart there is almost no difference between the destination decision-making of the organized crime for crime locations city center and business area during the normal hours or rush hours. However, there is a modest difference in destination for the criminals committing a crime during rush hours in the living area, a criminal prefers to take the A16 over the A20 a little more.

Figure 5.6: Destination Comparison Low-, and High Traffic Density

5.3. Decisions of the Criminals

This section presents the results of the taken decisions on a micro-level scale. First, based on the taken decisions the different road categories are visualized. Second, the preferred roads are visualized. Last, the characteristics that influenced the decision-making of the criminal are visualized.

5.3.1. Road Type Decisions

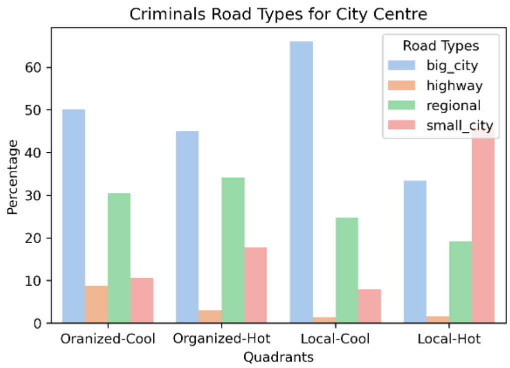

Figure 5.8: Road Type for City Centre

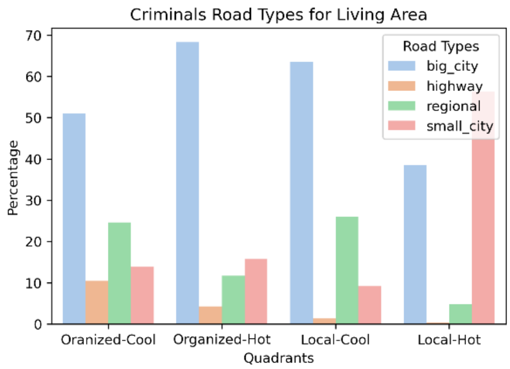

Figure 5.7: Road Type for Living Area

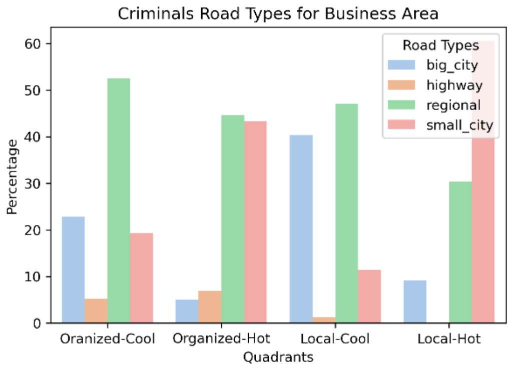

Figure 5.9: Road Type for Business Area

Comparing the road types of each crime location shown in Figure 5.8, Figure 5.7, and Figure 5.9. It can be seen that there are notorious differences between the crime location and the road use. First, the criminals committing a crime in the city center (Figure 5.8) prefer to take small city and big city roads. For organized crime criminals in both the cool and hot mode the distribution of the road types are similar, resulting in particular big city and regional road use. Whereas local criminals in the cool mode particularly prefer big city roads and local criminals in the hot mode prefer small city roads. Second, the criminals committing a crime in the living area (Figure 5.7) are comparable to the criminals in the city center. However, the biggest difference is that criminals in Organized-Hot particularly big city roads prefer. Moreover, the use of regional roads and highway roads are insignificant. Third, the road use of criminals committing a crime in the business area (Figure 5.9) are notoriously different compared to the previous two crime locations. The distribution of the different roads between Organized-Cool and Organized-Hot are significant. Therefore, the Organized-Cool criminals prefer particularly the regional road and partially the big city and small city. Whereas the Organized-Hot criminals both the regional and small city roads prefer. Furthermore, between Local-Hot and Local-Cool there are differences as well. The Local-Cool criminals prefer the big city and regional roads, whereas Local-Hot criminals prefer the small city and regional roads. Therefore, the differences is notorious in the big city use for the criminals do not begin chased versus criminals being chased.

Road Type use with High Traffic Density

Next, the influence of time and therefore traffic density on road type for each crime location is discussed. Therefore, the road type data of the Organized-Cool and Organized-Hot is compared with a higher traffic density and a normal traffic density. Figure 5.10 visualizes the road type use comparison for the city center. There are almost no differences in road use for the criminal committing a robbery in the city center, therefore this effect of traffic density can be ignored.

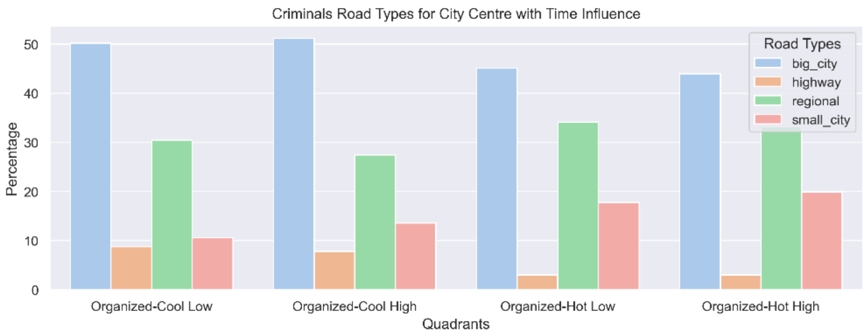

Figure 5.10: Road Type Comparison Time of Crime City Centre

Figure 5.11 visualizes the road type use comparison for the living area. The use of small city roads in Organized-Cool with low traffic has almost been multiplied by two, resulting in less use of big city roads. Differences with the organized criminals in hot mode are small, but regional roads are a little more used compared to the big city roads during rush hours and vice versa during normal hours.

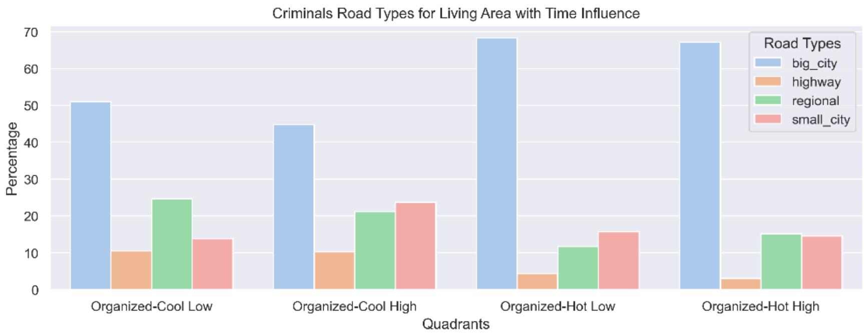

Figure 5.11: Road Type Comparison Time of Crime Living Area

Figure 5.12 visualizes the road type use comparison for the business area. Also, in the business area there is a difference within Organized-Cool in the use of small city roads, however compared to the living area the regional roads are less used.

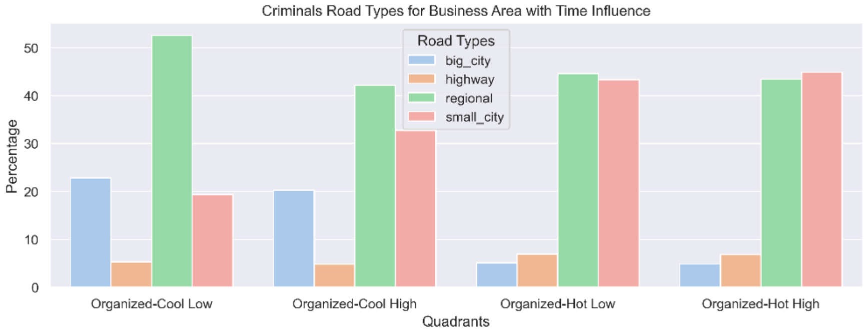

Figure 5.12: Road Type Comparison Time of Crime Business Area

5.3.2. Escape Route Choices

Next, the criminals' decision-making on a micro level are presented as Figure 5.13 and Figure 5.14. Hereafter, the criminal decision-making compared with high traffic density is discussed. The type of decisions for both the organized and local criminals in the hot mode during normal traffic hours are discussed. It stands out that for the organized crime criminals prefer the number of lanes over speed. However, roads with more lanes and lower speed are neglected by the criminals. While driving on roads with only 1 lane, the criminal prefer to continue his driving on the same road with the same speed. Furthermore, the local criminals prefer to drive randomly compared to driving straight in the city urban area (e.g., small city-, and big city roads). Furthermore, for both the local and organized crime a distinction between the locations can be made in terms of the decision to take shortest route. Criminals in the living area are less likely to take the fastest route, resulting in more unpredictable driving compared to criminals in the business area and the city center.

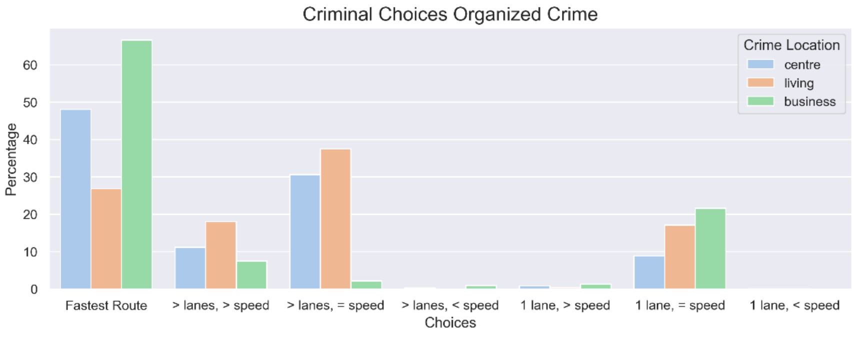

Figure 5.13: Criminal Choices Organized Crime

Figure 5.14: Criminal Choices Local Crime

Combining all the above, one can conclude that the criminals' choices can be distinguished. Therefore, using this knowledge it could be beneficial and possible for the police to predict criminals' choices during the chase in order to catch the fugitive. Predicting would be based on the characteristics of the roads. For the organized crime this results in choosing the road segments with more than 1 lane and higher allowed speed. Whereas the local criminals prefer to drive randomly over taking the straight line. Next, the influence of time and therefore traffic density on criminal choices for each crime location is discussed. Figure 5.15 visualizes the micro-level comparison between organized crime criminals and the different crime locations. The differences between the low traffic and high traffic can be seen as almost none, therefore one can conclude that the influence of traffic time does not influence the decision-making of the criminal.

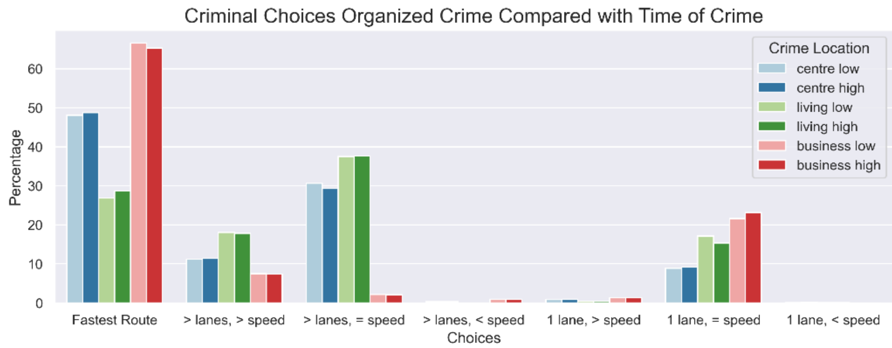

Figure 5.15: Criminal Choices Comparison Time of Crime

5.4. Escape Routes over Time

This section presents the results of escape routes over time. After the crime, the knowledge about the location of the criminals could potentially help the Police to distribute his resources. Nowadays, the Police uses web applications to create a reachability circle, to predict potential locations of the criminals. The escape routes heatmap over time can be used as an alternative to see the possible locations of the criminals over time, which is more specific and detailed compared to the reachability circle.

Heatmaps with Low Traffic Density

The heatmaps over time are visualized in the appendix D, as Figure D.13 till Figure D.17. Next, a summary of these results are given. Hereafter, the heatmaps over time with a high traffic density are visualized as Figure D.18 and Figure D.19. The first minute after the start of the escape one can see that the criminals are still in the local area of the crime location. However, a distinction can be made between the criminals being chased and not being chased. The criminals that are chased by the Police, prefer to take smaller roads and the used roads are more distributed. Moreover, the local criminals that are chased by the police do not use bigger roads, and only use the small city roads (e.g., living streets, residential streets, etc.) Criminals not being chased try to escape using the bigger roads within the local crime destination. Second, from the first minute till the second minute, one can see that criminals that are not being chased use bigger roads. These bigger roads are connecting to regional and highway roads. Furthermore, the distribution of the roads is more fragmented for the local criminals. Organized crime criminals use only the two roads whereas local criminals used several more roads. Third, from the second till the fourth minute the criminals are getting closer to the highway and regional roads connecting the destination to escape the local area. Criminals that are not being chased are mostly at the highway or regional roads to escape the local area. Whereas criminals being chased are still at bigger city roads. Moreover, the local criminals used several roads to escape the area, where the organized crime uses fewer roads. Fourth, from the fourth till the eighth minute, the location of the criminals are less fragmented. Both, the organized crime, and local criminals use the roads connecting to the destination to escape the area. Therefore, the criminals use less big city roads and more regional and highway roads. Lastly, from the eight minutes till the end of the escape, one can see that almost all criminals are at the end of their escape from the local area. Criminals are at the roads connecting to the destination and are mostly at the end of the roads. The roads that are used are the regional roads for local criminals, and organized crime criminals use highways to escape the area. However, it should be noted that a few local criminals being chased by the police officers are still close to the crime location.

Heatmaps with Low Traffic Density

Next the influence of the time of crime and therefore traffic density on the fugitives escape routes over time is discussed. Both the Organized-Cool and Organized-Hot criminals heatmaps are visualized with the Figure D.18 and Figure D.19 in Appendix D. First, for the Organized-Cool criminal committing the crime during rush hours the following can be concluded. The distribution of used roads are complementary within rush hours and normal hours. However, the influence of traffic density is evident over the course of time, whereas the criminals within normal hours are closer to the destination compared to the criminals within rush hours. Second, for the Organized-Hot criminals committing the crime during rush hours the following can be concluded. In conjunction with the Organized-Cool criminals the distribution of used roads are complementary to both the criminal during rush hour and normal hours. Moreover, the distribution over time is comparable to each other, therefore it can be seen that traffic has a little influence on how far the local criminal can reach within the cool mode .

5.5. Summary of Results

In this chapter the outcome results of the experimental set-up are summarized. Therefore, Table 5:3 is created to summarize the outcome results of the analysis conducted in the previous sections.

Table 5:3: Summary of Outcome Results

			Destinations	Road Type	Route Choices
Organized-Cool	City Center	Low Traffic	Assumed based on uniform distribution, see Section 3.2	Mostly big city roads in the beginning and later regional roads are used. Time has no significant influence. Insignificant difference between city center and living area.	Fastest Road is used to based on travel time and traffic density, see section 3.2.
		High Traffic			
	Living Area	Low Traffic			
		High Traffic			
	Business Area	Low Traffic		Mostly regional roads are used, and partly small and big city roads. Time has a little influence on preferring small city roads.	
		High Traffic			
Organized-Hot	City Center	Low Traffic	Mostly A16 South, partly A20 West and A13 North. No A20 East. Highways close to crime location. Insignificant influence of traffic density	Mostly big city roads in the beginning and later regional roads are used. Additionally, there is an insignificant difference between this criminal in hot or cool mode. No influence of time	Criminals mostly take decisions based on more lanes; however, speed is less important. Roads with lower speed are not chosen. Almost 50 percent is based on the fastest route. Time has no influence.
		High Traffic			
	Living Area	Low Traffic	Mostly A20 West, partly A16 South and A13 North. No A20 East.	Mostly big city roads are used, and only a few uses small city roads. Big city roads are used to the escape the area. Time has no influence.	Criminals mostly take decisions based on more lanes; however, speed is less important. Roads with lower speed are not chosen. Speed is compared to city center more important. Time has no influence.
		High Traffic	Mostly A20 West, partly A16 South and A13 North. No A20 East. However, criminals prefer taking roads heading South/East instead of West.		
	Business Area	Low Traffic	Only A13 North is used, mainly because of closest destination. Time makes no differences.	Mostly small city in the beginning and later on regional roads are used. There is almost no influence of time.	Criminals mostly take decisions based on lanes, however compared to the living and city center, lanes are less important. Criminals prefer to take the fastest route. Tim has no influence
		High Traffic			
Local-Cool	City Center	Low Traffic	Assumed based on uniform distribution, see Section 3.2	Mostly big city roads are used. Also, in the beginning and later on the big city roads are used towards the destination. Time has no significant influence. City Centre and Living area are comparable.	Fastest Road is used to based on travel time and traffic density, see section 3.2.
		High Traffic			
	Living Area	Low Traffic			
		High Traffic			
	Business Area	Low Traffic		Both big city in the beginning and later regional roads are used to escape the area. Time has no influence.	
		High Traffic			
Local-Hot	City Center	Low Traffic	Both S109 and N741 to North are mostly used. N210 East is not at all used. Traffic density has no influence, see Section 3.2.	Mostly small city roads are used in the beginning, whereas big city roads are used later. Only a few regional roads are used. Time has no influence.	Criminals prefer to drive randomly on both small city and big city intersections. Partly the fastest route is preferred. Time has no influence
		High Traffic			
	Living Area	Low Traffic	Mostly the N471 is used, with a few criminals using the S109 North, and no N210 East and S122 South. Time has no influence, see section 3.2	Mostly small city roads are used, later on big city roads are used. However, no highway roads are used. Only a few regional roads are used. Time has no influence.	Criminals prefer to drive randomly on both small city and big city intersections. The fastest route less preferred. Time has no influence
		High Traffic			
	Business Area	Low Traffic	Only S122 South is used, mainly because of closest destination. Time makes no differences, see section 3.2.	Mostly small city roads are used, and later partly regional roads are used. Time has no Influence.	Criminals prefer to drive randomly on small city roads, big city roads are less used. Also, the fastest route is preferred. Time has no influence
		High Traffic			

Moreover, there are additional insights retrieved from the analysis. First, within the city of Rotterdam the river 'Maas' separates the city with two possibilities to travel from north to south and vice versa. However, only one is used, which is called the 'Maas tunnel.' Therefore, the criminals do not use the Erasmus Bridge to travel from the North to the South of Rotterdam or vice versa. Second, the city routes S107 and S112/S113 are imperative for the criminals with almost all the different input parameters. Third, destinations in the east to escape Rotterdam are not used by the criminals.

6. Discussion on Results

This chapter discusses the results of the discrete-event model to predict the prospective escape routes of criminals after a robbery in Rotterdam. The focus lies on the process of designing the model, the use of the model and the effect of the limitations on the model's results. Challenges for the use of the model and the impact of the results in academia and business are addressed sequentially.

6.1. Conceptualization Challenges

This section discusses the challenges related to the conceptualization part of the research. During the design and execution of experiments, several challenges occurred on the conceptualization side. Moreover, this section describes challenges, applied solutions and the remaining difficulties of the conceptualization as follows:

Use of Dual-Process Theory. The dual-process theory is chosen as the theoretical foundation of the criminal decision-making. The dual-process theory separates the criminal's behavior in two modus operandi, either the hot or cool mode. For this research it is assumed that there are only two different inner states of the criminals, based on this state the criminal acts differently. Being chased by the police officers is the best predictor for the criminal to be in either the hot or cool mode (see Section 2.1.2). However, according to van Gelder et al. (2009) the hot or cool mode does not act in isolation but can coexist. Accordingly, other (personal) characteristics can influence the hot and cool ratio. For example, the experience, level of anger, level of risk, level of self-control, etc. are factors influencing to what extent criminals are in either the hot or cool mode (Motro et al., 2018; van Gelder & de Vries, 2014). Furthermore, the entire run the inner state of the criminal is assumed to be the same. In reality, the state of being in either the hot or cool mode can change over the course of time during the fugitive escape. Due to time limitations and system boundary choices these (personal) factors and combinations of hot and cool modes are not included in this research. The above-described challenges result in static behavior based on the dual-process theory, whereas adding factors to influence the hot and cool mode potentially result in changing behavior over time, which is more realistic to real life escape route decision-making. However, knowledge is needed about factors influencing the hot and cool ratio.

Micro-Level factor factors influencing the criminal behavior. Modelling human behavior and criminal behavior proves to be a great challenge (Mehlkop & Graeff, 2010; Osman, 2010; van Gelder, 2013). Modelling human behavior results in great deep uncertainty (Osman, 2010), however, the researcher tried to simplify the rules of behavior to deal with this deep uncertainty. Therefore, I considered the escape route behavior of a criminal as a whole (high-level) instead of individual and homogenous entities (low-level). Additionally, solely the high-level expert knowledge from the police is used, resulting in a high-level conceptualization. The behavior of the criminals is based on the developed four quadrant framework, whereas factors influencing the criminal decision-making are based on the high-level decision-making. Therefore, various low-level factors potentially influencing the criminal behavior are not considered. First, the model assumes that all the criminals use the same vehicle with the same maximum speed. However, different criminals use different cars with different characteristics (Cesar & Decker, 2017). Furthermore, the criminal's driving behavior (e.g., driving speed, perceived risk, driving experience, etc.) differs from one criminal to another. Second, the criminal decides based on several factors relating to micro-level characteristics of the intersections. For example, using or avoiding traffic island, bus ways, and the traffic lights, etc. to determine the next road. However, these micro-level factors are not included and solely high-level factors such as speed, traffic density, number of lanes, and travel time are implemented. Third, the model assumes an average traffic density of the road segments, however, at different points in time the amount of traffic can change. For example, an open bridge or a red traffic light can cause a local traffic jam, which influences the route choices of the criminals. Adding additional factors on a low-level decision-making could increase the knowledge on escape route decision-making of criminals in more detailed manner. Furthermore, the modelling of escape routes could potentially become more valid.

Origin and Destination location of the criminals. The model assumes the start of the escape as the starting location with the second vehicle. However, the actual starting location is the location of the crime. The escape route decision-making with the first vehicle is due to lack of knowledge not included in this research. Furthermore, it is assumed that all the possible locations of the start are small city streets within 750 m till 1 000 meters. However, in reality the criminal parks his car at parking spots to remain inconspicuous. In this model the final destination for the criminal is set at the end of the spatial area. Therefore, for each type of criminal 4 potential locations to escape the area are assumed. In reality the potential escape locations are not bounded by the assumed locations, due to lack of knowledge the potential destinations are assumed. Thus, gaining knowledge on the destination decision-making and first vehicle decision-making could improve the usefulness of the model and improving the knowledge on escape route decision-making in a more detailed manner.

6.2. Societal Challenges

This section discusses the challenges related to the implementation of the model to predict fugitive escape routes. For the police, it is interesting to know whether it is feasible to use this model for forecasting the criminal escape routes and analyzing their associated behavior. This research defines various challenges for using the model to improve the validity to predict prospective fugitive escape routes in order to increase knowledge on escape route decision-making. Based on the results, the following challenges and recommendations are identified.

Theoretical decision-making framework. The dual-process theory is chosen as the theoretical foundation of the criminal decision-making. Due to scientific reasons (see Section 1.2.3) this framework is chosen, however developing several models with different theoretical decision-making framework could potentially give additional insights in the criminal escape route decision-making. Nonetheless, this model offers help and clarity in the criminal escape route decision-making process and could already be used as a support gaining knowledge on escape route decision-making.

Adding more complexity to the model. The model to predict prospective fugitive escape routes is simplistic compared to the real-life human and criminal decision-making. First, this model includes only the four most important input parameters (e.g., type of criminal, state of mind, location of crime, and time of crime), based on these parameters the criminal behavior is determined. However, adding more parameters (e.g., personal characteristics) it potentially could increase the scientific value for gaining knowledge on criminal escape route decision-making. Second, within the decision-making process criminals based their decisions on macro-level spatial characteristics. Therefore, adding decision-making on micro-level spatial characteristics (e.g., traffic lights, traffic signs, traffic island, bus ways, etc.), it could improve the understanding of criminal decision-making on a micro-level. Currently, there is a lack of knowledge on to what extent the proposed complexity influences the criminal escape route decision-making. Thus, when adding this proposed complexity researched has to be done about the influence of additional personal and micro-level characteristics on the criminal escape route decision-making. In my opinion, adding more complexity to the model do not change the outcomes of escape routes on a heatmap level, however it could increase the scientific value to analyze the factors influencing escape route decision-making in a more detailed manner.

Rotterdam as a case-study. The spatial network of Rotterdam is used to predict the escape routes of the criminal. Results from the model are solely used to determine the criminal decision-making within Rotterdam. However, since Rotterdam can be seen as an average European city with 500 000 - 1 000 000 citizens, the results can only be generalized to European cities similar to Rotterdam. However, using several cities as input for the spatial network could increase the understanding of general criminal escape route decision-making. Therefore, comparing the outcome results for different types of cities could potentially give new insights and increase the knowledge on the criminal escape route decision-making.

Real-time Data Driven. The developed model is based on a static network of Rotterdam, however in reality the road network is dynamic over time. Therefore, traffic density is assumed based on the type of road (see Section 3.1), however, adding a live traffic density allows the model to make more accurate predictions of the criminal's escape route decision-making. Furthermore, adding data of traffic lights could influence the criminal decision-making on a micro-level. Outcome results of the simulation could potentially change due to the influence of live traffic; however, it is unknown to what extent. Eventually, it could lead to increased knowledge on the influence of traffic on escape route decision-making. Moreover, the potential location of the criminal can be determined in a more detailed and valid manner.

7. Conclusion of Results

The final chapter concludes the research with answering the sub-questions, main research question and lastly the impact of the research. .

This section addresses the research question posed in Chapter 1*:*

"What are the effects of the time-, the location-, and the type of crime on the criminal escape route decision-making after a High-Impact Crime using the dual-process theory?"

7.1. Sub-Questions

To do so, the answers sub-questions are briefly discussed, after which the proposed framework to predict the prospective fugitive escape routes after a robbery are presented.

1. *Given the dual-process theory how to conceptualize the fugitive escape route decision-making of a criminal after a High-Impact Crime?*

According to the police there are two types of crimes committed by a different type of criminal. Local criminals mostly commit smaller crimes, such as burglaries, shop-, and restaurant robberies. Organized crime criminals commit bigger crimes, such as bank robberies, liquidations, and thuds. Furthermore, within the type of criminal a distinction need to be made between the criminals being chased and not being chased by the police, resulting in behavior based on either the hot-, or cool mode. Based on both the type of crime and the hot or cool mode a distinction can be made in terms of escape route decision-making resulting in the 4 quadrants framework. First, the organized crime criminals in the cool mode are being influenced by the allowed speed and traffic density, resulting in the travel time as important factor. Second, the criminals from organized crime in the hot mode, are influenced by the road category, number of lanes, and allowed driving speed. The criminals prefers roads with higher speed and more lanes. Third, the local criminals' decision-making in the cool mode are influenced by the travel time and the road category. Because of the knowledge about the local area and the idea to be inconspicuous for the police while driving in smaller streets, the criminal prefers driving over smaller city roads. Fourth, the local criminals in the hot mode are influenced by the road category and number of lanes. Because of knowledge about the local area on micro level the criminals try to add randomness to the escape route decision-making.

2. *How can the criminal escape route decision-making be simulated given the spatial-, temporal-, and situational factors?*

The answer to this question is a discrete-event simulation model to predict the prospective fugitive escape routes is built. This model is build consisting of three different components. First, there is a need of a network graph based on a specific spatial area. This graph consists of edges being the roads, and nodes being the intersections. Additionally, destination nodes and crime location nodes should be added for the construction of sources, servers, and sinks. Furthermore, it is imperative to add several characteristics to the edges and nodes as attributes (e.g., allowed speed, number of lanes, length, travel time, etc.). Second, the decision-making functions based on the 4 quadrants framework and the influencing factors are added to the model elements. These functions determines what road segment to take next for the criminal. Third, all the above is changed into a PyDsol model in python. Therefore, the crime location nodes, intersections, and destination nodes are changed into sources, servers, and sinks. Additionally, the roads are the links connecting to the servers. The inner workings of the servers are the route decision-making functions, which determines the next road for the criminal.

3. *What are the effects of time, location, and type of crime on the escape route decision-making of criminals after a HIC in Rotterdam?*

Based on the three factors the researched question is answered next per factor.

Type of Crime

Next, the resulting behavior based on the type of crime is discussed for each quadrant. First, the organized crime criminals in the cool mode. The first moments after the crime the criminals take bigger roads, moreover small city roads are avoided. After the first moments the criminals uses only a few roads. These roads, S112/S113 and S107, are connecting roads to the highway towards their destination to escape the local area. Second, the organized crime criminals being chased, start their escape using small city roads, however shortly after the crime the bigger city roads are used. Shortly after, the criminals take different roads, therefore compared to the criminal not being chased the road use is more fragmentated and distributed, resulting in several different used S roads. These bigger city and S roads are mostly roads with higher speed and more lanes. Third, the local criminals not being chased, start their escape using smaller roads. Whereas, shortly after the bigger city roads are used, also the used roads are fragmented during the first minutes after the escape, resulting in the use of several bigger city roads connecting to the S roads. However, closer towards the destination of the criminals only 4 roads different roads are used (S103, S107, S112, and S109). Fourth, the local criminals being chased by the police, use mostly small city roads and big city roads. Therefore, the criminals takes mostly random decisions to drive through the neighborhood. During these first moments the road use is distributed over living streets and residential areas. After a few minutes, the criminal drives as fast as possible to the closest destination node using only a few S roads. Moreover, the S103, S112 to N471 and the S107 to the N210 are the used roads to the destinations of the criminals.

Location of Crime

Next, the conclusion of the comparison between the different locations are discussed. In terms of destination choices one can conclude that there is a big difference between the location of crime and the destination of the criminal. First, criminals within the organized crime prefer to take destinations close to their position. Therefore, criminals at the business area prefer the A13 North. Whereas criminals in living area and city center prefer A16 south and A20 West. Second, similar to the organized crime criminals there is a big difference between the business area and the living area/city center. Criminals in the business area prefer to take the S112 South, whereas the others prefer both de S109 and N471 North. Furthermore, the location of crime does influence the road type use. The road type use of the criminals in the living area and city center are almost similar to each other. However, a distinction between those and the business area can be made. Therefore, regional, and small city roads are preferred to take by those criminals. Lastly, the location of the crime does influence the used roads based on the heatmap analysis. Criminals in the hot mode within the living area and city center do have similar behavior, resulting in a fragmented and distributed use of roads. Whereas the criminals in the hot mode from the business area use only 1 road to escape the area.

Time of Crime

The results of the analyses about the influence of time and therefore traffic density are concluded next. Based on the analysis of destination one can conclude that a difference in traffic density results in different destinations for the organized criminals in the living area. Organized-Hot Criminals choose to change their destination to A20 West instead of A16 South. Moreover, organized crime criminals in the hot-, and cool mode move slower over time due to the traffic density. Time of crime has little or no influence on the type of decision making.

7.2. Main Research Question

So far, this research has drawn conclusions particularly for Rotterdam. Next, these results are taken towards a higher level to answer the main research question and therefore adding scientific value to this research. Rotterdam can be seen as a city that is similar to an average city in Europe between 500 000 and 1 000 000 citizens, layout and characteristics are comparable to each other. Moreover, Rotterdam is rebuilt after bombing in the second world war, resulting in a modern designed spatial layout. Resulting in the used case study of Rotterdam being generalized towards an average European City. The main research question imposes the influence of 3 important factors influencing the decision-making of the criminals during the escape after a HIC. The influence of all the three factors, type of crime, time of crime, and location of crime are described next.

Type of Crime

First, the influence of type of crime on the escape route decision-making is explained next. As aforementioned there are two types of criminals committing different types of crimes, resulting in a different escape route decision making based on the type of crime. HIC committed by organized crime organizations are crimes which requires a high degree of preparation, and result in crimes such as thud, bank robbery, and liquidation. Crimes committed by local criminals are crimes that are with a lower degree of risk, whereas smaller shops, restaurant, and houses are robbed to get easy and fast money. Furthermore, a distinction needs to be made between the criminals that are chased by the Police and the criminals that are not chased by the Police. Criminals from the organized crime use, in particular, S-roads and N-roads with the direction to the ring road highway network of a city. Whereas, the criminal being followed by the police, in particular, start the escape with using S-roads and city access roads. Furthermore, the first minutes the criminals are closer to the crime location, hereafter the criminals use the most critical S-roads connected to the regional access roads. Consequently, the criminals not being chased escape the area minutes faster. The local criminals use, in particular, collector roads and S-roads with the direction to escape the area with regional roads. For criminals not being chased, in the first minutes after the crime, the collector roads are used. Furthermore, there is a bigger variety of used roads compared to organized crime criminals. After a few minutes, the variety of roads is smaller and the several S-roads connecting to the end of the escape area are used. In the first minutes after the crime, criminals being chased mostly use living streets and residential areas. Whereas, after a few minutes only a few S roads connecting the regional access roads are used to escape the region.

Time of Crime

Second, the influence of the time of the crime on the escape route decision-making is explained. The time of crime results in different decision-making for only the organized crime criminal. The different time of crimes are related to the traffic density during the escape. Therefore, during normal hours the traffic density is normal, and the criminals are not affected by the traffic. The time of crime result in different behavior in terms of destination and road type use. The destination choices do change based on the road categories connecting to the escape highway. The criminals avoid the roads with a high traffic density; therefore, they use collector roads. Furthermore, the traffic density influences the travelled distance over time. If the traffic density is higher, it takes longer for the criminal to reach his destination.

Location of Crime

Third, the influence of the location of the crime on escape route decision-making is explained. This research looked at the influence of three locations of crime with various characteristics. First, the living area, with a high road density and mostly living streets and residential areas as road types. Only local criminals being chased use those small streets, whereas the others try to escape as fast as possible using the S roads connecting to the living area. The distribution of the used roads are segregated over several S roads. Second, the city center, is with a relatively low road density and both living streets and S-roads. Compared to criminals in the living area only a few local criminals use the living streets and residential areas. The biggest difference is in the distribution of the roads that have been used, the road use is less segregated, and only the biggest and most critical roads directly connecting to the regional access roads and highways are used. Third, the business area is with a low road density, consist of mostly S roads, and are close to regional roads and highways. Compared to the previous locations, there is no difference between road use. Both local and organized crime criminals take the S roads and regional roads to escape the local area as fast as possible.

7.3. Impact of Research

In this research a simulation model is developed to predict the prospective fugitive escape routes. Based on the outcome results of the simulations, an analysis of the escape route decision-making is done. Therefore, one can conclude that the location of crime, time of crime, and type of crime influences the escape route decision-making of criminals. The acquired knowledge of this research can result in catching the criminals faster after the crime, due to improved knowledge on potential decisions a criminal could take. However, the model is developed based on the high-level escape route decision-making of criminals. Consequentially this research cannot argue on the low-level decision-making, therefore, this research focuses on the high-level decision-making. Furthermore, because this research presents a model to predict prospective fugitive escape routes the generation of prospective escape routes allows the police to determine the location of the criminals. This is more specifically compared to the reachability circle that is used at the moment. Based on both the acquired knowledge on escape route behavior combined with knowing the potential locations of the criminals, the police can potentially improve resource distribution to catch criminals faster after a crime, resulting in the societal impact. Furthermore, this scientific impact follows from the fact that there is no research done both in predicting prospective escape routes of criminals and in analyzing the outcomes of the prospective escape routes.

8. Future Directions of Research

This research presents a model to predict the prospective fugitive escape routes, moreover, the model's outcomes increase knowledge on criminal escape route behavior. Due to system boundaries, time limitations, and lack of knowledge, elements are simplified and could be expanded in the model. This chapter discusses the future directions of this research. The future directions are explained in twofold. First, the scientifical improvements are aimed to explore the escape route decision-making in order to improve knowledge on escape route behavior of criminals. Second, the societal improvements aimed to increase the model's usefulness for the Dutch Police.

First, to improve knowledge on fugitive escape behavior, the following elements could be expanded in future work:

- **Adding personal characteristics.** The current model assumes only two different types of criminals. For further work, it would be valuable to add different criminals with different personal characteristics. Hereby, the research should focus on the influence of personal differences (e.g., experience, level of self-control, age, level of risk, etc.) on the escape route decision-making. However, further research is needed on the conceptualization these personal characteristics. Consequently, further research should focus on gathering information from different sources (e.g., criminologists, ex-convicts, psychologists, etc.).
- **Different type of driving.** The model currently does not distinguish different cars. It could be beneficial to expand the model with different cars and driving speeds, this would be necessary since the current model assumes that every criminal has the same car, as all criminals' car and driving style is different. Therefore, this further research should focus on the different cars and driving styles of the criminal.
- **Destination decision-making.** Currently, the final destination of the criminal to escape the spatial area is based on an assumed uniform distribution. To expand the model with a more accurate destination decision-making, it would be necessary to look into the reasoning of a criminal on destination decision-making.
- **Increasing spatial locations.** Solely, the spatial network of Rotterdam is used as case to study the criminal decision-making during the fugitive escapes. To improve the knowledge on escape route decision-making further work should focus on different spatial layouts with different characteristics. Hereby, an analysis of several different network graphs from cities would be interesting for further work.

Second, this model could potentially predict the possible location of the criminals during the fugitive escapes in Rotterdam. To increase the societal value of this model for the Dutch National police the following improvements could be made:

- **Automatic network generation.** This model focuses on Rotterdam, it is beneficial to develop a model that automatically generates a network with necessarily attributes for every area in the Netherlands. Therefore, the police could use the model to predict the potential locations of the criminals after a robbery in every city in the Netherlands.
- **Live traffic density.** Traffic density assumed based on road type is already added to the current model. However, adding a live traffic density allows the model to make more accurate predictions of the criminal's location.
- **Dashboard.** If the Police could use a dashboard to put in known parameters of the criminal, the model could be used to determine potential locations of the criminal.

In this research, the model is used as a tool to generate data for analysis of criminal escape route decision-making based on different scenarios with different parameters. Further research should improve in analysis of the generated data, it is recommended that effects of different input parameters are analyzed in a more detailed manner. Therefore, cluster analysis as technique for pattern recognition is recommended for further research. Improving both the social and scientific value could result in additional purposes of the model. Additionally, to this simulation model, a model could be developed to explore the impact of the Police's resources. Exploration of the impact of resource could potentially increase strategy development for catching the criminal faster after a crime.

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A. Expert Interviews

In this appendix A, all the necessary information about the interviews held with experts are added. First, the semi-structured outline of the conversations are viewed. Second, the summaries of the interviewed Police experts are added.

A.1. Outline of Semi-Structured Interviews

A.1. Form of Confidentiality

Before the interview started all the interviewed expert agreed and signed the form of confidentiality. The form is added as Figure A.1.

Formulier geïnformeerde toestemming

U bent uitgenodigd om deel te nemen aan een studie genaamd MSc thesis: Fugitive Escape Route Decsion-making. Deze studie wordt uitgevoerd door Tom Kempenaar, MSc student Engineering and Policy Analysis aan de Technische Universiteit Delft, in samenwerking met de Nederlandse Politie. Het is belangrijk om te weten dat ik alleen een geheimhoudingsverklaring getekend heb en geen screening ben ondergaan. Mocht u deze willen inzien is dat mogelijk. Let hier alstublieft op bij het beantwoorden van vragen.

Het doel van dit onderzoek is het verkrijgen van inzichten in het route keuze gedrag criminelen nadat zij een overval gepleegd hebben. Deze inzichten worden verkrijgen door modelleer- en simulatiestudie. De verkregen informatie wordt anoniem gebruikt voor kennis input voor het computationele model. Ik zal open vragen stellen met betrekking route keuze gedrag van criminelen.

Uw identiteit zal vertrouwelijk zijn. Ik zal veilig en anoniem interview transcripties, email gesprekken en meeting samenvattingen opslaan, alleen toegankelijk door mij. De uiteindelijke MSc thesis zal publiek beschikbaar zijn en geen transcripties van de gesprekken met u bevatten of enige verbanden naar uw identiteit. Ook zal een aparte versie voor de Politie beschikbaar komen: hier worden bovenstaande factoren hetzelfde gewaarborgd.

Uw deelname aan deze studie is volledig vrijwillig en u kunt op elk moment besluiten te stoppen met deelname. U bent vrij om vragen niet te beantwoorden. In geval van een vragenlijst via email wordt u gevraagd expliciet te vermelden dat u dit formulier heeft gelezen en of u wel/niet uw toestemming geeft. In geval van face-to-face (of online) gesprekken zult u gevraagd worden om expliciet akkoord te gaan met de inhoud van dit formulier door dit te benadrukken.

In geval van face-to-face gesprekken (of online) gesprekken, kan ik eventueel vragen om het gesprek op te mogen nemen met mijn computer of telefoon, om de inhoud van het gesprek nogmaals te beluisteren voor gedetailleerde informatieverwerking. Ik zal deze bestanden veilig opslaan beschermd met wachtwoorden -alleen mij toegankelijk- en deze direct verwijderen zodra ik afgestudeerd ben. Dit is optioneel en heeft uw expliciete toestemming nodig. In geval er geen toestemming wordt gegeven, als ik alleen eigen aantekeningen van het gesprek maken die ook veilig worden opgeslagen.

Voor vragen kunt u mij of mijn dagelijkse afstudeerbegeleider Ir. Irene van Droffelaar (i.s.vandroffelaar@tudelft.nl) aan de Technische Universiteit Delft benaderen. Irene van Droffelaar is in dienst bij de Nederlandse Politie via het Nationaal PolitieLab AI.

Figure A.1: Form of Confidentiality

A.1.1. Presentation Slides for the Interviews

The following PowerPoint presentation slides are added as Figure A.2 until Figure A.4. These slides are used to gather the expert data that is needed to answer the sub questions and therefore main research question.

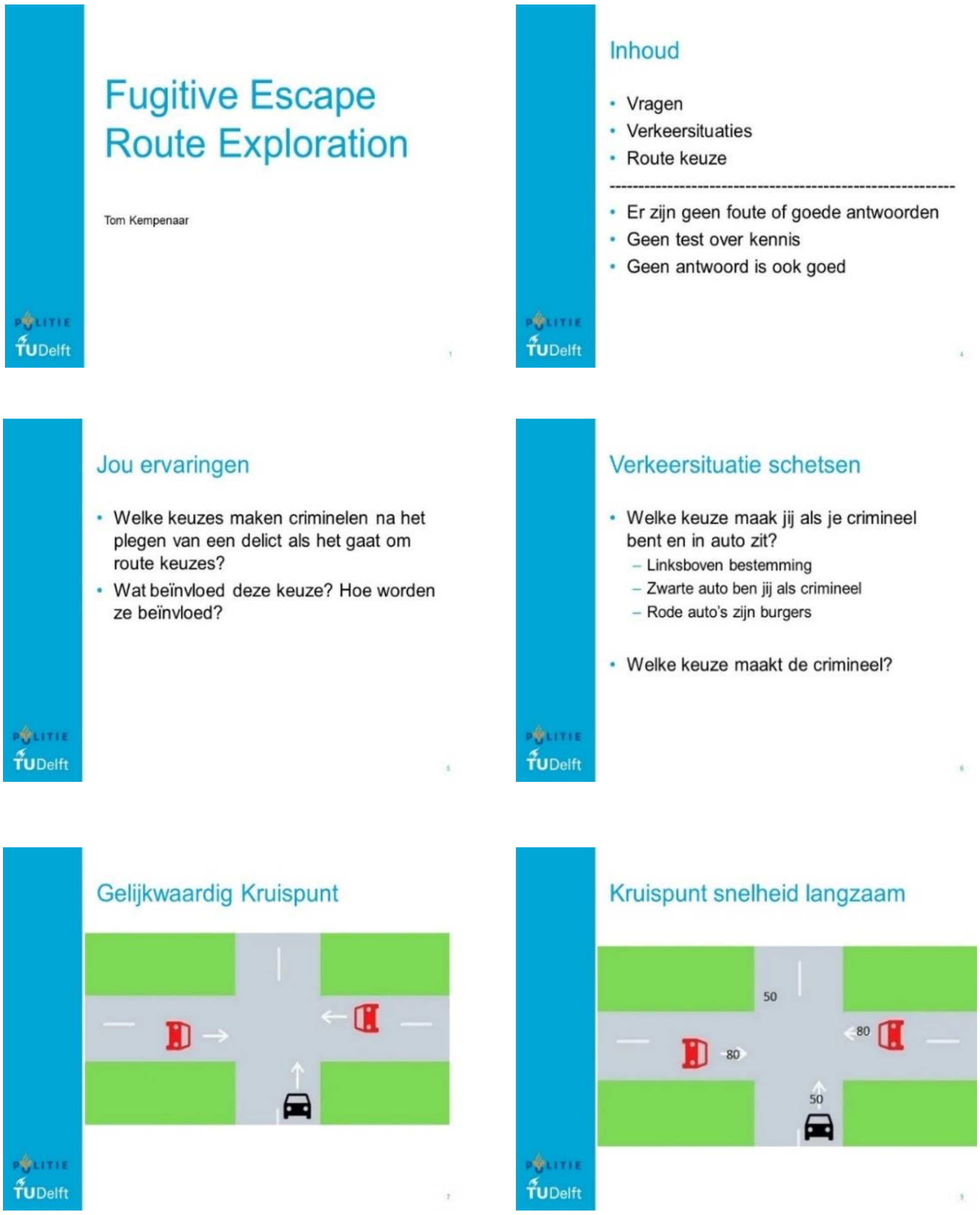

Figure A.2: Interview Slides 1-6

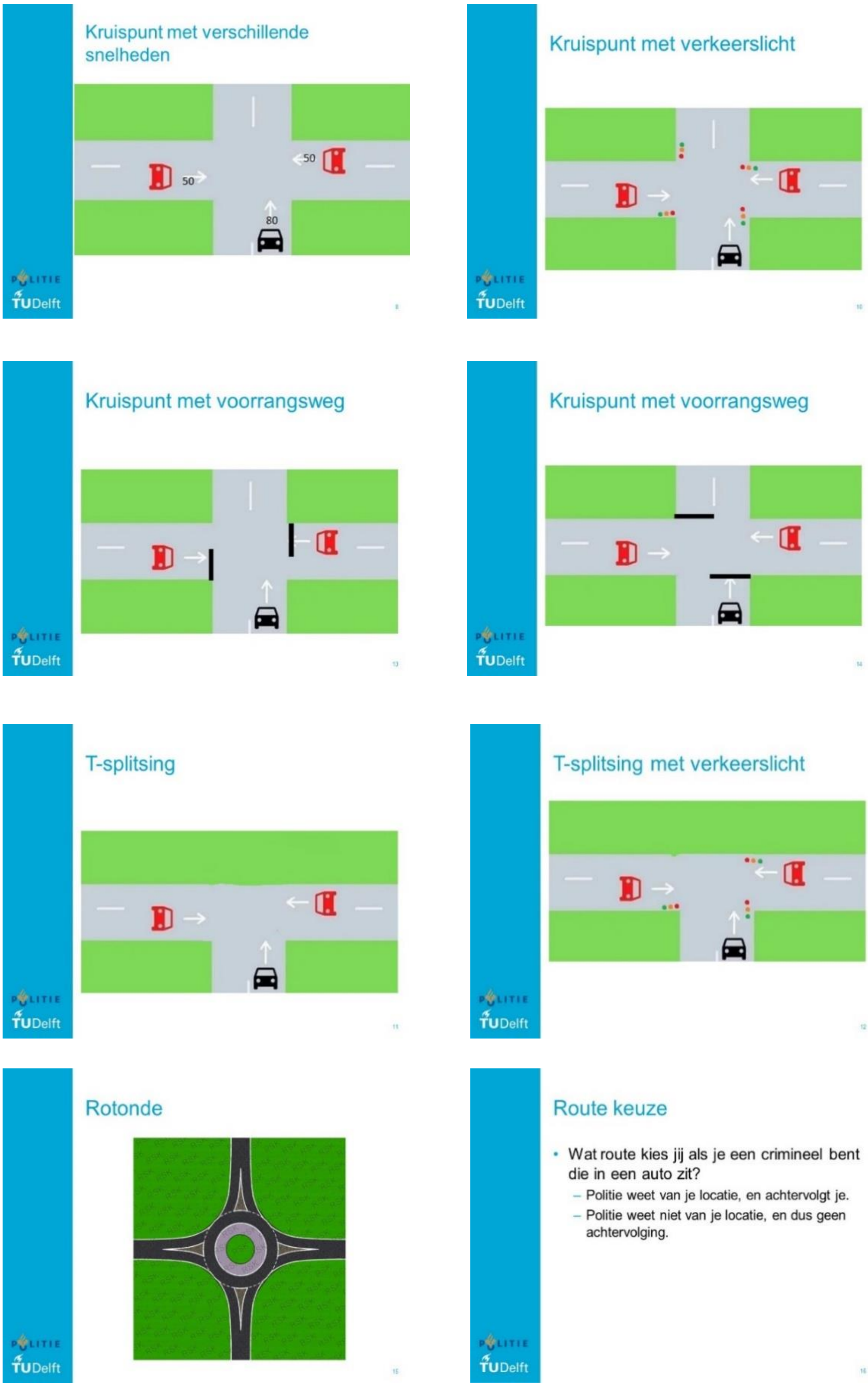

Figure A.3: Interview Slides 7-15

Figure A.4: Interview Slides 16-19

A.2. Expert Interview Summary

In this appendix Section A.2, the interviewed police officers are summarized, because of social sensitivity and confidentiality a full transcript of records is not available.

B. Model Formulation

This chapter contains all additional information to support the model formulation in Chapter 3.

B.1. Spatial Network

The spatial network generated from the OSMNX library is visualized in Figure B.1. This graph is used as the backbone of the simulation model to prospect the fugitive escape routes of criminals after a robbery in Rotterdam. The red dots are the possible destination nodes for the organized crime, those are at the end of highways to escape the area. The green dots are the destination locations of the local crimes, at the end of the bigger city roads and regional roads to escape the local area.

Figure B.1: Spatial Network Graph of Rotterdam

B.2. Criminal's Life Cycle in a Single Run

Figure B.2 visualizes the life cycle of a criminal in a single run of the model. The criminal is generated at a source, goes to through links to server, where the criminals determine his new next node based on the criminal decision-making framework. The entity is destructed when he enters a sink.

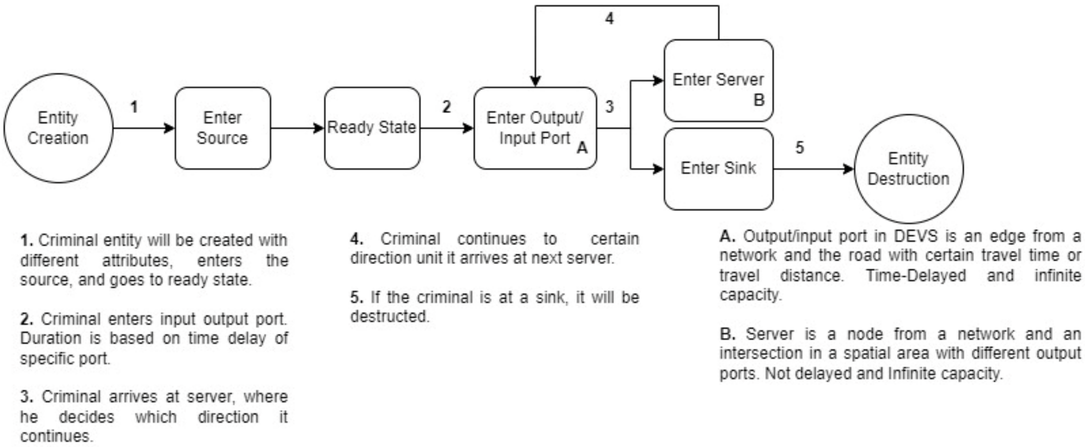

Figure B.2: Life Cycle of an Entity

C. Model Validation

This chapter contains all additional information to support the model validation in chapter 4.

C.1. Road Map of Rotterdam

This road map, Figure C.1, shows all the roads within the spatial boundaries of this research. The research used this map to point out a crime location, and consequently asked what route the expert should take to escape the area.

Figure C.1: Road Map of Rotterdam

C.2. Single Experiment Outcomes

In this section several outcomes with different variations with input parameters are shown to show to the experts. These are examples of runs that are used to validate the model.

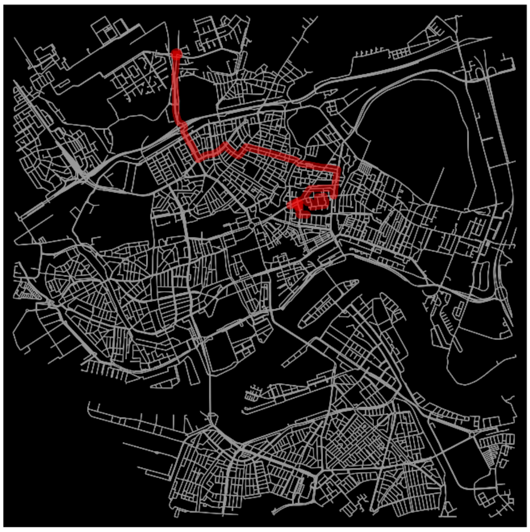

Figure C.2: Single Run City Centre Organized-Hot

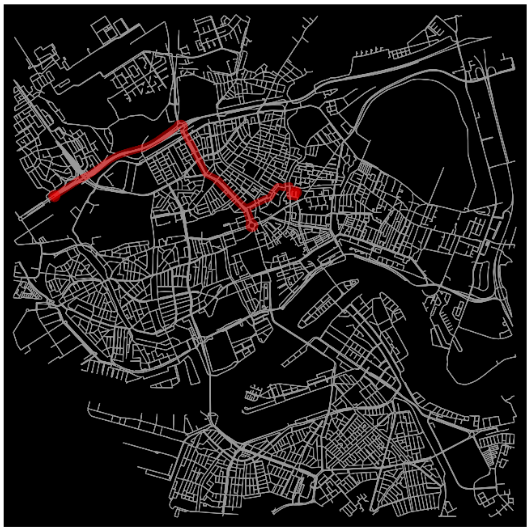

Figure C.3: Single Run City Centre Organized-Hot

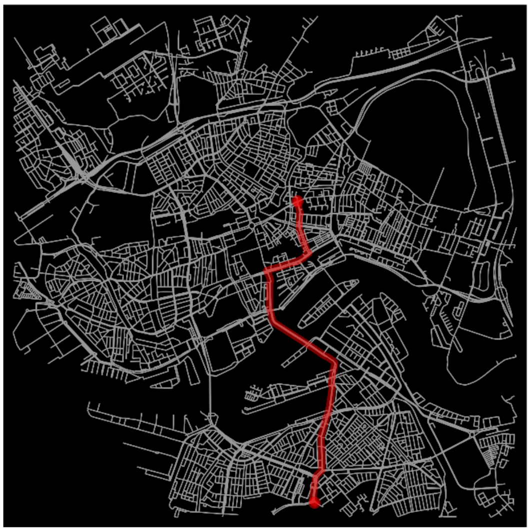

Figure C.5: Single Run City Centre Local-Hot

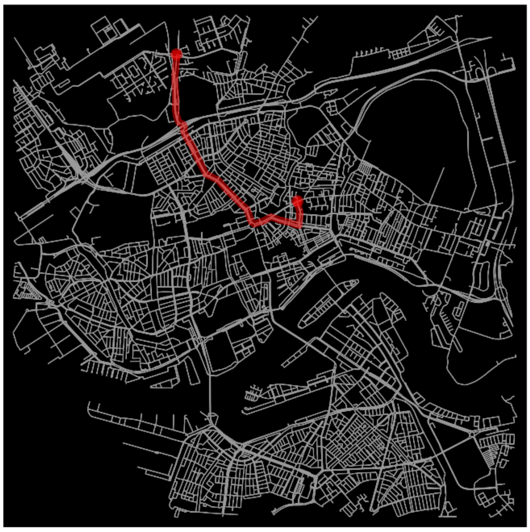

Figure C.4: Single Run Business Area Local-Hot

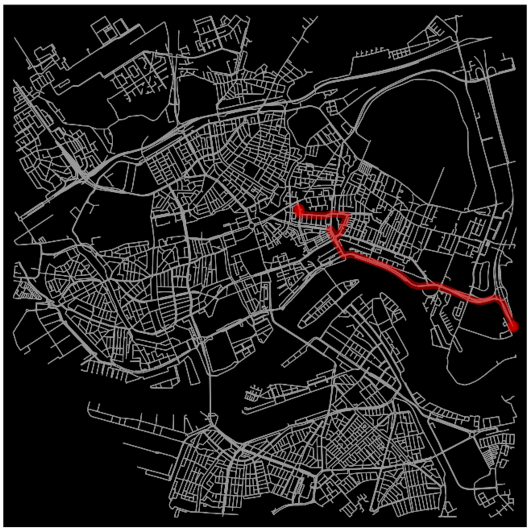

Figure C.7: Single Run Living Area Local-Cool

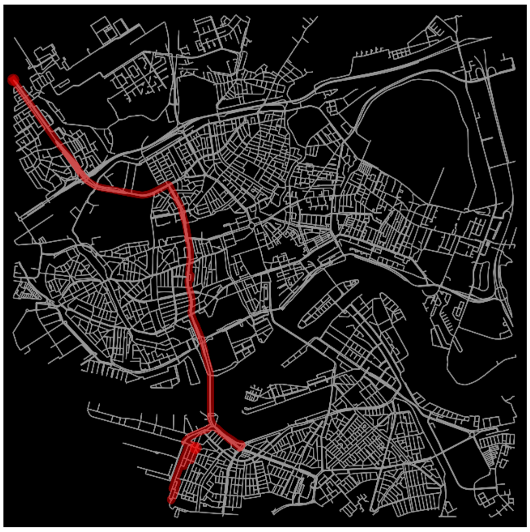

Figure C.6: Single Run Living Area Local-Hot

D. Model Outcomes

This chapter contains all additional information to support the outcome analysis of chapter 6. First, the heatmaps for each location and each quadrant is shown. Second, both the heatmaps of the escape routes of criminals over time influenced by a high traffic density and low traffic density are shown.

D.1. Heatmaps of Escape Routes

This section visualizes all the generated heatmaps for each crime location and quadrant of the criminals.

City Centre

Figure D.2: Heatmap City Centre Organized-Cool

Figure D.1: Heatmap City Centre Organized-Hot

Figure D.4: Heatmap City Centre Local-Cool

Figure D.3: Heatmap City Centre Local-Hot

Living Area

Next, the escape routes from a crime in the living area are viewed as heatmap.

Figure D.6: Heatmap Living Area Organized-Cool

Figure D.5: Heatmap Living Area Organized-Hot

Figure D.8: Heatmap Living Area Local-Cool

Figure D.7: Heatmap Living Area Local-Hot

Business Area

Next, the escape routes from a crime in the business area are viewed as heatmap.

Figure D.12: Heatmap Business Area Organized-Cool

Figure D.9: Heatmap Business Area Organized-Hot

Figure D.10: Heatmap Business Area Local-Cool

Figure D.11: Heatmap Business Area Local-Hot

D.2. Heatmaps over Time

In this section the heatmaps over time are visualized, per timeframe the heatmaps for all the four quadrants are given.

From 0 second until 60 seconds.

Figure D.13: Heatmaps for 0 till 60 seconds

From 60 seconds till 120 seconds

Figure D.14: Heatmaps for 60 till 120 seconds

From 120 seconds till 240 second

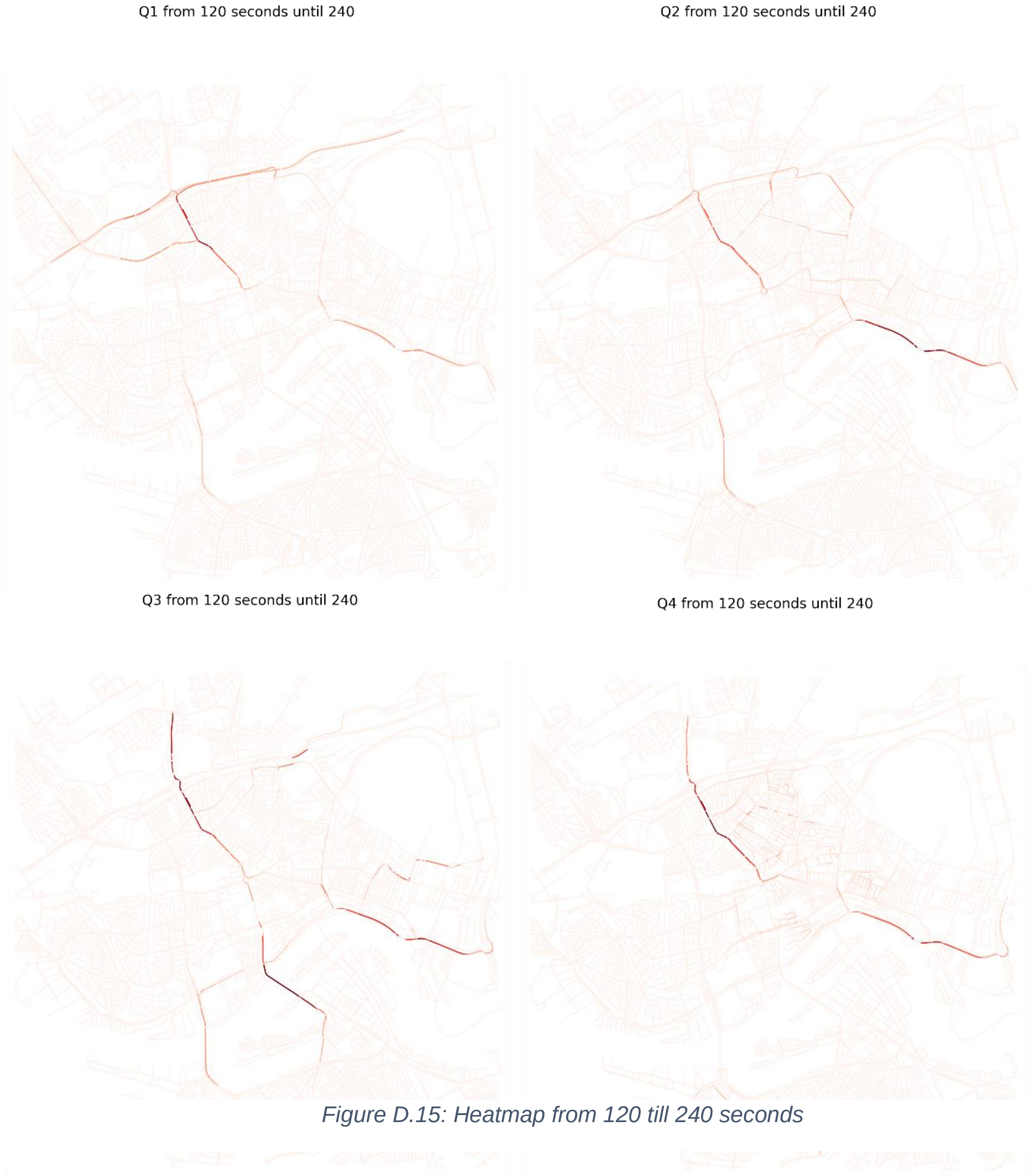

Figure D.15: Heatmap from 120 till 240 seconds

From 240 seconds till 480 seconds

Figure D.16: Heatmap from 240 till 480 seconds

From 480 seconds till 960 seconds

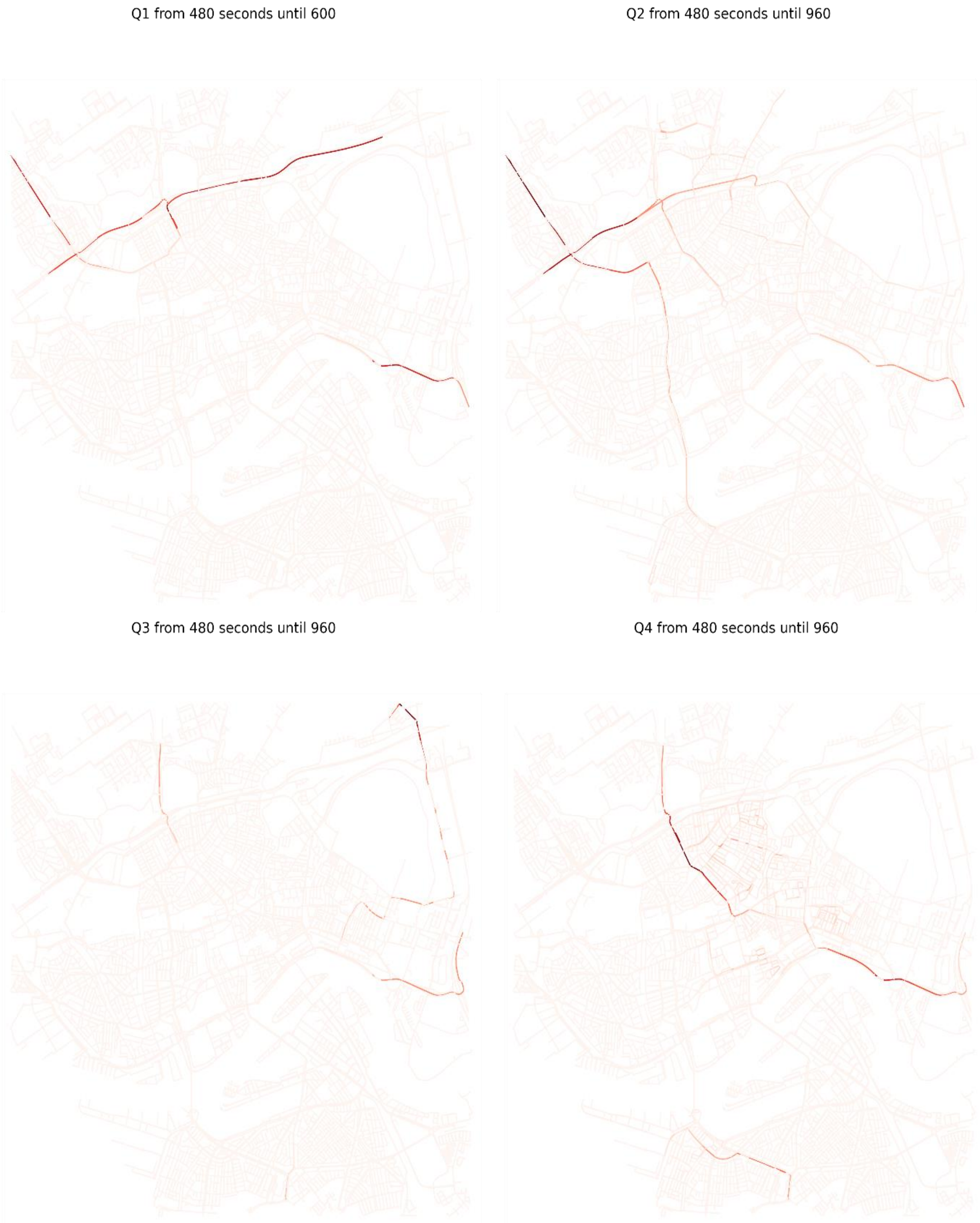

Figure D.17: Heatmap from 480 till 960 seconds

D.2. Heatmaps over Time Influenced by Traffic

In this section the heatmaps over time are visualized, per timeframe the heatmaps for the first and second quadrant are given.

Heatmap of Organized-Cool over time

Figure D.18: Heatmap over Time with High Traffic Density Organized-Cool

Heatmap of Organized-Hot over time

Figure D.19: Heatmap over Time with High Traffic Density Organized-Hot