Helicopter view

Positioning helicopters where they make a difference

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Preface

At some moment during my Master Industrial Engineering & Management, in the direction of Production & Logistics, I discovered why I like this research area so much: optimizing real-world problems, or at least find a better method to solve them. From that moment on, I knew I wanted to do my thesis at an organization where I could make a difference for the organization, although I had no clue yet where that would be. However, graduating at a government organization never crossed my mind.

Months later, Erwin Hans and Martijn Mes asked me, independently of each other, yet in a timespan of fifteen minutes, whether I had already found an organization to do my Master assignment. They told me that a master assignment might become available at the Korps Landelijke Politiediensten (KLPD) that had to do with police helicopter positioning. From that moment on, I got more and more excited about doing this research as it was likely that the KLPD would really benefit from this research and I could do an optimization project.

On my first day at the KLPD, I had a flying start, as Arjen Stobbe and Edo van den Brink were presenting an initial review of the performance of the Luchtvaartpolitie (LVP). During this presentation, I became aware what the impact of this research could be: I would direct the police helicopters in such a way that they could make a difference. I would not only make a difference in the performance of the LVP, but also in the safety of the Netherlands.

During this research, I received support from many different people. First, I would like to thank Martijn Mes and Erwin Hans for their critical questions and valuable feedback. Next, I would like to thank the KLPD and especially Rutger Rienks, Edo van den Brink, and Arjen Stobbe for their feedback and their enthusiasm when I showed them intermediate results. It gave incredible motivation to keep going. Furthermore, I would like to thank my parents for their support during my study. I thank my younger brothers and my friends for all the fun during my study to make it a time to remember forever.

At last, I want to thank my girlfriend and fiancée Debbie van der Zee for all her love, support, care, fun, and motivation during my study.

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Rick van Urk

Management summary

Motivation

In 2011, Buiteveld developed a tool to support tactical decision-making regarding the determination of which bases to use, and how many helicopters to station on each basis. This tool improved the performance of the Dutch *Luchtvaartpolitie* (Aviation Police & Air Support). As they have to make operational decisions as well, the Luchtvaartpolitie would like an instrument to support operational decisions to further improve their performance.

Research goal

The goal of this research is to develop a prototype instrument that supports the *Luchtvaartpolitie* with its operational decision-making regarding the planning of flights of the police helicopters for the next day. This prototype instrument uses historical data and intelligence. The improved planning of helicopter flights should lead to more arrests in which helicopters have a successful assist.

Forecasting

Positioning helicopters in such a way that they maximize the likeliness of having a successful assist requires an incident forecast. This forecast is made for areas in the shape of regular hexagons with a surface of approximately 47.5 square kilometer. The forecast is based on historical data of incidents. As the number of incidents is too small to get an accurate forecast, generalization is used. Generalization is based on the idea that an event in one area gives information about the likeliness of such events in the neighborhood. Besides historical data, intelligence can be used to improve the quality of the forecast.

Positioning model

A helicopter-positioning model has been developed to solve the positioning problem to optimality. As this positioning model requires too much computation time to be of practical use, two heuristics have been developed that give a good result within a day. This implies our heuristics can be used to run today to make tomorrow's plan. The first heuristic will take an entire day as it keeps trying to improve its current result, whereas the second heuristic gives a reasonable result in eleven minutes.

Instrument

We developed a prototype instrument that makes use of the proposed forecasting and positioning models. As our prototype instrument requires intelligence, it is not possible to give an accurate performance measurement without using it in practice. We recommend the LVP to validate this prototype instrument during the upcoming *Donkere Dagen Offensief*, as it has the potential to significantly improve the number of successful assists of the police helicopter fleet.

Conclusion

The decision support prototype instrument is likely to increase the number of successful assists significantly. Based on a small experiment, we believe our approach, a combination of a forecasting method, followed by the helicopter routing heuristics we developed, outperforms the current planning methods

used by the *Luchtvaartpolitie*. This small experiment showed our quick heuristic, which runs in 11 minutes, would have led to 20.65 expected successful assists during the last seven days of 2011. This is 2065% more expected successful assists than the Luchtvaartpolitie had successful assists in the same period and 138% more successful assists than the Luchtvaartpolitie had an assist, regardless of the outcome. Obviously, a more in depth analysis is required as this was a small validation based on a single week.

Recommendations

Our main recommendation is using the upcoming *Donkere Dagen Offensief* to validate the prototype instrument. Besides this main recommendation, we also recommend the following:

- Continuously track the number of successful assists such that the performance is known at any time.
- Use multiple bases to have a larger base coverage of the Netherlands, as proposed by Buiteveld (2011), and to ensure air support when a basis is not operational due to, for example, fire.
- Mention successes. Everyone in the organization has a role in the performance, so share successes for example in a weekly bulletin to let everyone in the organization know that they make a difference.
- Make regional departments aware of the importance of complete data. When they do not enter all incidents, they appear to perform better and will receive less air support.

Further research

During this research, we encountered several issues that we believe require further research. This further research should focus on the following:

- Research cooperation with Belgium and Germany to improve coverage of border areas at lower costs.
- Research the probability of a successful assist to improve the decision making for both scheduling and ad-hoc deployment.
- Research the preventive effect of police helicopters. Based on common sense, we believe the appearance of a helicopter has a preventive effect on criminal activity.
- Research more advanced forecasting methods to allow for more realistic forecasts and therefore better input for the routing algorithms.
- Research the possibilities for an integral scheduling approach. This applies to the hierarchical planning levels as well as integrating the scheduling of police helicopters, police cars, and policemen. We believe this will reduce costs or lead to improved overall performance.

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1 Introduction

It is night. Most of the citizens in the Netherlands are asleep. Two burglars try to enter the storage of an industrial company. After a while, the burglars set off an alarm and flee by car. In the mean time, police cars arrive at the scene. A witness tells the police he saw the car fleeing in the direction of a certain neighborhood. Heading in that direction, the policemen find the car. However, the burglars have left the car and flee by foot. One of them ran into the nearby park, the other one must be hiding somewhere between the houses. Searching the entire park and the neighborhood will take too long by foot. A nearby police helicopter arrives in the neighborhood to assist. The heat camera shows an unusual warm waste container: the first burglar is found and arrested. The other burglar is still on the run, somewhere in the park. The helicopter starts flying over the park to detect the fleeing burglar. Once found, the helicopter crew directs the police on the ground to the burglar, who appears to be hiding under fallen leaves. Due to the assistance of the police helicopter, both burglars are found quickly. Without the helicopter, the burglars might still be at large.

Another night. An explosion happens at a depot of a value transport in the middle of the Netherlands. Two sports cars leave at high speed in southern direction. The police helicopter leaves as soon as possible from Schiphol to tail the cars. However, as the sports cars have a twenty-minute head start and a top speed in the same order as the helicopter, they are able to remain at large.

As can be seen from the example above, the position of a helicopter at the time of an incident has a great impact on the likeliness of criminals to remain at large. In order to make the Netherlands more secure, the police want to plan its helicopters flights in such a way that the police helicopters cover most of the incidents. This is the goal of this research.

This chapter contains the motivation for this research and is an introduction for the remainder of this report. This chapter is organized as follows. Section 1.1 contains a description of the organizational structure of the

Korps Landelijke Politiediensten, the Dutch National Police Services Agency. The motivation for this research is described in section 1.2, followed by the scope in section 1.3. Section 1.4 contains the research goal, followed by the research questions in section 1.5. Section 1.6 states the structure of the remainder of this report.

1.1 Organization

The Dutch police consist of the *Korps Landelijke Politiediensten* (KLPD) and 25 regional departments. The Dutch police report to the *Ministerie van Veiligheid en Justitie*, which is the Dutch Ministry of Security and Justice. The KLPD supports regional departments and is furthermore responsible for the specialist tasks and countrywide police tasks. An example of a countrywide police task is the railway police, as the railways cross the borders of regional police departments. Appendix A gives the organizational structure, in Dutch, of the KLPD. The highest layer in the KLPD is the agencies top management. Staff offices, such as Communication, and agency wide services, for example Human Resources, support top management. The layer below the agencies top management consists of the services of the KLPD. These services are based on special topics such as Specialist Interventions and Royal and Diplomatic Security.

This research is executed for the Dutch *Luchtvaartpolitie* (LVP), which is the Dutch Air Support & Aviation Police. The LVP is a unit of the *Dienst Operationele Samenwerking* (DOS), which is responsible for the operational cooperation within the Dutch police. The LVP and its air fleet support the regional police departments in the air, for example during a car chase after a robbery. Furthermore, the LVP gives air support for the specialist tasks and countrywide police tasks. The organization of the air support consists of the following six functionalities:

- **Flight Dispatch** does the flight preparation, flight support, and flight completion.
- **Pilot** controls the helicopter during a flight.
- **Observer/operator** sits in the back of the helicopter during a flight and controls the sensors of the helicopter.
- **Maintenance** is responsible for keeping the air fleet ready for use.
- **Planning office** is responsible for making a base planning for each year/month/week.
- **Flight Information Center** is responsible for gathering, preparing, and operationalizing the intelligence and non-emergency requests. The intake of emergency requests is done at the Communication Center in Driebergen. If necessary, the Flight Information Center (FIC) requests a change in the base plan.

Apart from air support, the LVP is also responsible for the supervision of the aviation. Aviation supervision is not considered in this research.

1.2 Motivation

In 2011, Buiteveld developed a tool for the LVP to support tactical decision-making based on historical data. The tool supports in deciding which bases should be used, and how many helicopters to station on each basis. After the introduction of this tool, significantly more arrests have been made where helicopters had a successful assist. As the tool of Buiteveld has been proven to have a positive effect on the performance, the LVP wants to further improve its performance by adopting an instrument for their operational decisions. This instrument should give support for the positioning of helicopters on a daily basis and take both historical data and intelligence about future events into account. In the remainder of this report we abbreviate intelligence about future events as intelligence.

The research of Buiteveld and this research focus on a different level of the hierarchical structure of Hans et al. (2007). This hierarchical structure consists of three levels:

1. **Strategic:** On the strategic level, long-term decisions are made. An example of such a decision is the number and type of helicopters to use in the fleet.
2. **Tactical:** On the tactical level, mid-term decisions are made. Examples include the selection of bases to use, as considered in the research of Buiteveld (2011), and the planning of major maintenance for the helicopters.
3. **Operational:** On the operational level, short-term decisions are made. The operational level is split into offline and online decisions. Offline decisions are made beforehand, whereas online decisions are made when something unplanned occurs. An example of offline operational decisions is planning tomorrow's flights. Deciding which helicopter to send to an incident that happens right now is an example of an operational online decision.

The goal of the previous research was to select bases in such a way that the expected percentage of incidents to be covered within the reachable radius of a basis is maximized. The goal of this research is to plan helicopter flights in such a way that the probability that no helicopter is able to arrive in time at an incident is minimized. This research is on the operational offline level. Contrary to bases, helicopters can change position during the day. Furthermore, in this research we do not force helicopters to go back straight to their basis after air support has been given.

1.3 Scope

The LVP wants to use the new instrument during the *Donkere Dagen Offensief* (Dark days offense) from October 2012 until and including March 2013. Therefore, this research has to be finished before this period. In order to finish this research in time, it is important to set boundaries for the scope of the research. In this section, we discuss the boundaries we set.

This research takes place on the 'operational offline' level of the functional planning area 'resource capacity planning' of the model described by Hans et al. (2007). This means that we do not focus on strategic and tactical decision-making. Furthermore, we do not focus on 'operational online' decisions, which means our instrument does not support real-time decision-making. However, we do try to optimize the real-time decisions by improving the coverage of the police helicopters and therefore take the operational online dispatching rules into account.

In this research, we focus on the six Eurocopter helicopters (EC135) that are primarily used for emergency support. The LVP also has two Agusta Westland helicopters (AW139), which are primarily used for countrywide police tasks and three Cessna airplanes (C182), which are primarily used for specialist tasks such as observation flights. Although the AW139 and C182 aircrafts are not primarily used for emergency support, we do take them into account to allow for such use in the future. Figure 1.1 shows photos of the two helicopters.

Figure 1.1 - Photos of the Eurocopter (left) and the Agusta Westland (right). (source: KLPD 2012b)

Helicopters hovering over an area might have a preventive effect on the number of incidents in that area. As the impact of this effect is not known, we do not take it into account. Therefore we 'maximize the number of successful assists of an helicopter' instead as the definition of our goal instead of minimizing the probability of no helicopter being able to arrive in time at an incident.

As incidents are not known in advance, deciding where to position the helicopters during the day is an example of anticipatory decision-making. In anticipatory decision-making, decisions are made based on a forecast. Forecasting when and where incidents might happen will be based on both historical data and intelligence.

In this research, we assume it is not necessary to take the costs into account that are directly related to the number of flown hours, as we believe all available flight hours will be used. This implies we aim for results that are as good as possible, with the pre-determined number of flying hours. Furthermore, we assume the crew schedule will not be adjusted on a daily basis. Therefore, the helicopter schedule will be limited to the times when shifts are scheduled.

1.4 Research goal

The goal of this research is to develop a prototype instrument that supports the LVP with its operational decision-making regarding the planning of flights of the police helicopters throughout the day. This instrument should use historical data and intelligence. The improved planning of flights of helicopters should lead to more arrests in which helicopters have a successful assist.

1.5 Research questions

In order to reach the before mentioned goal, information is required about how the decision support instrument should work. To obtain this information, we formulate research questions. Each research question covers a separate part of the problem and its answer yields part of the required information. The research questions are:

1. **What is the current situation at the Dutch Air Support & Aviation Police considering the daily positioning of police helicopters?** By answering this question, we want to get a good view of the current situation and the context in which the instrument will have to work. This is done by interviewing personnel of the LVP.

2. **What literature is available related to forecasting and positioning?** By answering this question, we want to get a starting point for our solution. This is done by a literature research.
3. **How should incident forecasts be made for use in a model for the operational positioning of helicopters?** By answering this question, we want to find out how to make good incident forecasts. This is done using insights gained from literature.
4. **How should a model for the operational positioning of police helicopters look like?** By answering this question, we want to present a good operational planning methodology to support daily positioning of police helicopters. This results in a decision support instrument and is done using insights gained from literature.
5. **How can the model for operational planning of police helicopters be successfully implemented at the Dutch Air Support & Aviation Police?** By answering this question, we want to give guidelines on what has to be done to implement this instrument successfully in the processes of the LVP. This is done by interviewing personnel of the LVP.

1.6 Structure

The structure of this report is as follows. Section 2 describes the current situation, followed by the relevant literature in section 3. Section 4 describes the process of making a good forecast of future incidents using historical data and intelligence, followed by the planning model in section 5. Section 6 contains the description of the prototype instrument. The conclusion and recommendations are given in section 7.

2 Situation description

This chapter describes the current situation at the LVP and what the future situation should be. Section 2.1 describes the process to get a helicopter airborne. The probability that a helicopter has a successful assist at an emergency situation is described in section 2.2. The distribution of incidents is given in section 2.3, followed by the results of the LVP at the *Donkere Dagen Offensief* in section 2.4. Section 2.5 describes the desired situation. Finally, section 2.6 contains the conclusions that can be made based on this chapter.

2.1 Getting airborne

For emergency support, requests arrive via the Communication Center in Driebergen. Requests for non-emergency support arrive at FIC and are required to have a goal, detailed information (e.g., date, time, location), information whether the flight can be interrupted for ad-hoc requests, and risk analysis if applicable. FIC decides whether to accept the request. These requests vary from an intervention where a helicopter is desired for an overview to a flight over cornfields to search for drugs plantations.

When an emergency request arrives, or a planned flight is about to start, the crew is notified. The pilot starts the process to take off. He does a quick check of the helicopter, as he already did this extensively when he started his shift. After this quick check, he starts performing the checks to start the helicopter. In the mean time, the observer/operator gets flight information at Flight Dispatch. A flight plan is included when flying from Schiphol, as other air traffic has to be taken into account. When the observer/operator arrives at the helicopter, it is ready for lift off.

The required time to get the helicopter airborne from the moment of notification varies between four and seven minutes. Due to this takeoff time, it is sometimes more effective to send a helicopter that is already flying.

2.2 Probability of successful assist

The probability of a successful assist is defined as the chance that a helicopter is in time at a crime scene to have added value in getting an arrest. Buiteveld (2011) and the LVP cooperatively developed a function to calculate the covering percentage of a basis. This function is based on the Generalized Maximal Covering Location Problem of Berman & Krass (2002). As the used input is time to arrival at the crime scene, this function can also be used for helicopters in the air. The function is based on an one hundred percent success rate when arriving within ten minutes, an eighty percent success rate when arriving at twelve minutes, a forty percent success rate when arriving at fourteen minutes and no chance when arriving after fifteen minutes. In this function, all values between ten and fifteen minutes are evaluated using linear interpolation.

A piece-wise linear function is unlikely, as this obviously does not correspond the real system. Therefore, we propose the use of a smoother function. As decline of the function doubles every two minutes, we propose a formula that takes this into account. Furthermore, we propose to intersect the function at twelve, fourteen, and sixteen minutes. In order to do so, we use the value of sixteen minutes if it would have been allowed to be negative. This leads to the following formula, where x is the arrival time in minutes:

$$f(x) = 1{,}2 - 0{,}2 \times 2^{\frac{x-10}{2}}$$

This formula doubles the decline every two minutes and intersects the function at twelve, fourteen, and sixteen minutes. Results above 100% and below 0% are set to respectively 100% and 0%. Figure 2.1 shows a graphical representation of the previous function (red) and the new formula (blue).

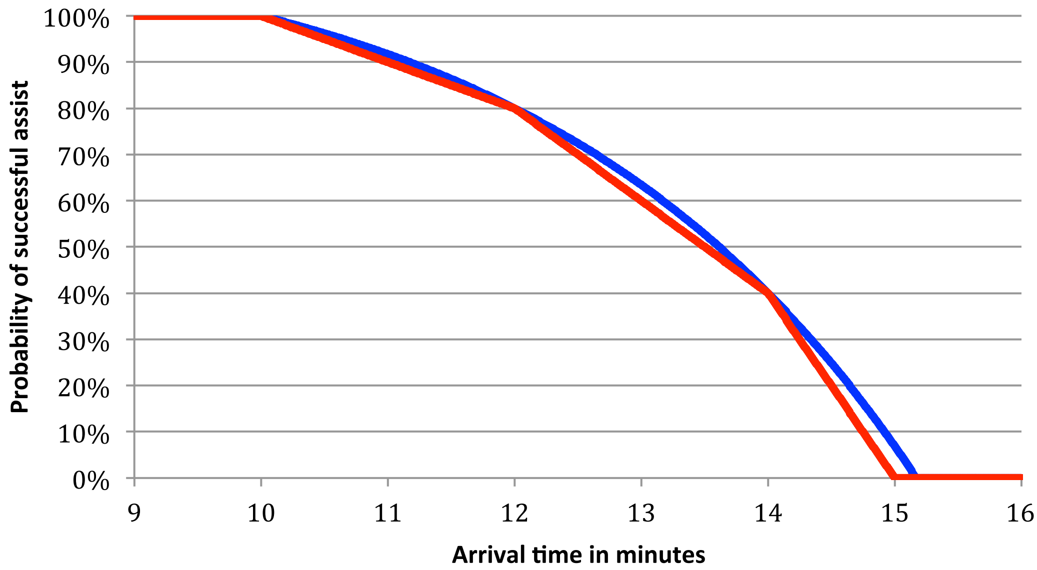

Figure 2.1 - Graphical representation of the previous function (red) and the new formula (blue).

As the probabilities estimated by this formula are still based on expert opinion, we recommend validating this in a subsequent research, as this is out of the scope of this research.

2.3 Incident distribution

Inherently, incidents happen unannounced and can happen at any moment during the day, and on every day of the year. However, we can recognize patterns. In this section we give a first overview of those patterns, to give a view on the current situation. Potential correlations between incidents and other phenomena are discussed in section 3.2. The use of historical data will be discussed in more detail in section 4, in which we discuss forecasting future incidents.

As can be seen in Figure 2.2, more incidents happen in the months where the period between sunrise and sunset is shorter.

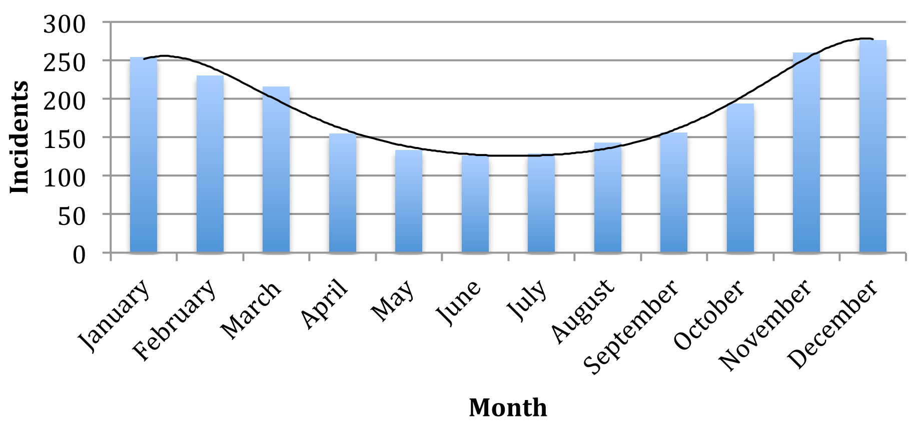

Figure 2.2 - Number of incidents per month in 2011. (source: KLPD 2012c)

This observation is supported by Figure 2.3, which shows most incidents happen in the evening. These results are to be expected, as sight is decreased and fewer people are on the streets when it is dark outside, which leads to fewer potential witnesses.

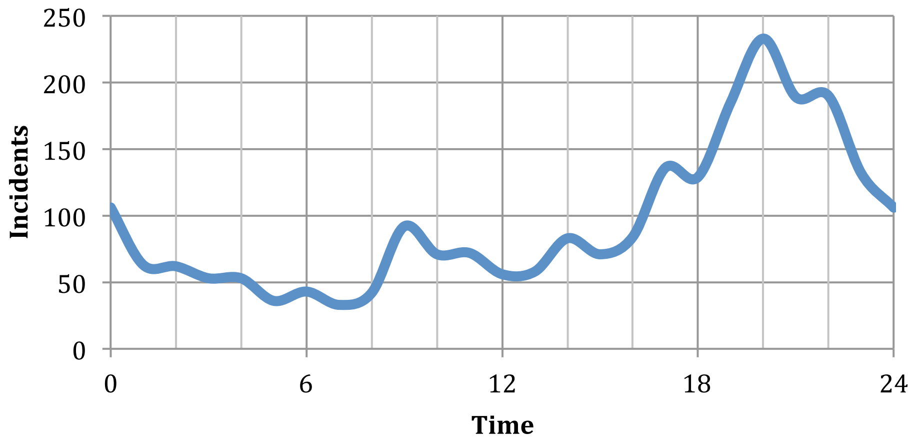

Figure 2.3 - Number of incidents in 2011 per hour of the day. (source: KLPD 2012c)

Figure 2.4 shows the distribution of incidents for each day of the week and it can be seen that most incidents happen on Fridays and during the weekend. Possible explanations are that criminals have a job or expect fewer policemen on duty during weekends.

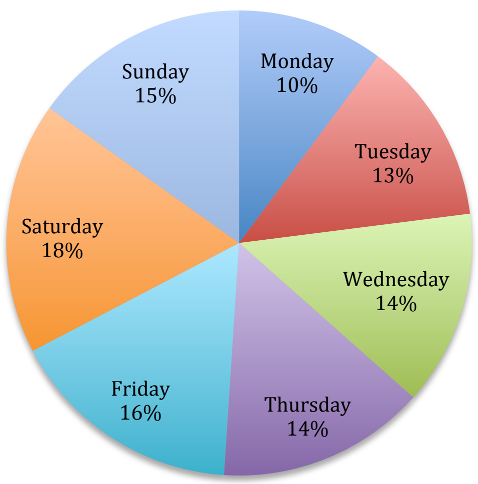

Figure 2.4 - Number of incidents in 2011 per day of the week. (source: KLPD 2012c)

When the LVP focuses on the dark hours, the expectation is that this will lead to more successful assists of helicopters. Besides a higher probability something happens during the dark hours, the helicopters are also more capable of finding suspects when it is dark and quiet than when it is crowded. For example, a gray car on the highway is distinguishable from kilometers away at night; however, during the day, one cannot distinguish a gray car as easily due to the high traffic. However, it is important that the police are also visible during the day, as not only safety is important but also the perception of safety in the eyes of civilians.
Besides distribution in time, there is also a geographical distribution, as depicted in Figure 2.5. In this figure, it can be seen that incidents are mostly situated in the Randstad. Although most incidents are happening there, the police should focus

on the Netherlands as a whole, as focusing on the Randstad will make the rest of the Netherlands more attractive for criminals. Furthermore, this shows the importance of working with recent data, the skills to recognize trends, and ability to respond to those trends.

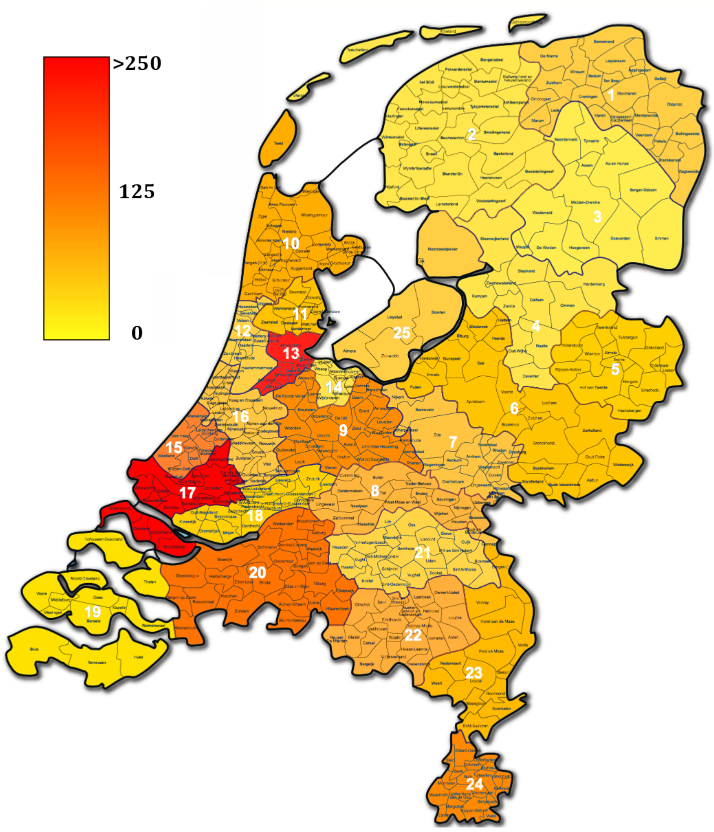

Figure 2.5 - Geographical distribution of incidents in 2011. (source: KLPD 2012c)

Besides distribution in time and place, the impacts of incidents are different as well. This is partially due to the type of incident. For example, a robbery on a money transport with the use of extreme violence is different from a robbery on a gas station with “just” the threat of a knife. Furthermore, the location also influences the impact. For example, a robbery on a supermarket in the Randstad has a smaller impact on the local society than an identical incident in a small town in the northeastern part of the Netherlands. This is due to people getting used to incidents in the Randstad, because of the higher frequency. We will not discuss the impact of crimes in more detail and assume the impact is taken into account in the priority given to each incident, which serves as input for our instrument.

2.4 Results ‘Donkere Dagen Offensief’

In this section, we discuss the results of the LVP during the last *Donkere Dagen Offensief* (DDO), which is the period in which there is less daylight. The LVP uses this period to pilot new concepts that will get implemented permanently on success. The last DDO was from October 2011 until and including March 2012. During the DDO, the LVP positioned their helicopters better. Instead of having all helicopters stationed at Schiphol, the LVP had one helicopter in the evenings in Rotterdam and one helicopter during daytime at Volkel. Furthermore, the flight planning was changed to fly over the hotspots, the locations with relatively many incidents, at the hot times. This is partially in line with the recommendation of Buiteveld (2011) to have the helicopters distributed over several bases in the Netherlands. The main difference is that the helicopters were not permanently stationed at Rotterdam and Volkel and had to fly to Rotterdam and Volkel at the beginning of their shift and back at the end. This had a cost of about half an hour flight time in each direction. Furthermore, there was a helicopter stand-by 24/7 at Schiphol.

During the DDO, there was a significant increase in the number of arrests where a helicopter had a successful assist. The twelve months before the start of the DDO, a helicopter of the LVP had a successful assist at eight arrests, while during the six month of the DDO, helicopters had a successful assist at 57 arrests. These 57 arrests were made in 37 flights. This improvement is due to the tool developed by Buiteveld, but also because the LVP now also has a helicopter standing stand-by 24/7 at Schiphol, instead of partial availability of a stand-by helicopter.

For 13 of the 37 flights in which the arrests took place, the helicopter still had to take off, and in the other 24 flights the helicopter was already flying. This does not per definition mean the helicopters were flying in anticipation of a crime, as they might have been on their way back from another incident. Furthermore, they discovered that when a helicopter was flying above Rotterdam, no incidents happened, while incidents started happening again when the helicopter returned to Schiphol. However, as flying 24/7 all around the Netherlands is too expensive, this ideal situation cannot be reached.

2.5 Desired situation

In the ideal situation, the LVP would already have a helicopter hovering above an incident when it happens. However, this requires knowing in advance when and where each incident will happen, and sufficient helicopters to be hovering everywhere. As both solutions are not realistic, we will describe a more realistic desired situation.

In the desired situation, the LVP will be able to make a plan in such a way, that the expected number of arrests where a police helicopter makes a difference is maximized. A system will generate a plan for each helicopter showing when it has to be where. This system should operate with minimal required human intervention, however, it should allow for human input.

We aim at reaching this desired situation by making an instrument that will use historical data to come up with a forecast. Furthermore, a forecast based on intelligence can be given as input. Those two forecasts will be combined and this combined forecast will be input for an optimization model. This optimization model will generate a plan for each helicopter.

2.6 Conclusion

In this chapter, we searched for an answer to the question 'What is the current situation at the Dutch Air Support & Aviation Police considering the daily positioning of police helicopters?'. We described the process for getting a helicopter airborne. Part of the effectiveness of the helicopters is lost due to helicopters standing stand-by on the ground until the moment a request arrives. The difference in arrival time between a helicopter waiting on the ground and the same helicopter hovering above the basis is between four and seven minutes, depending on the location.

Furthermore, we defined a formula for the probability a helicopter has a successful assist. This formula is based on the function developed by the LVP during the research of Buiteveld. The number of times a helicopter has a successful assist can be increased by focusing on the dark hours, and on the Randstad and larger cities. However, the police should be aware it is responsible for security everywhere in the Netherlands.

We can conclude significant progress has been made since the research of Buiteveld (2011). It appears helicopters hovering above an area might have a preventive effect on the number of incidents. We described the ideal situation, which cannot be reached in the foreseeable future. Therefore, we described a desired situation that can be reached in the foreseeable future. In this desired situation, the number of successful assists of police helicopters is maximized. Furthermore, an indication is given on what our contribution will be towards the desired situation.

3 Literature

In this chapter, we discuss the literature relevant for forecasting and positioning. Section 3.1 discusses literature about the location covering problem. Section 3.2 discusses literature concerning the forecasting of incidents. Literature on anticipatory routing is discussed in section 3.3. The conclusions that can be made based on this chapter are in section 3.4.

3.1 Location covering problem

Cars and helicopters have different restrictions on their movement. However, the concept behind models to solve the problem of positioning emergency vehicles can be used for both types of vehicles. Analogously, although ambulances, fire trucks, and police vehicles have different objectives, it is critical for all of them to arrive in time. Therefore we combine those vehicles in the term emergency vehicle.

Among the first proposed models suitable for solving the problem of positioning emergency vehicles are the Location Set Covering Problem (LSCP) by Toregas et al. (1971) and the Maximal Covering Location Problem (MCLP) by Church & ReVelle (1974). In the LSCP a set of locations is given where a facility might be opened. A facility is an object that gives coverage to a given area around it. Furthermore, a set of demand points is given as well as the distance from each possible facility location to each demand point. The objective of the LSCP is to minimize the number of required facilities such that each demand point is at most a predefined distance away from the closest facility. Like the LSCP, the MCLP also has a set of location where facilities might be opened and a set of demand points. However, in the MCLP, a fixed number of facilities is given. Therefore, the objective function is to maximize the number of demand points lying within a predefined distance from their closest facility.

As Gendreau et al. (2006) state, both the LSCP and the MCLP make sense in practice for use with emergency vehicles: the LSCP can be used to determine the required number of emergency vehicles to cover all demand, where the MCLP can be used to optimally position emergency vehicles when insufficient vehicles are available to cover every demand point. Schilling et al. (1979) made an extension to take different types of facilities into account in the context of the Baltimore City Fire Protection System. However they argue their findings are general and can be used for other emergency vehicles as well. Daskin and Stern (1981) added a second objective to the LSCP to measure the number of times a point is covered above its required coverage. Hogan & ReVelle (1986) continued on this work by introducing the backup coverage problem. For an overview of extensions, we refer to Li et al. (2011).

The LSCP and the MCLP are static models. In order to account for a vehicle being dispatched to a call, probabilistic models have been developed. Larson (1974) was among the first to research the concept of emergency vehicles being a server in a region with demand. The demand arrives over time and enters the queue of the emergency vehicle as a new customer enters the queue at a bakery. As soon as the emergency vehicle has finished one request, it will start handling the next request. A request might also leave the queue, as it cannot be handled in time. Daskin (1983) developed an integer programming formulation for the probabilistic covering problem, the Maximal Expected Covering Location Problem (MEXCLP). Batta et al. (1989) made an extension to the MEXCLP, the Adjusted Maximal Expected Covering Location Problem (AMEXCLP), which relaxes the assumptions that servers operate independently, servers have the same busy probabilities and are invariant with respect to their locations. Repede & Bernardo (1994) also made an extension to the MEXCLP by adding time variation known as the TIMEXCLP. We refer to Owen & Daskin (1998) for a detailed review of probabilistic covering models.

Brotcorne et al. (2003) state that static models are for use in the planning stage and do ignore availability after a vehicle has been dispatched. Probabilistic models do take this into account to some extent. In order to really take dispatches into account, dynamic models are developed in which vehicles are relocated after a dispatch or when new information arrives. Kolesar & Walker (1974) note that in case of a large fire or multiple smaller fires, a new positioning of fire trucks will yield a better coverage. They developed a model specifically for the New York City Fire Department; however, they state their algorithm should be applicable to other cities as well. Gendreau et al. (2001) propose a dynamic model that uses Tabu Search and is based on the model of Gendreau et al. (1997). Furthermore, they note that more challenging problems can be solved with the use of parallel processing. Rajagopalan et al. (2008) propose the use of a reactive Tabu Search algorithm for relocation of emergency vehicles. Boctor et al. (2011) define the Emergency Vehicle Relocation Problem in which the cost of relocation is taken into account. Furthermore, they propose two heuristics to solve this problem.

From this section we learn that the problem it is likely we should use a heuristic, as the proposed models to solve similar problems are heuristics. Furthermore, uncertainty can be modeled explicitly into the model or assumptions can be made to implicitly take uncertainty into account.

3.2 Incident forecasting

A forecast is an estimate of what future observations will be if the underlying process continues as it has in the past (Brown, 2004). Gorr & Harries (2003) note that conventional forecasting methods are not or hardly effective for forecasting the next moment an individual criminal will commit a crime. They question whether crime forecasting is possible due to the uniqueness of crime. Their answer on this question is, that patterns can be recognized on a higher level. Sherman et al. (1989) discuss the phenomenon of hot spots, areas that have relatively much overall criminal activity. Block (1995) proposes a statistical tool for law enforcement decisions named Spatial and Temporal Analysis of Crime (STAC). STAC aims at discovering and describing hot spot areas. Felson & Poulsen (2003) discuss that crime varies by time of the day. Liu & Brown (2003) propose the use of a point-pattern-based density model, which uses criminal preferences obtained from past crimes. Deadman (2003) reviews forecasts made by Dhiri et al. (1999). These forecasts were made in 1999 and were for the years 1998-2001. Deadman (2003) notes that time series models perform reasonably well.

Corcoran et al. (2003) note that a continuous updating forecasting tool will help the real-time allocation of police resources. However, this is limited due to the low number of crimes per type, time, and location. Gorr et al. (2003) discuss that forecasting errors become acceptable when the number of crimes considered is at least in the order of thirty or more.

Buiteveld (2011) shows that the number of incidents is positively correlated with the population density in the given area. Field (1999) shows a correlation between the expenditure in the last four years by real consumers and the number of incidents. For every percent increase in the expenditure, incidents increase with two percent. Furthermore, Field (1999) shows a correlation between the number of incidents and the number of young males. An increase of a percent in the number of males in the age of fifteen to twenty, incidents also increase with a percent.

Besides generalization on characteristics such as population density, literature is also available on generalization in general. Sutton & Barto (1998) describe a method to predict values based on generalization. They argue that information about a point, also gives information about its neighborhood. Therefore they propose to make a prediction based on points in an area as well as points in neighboring areas.

From this section we learned several methods to forecast criminality. The forecast can be based on several aspects of historic data. This includes, but is not limit to, location, time, population density, the population distribution, and economic situation.

3.3 Anticipatory routing

Anticipatory decision-making is the concept of making decisions in anticipation of future events that are unknown at the time of decision-making. In the field of vehicle routing, this is known as anticipatory routing. Anticipatory routing is often used to route trucks, as carriers know only part of their orders when the initial plan is made (Mes et al., 2010), or to avoid traffic jams (Claes et al., 2011). In this section, we focus on routing in anticipation of future demand, as traffic jams do not apply to the police helicopters.

The Dynamic Vehicle Routing Problem (DVRP) is the problem where multiple vehicles are available to fulfill current and unknown future service requests (Flatberg et al., 2005). Many extensions and special cases of this problem exist. The Vehicle Routing Problem (VRP) is a special case of the DVRP where all requests are known in advance (Laporte, 1992). Most extensions of the DVRP are first researched as an extension of the VRP, as solving the DVRP was not possible in practice, due to the lack of sufficient computational power. Among the most used extensions are picking-up and delivering products in the same route, as the classic VRP allowed only for either picking-up or delivering products in a single route (Nagy & Salhi, 2005). Another often-used extension is the addition of time windows for picking-up and delivering products. Cordeau et al. (2002) distinguish two types of time windows: soft and hard time windows. Hard time windows are not to be violated, whereas soft time windows can be violated at the cost of a penalty. We refer to Eksioglu et al. (2009) for an extensive overview of the state of the field of vehicle routing. In anticipatory vehicle routing, routes are made for vehicles, in which the vehicles drive around and wait in anticipation of future demand to arrive. These routes are based on forecasts of future demand. Examples of anticipatory routing can be found in Branke et al. (2005), Ichoua et al. (2006), and Thomas (2007).

The problem of positioning police helicopters such that the number of successful assists is maximized can be described as a DVRP with only delivery (of air support) with hard and soft time windows. The hard time window is the fifteen minutes after the incident happens, as air support will not lead to a successful assist when they arrive later as can be seen in Figure 2.1. The soft time window is the time interval from ten until fifteen minutes after and incident, as the probability of a successful assist decreases during this period. Both time windows start at the time of an incident, which is also the time the request arrives.

Describing our problem as a DVRP is straightforward; however, proposed models to solve DVRP cannot be used to solve our problem due to the short time between incoming request and the end of the hard time window. Therefore, our problem is better described as a Location Covering Problem. This allows to route police helicopters in such a way that they cover as many future incidents as possible. We propose to name this special case the *Anticipatory Emergency Vehicle Routing Problem* (AEVRP).

3.4 Conclusion

In this chapter we searched for an answer to the question 'What literature is available related to forecasting and positioning?'. In section 3.1, we searched for literature on the subject of location covering problem. The found literature is written with ambulances or fire trucks in mind. However, this literature also applies to police helicopters, as the idea behind this literature is the positioning of emergency vehicles. The Location Set Covering Problem (LSCP) and the Maximal Covering Location Problem (MCLP) are among the first models. Many extensions to these models have been made, such as the MEXCLP, AMEXCLP, and TIMEXCLP. Static models do not take the effect on the availability of a dispatched helicopter into account. Therefore a probabilistic or dynamic should be used. In this research, we will consider a probabilistic approach.

Furthermore, we searched for literature on the forecasting of incidents. Criminal activities vary both in place and in time and hotspots and hot times can be identified. Conventional forecasting tools are not widely used by the police. This is due to (i) large forecasting errors in a small area due to the limited number of incidents, and (ii) an area that is too large to take preventive measures in the entire area. This can be solved by generalization in which the neighborhood of an area is taken into account when forecasting. Furthermore, there is a positive correlation between the number of crimes and the population density, number of young males, and the expenditure of consumers. This shows the potential of using generalization.

The field of anticipatory routing combines routing vehicles and forecasting. Although we can describe our problem as a Dynamic Vehicle Routing Problem with time windows, it cannot be solved with currently available models due to the small time windows that start at the time a request arrives. Instead, our problem should be modeled as a Location Covering Problem in which we maximize the weighted coverage of the forecasted incidents. We propose to name this special case the *Anticipatory Emergency Vehicle Routing Problem* (AEVRP).

The added value of this research is that we define a special case of both the Dynamic Vehicle Routing Problem, and the Location Coverage Problem. We propose a heuristic to solve this problem. Furthermore, we combine positioning emergency vehicles with forecasting incidents for relative small areas with at relatively high accuracy. To the best of our knowledge, the combination of positioning emergency vehicles on a detailed forecast has not been researched before.

4 Forecasting

In this chapter, we propose a forecasting technique for solving the operational police helicopter positioning problem. Section 4.1 describes the problem description, followed by the explanation for the chosen tiling in Section 4.2. Section 3 describes the forecasting model is described in section 4.3. Section 4.4 discusses how to take intelligence into account. Finally, Section 4.5 gives the conclusions of this chapter.

4.1 Problem description

The problem we address in this report has two aspects: *where will incidents happen* and *where to position the helicopters*. The latter will be discussed in detail in section 5. As the incident forecasts made by the model in this chapter will be used for positioning helicopters, the requirements implied by the positioning model have to be taken into account. Therefore we give a formal description of the problem before discussing our method to solve the problem in Section 5.

In order to give air support, the LVP has a set of helicopters $\mathcal{H}$. Each helicopter h $\in \mathcal{H}$ has a location l $\in \mathcal{L}$ and can be dispatched at any time interval t $\in \mathcal{T}$. The movement of a helicopter h $\in \mathcal{H}$ is restricted by its speed and other air traffic. Helicopters are flying, standby on the ground, or out of order due to, for example, maintenance. When a helicopter is standby on the ground, it takes a duration of p_l to get airborne. Different types of helicopters have different cruising speeds.

In order to position the police helicopters efficiently, an incident forecast has to be available. The LVP has two types of data for making an incident forecast. These types of data are historical data and intelligence about future events. The positioning model requires a forecast for each location l $\in \mathcal{L}$. As discussed in section 3.2, a forecast based on fewer incidents has a higher forecast error. However, a map with larger areas gives a less detailed view. Police helicopters travel at roughly two nautical miles (approximately 3.7 kilometer) per minute. Therefore, we will use a grid of equal shapes in which the distance from the center to the distance between two neighboring centers is four nautical miles, which equals the distance traveled in two minutes. This means a helicopter hovering above the center of a shape covers all points in that shape in roughly a minute.

The use of circles is most realistic. However, equally sized circles will either not cover the entire area or have overlap. Uncovered areas are not favorable, as incidents in such an area are not covered. Overlap is not favorable either, as it leads to the possibility of being in multiple areas at the same time. Therefore, we use an alternative shape. For each point in an area, we want the closest center to be the center of that area. Therefore, only convex shapes are considered. Grünbaum & Shephard (1977) note there are only three regular convex polygons that give an edge-to-edge tiling. These shapes are the equilateral triangle, the square, and the regular hexagon. We made an example of these tilings in Figure 4.1.

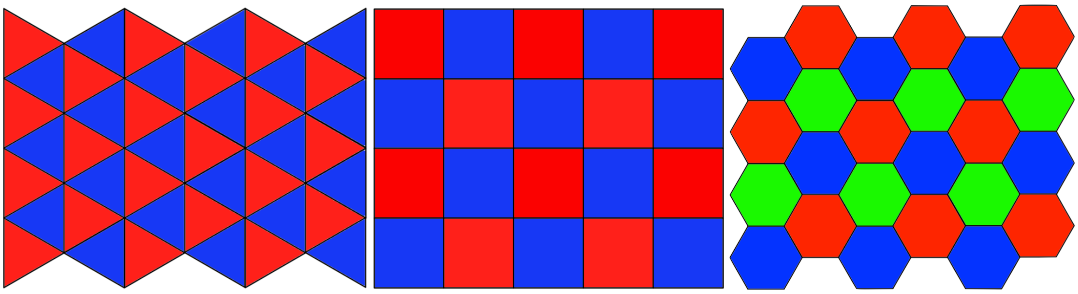

Figure 4.1 - Triangular tiling (left), square tiling (middle), and hexagonal tiling (right).

4.2 Preferred tiling

A circle can be defined as a polygon with an infinite number of corners. For example, a megagon (a polygon with a million sides) with the size of the earth can hardly be distinguished from a circle. As stated before, the circle would be the most realistic shape. Therefore we use the hexagon as it satisfies all restrictions and is closest to a circle. Figure 4.2 gives an example of a visualization of a hexagonal grid on top of the Netherlands.

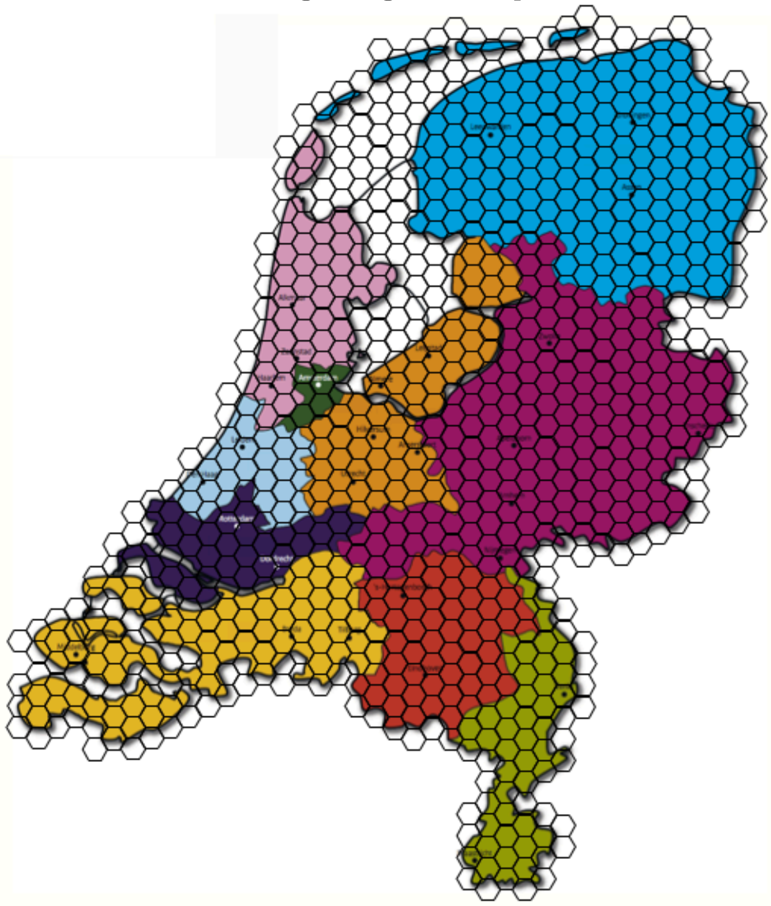

Figure 4.2 - The Netherlands with a hexagonal grid.

The set of locations $\mathcal{L}$ is a combination of the set of x-coordinates $\mathcal{X}$ and the set of y-coordinates $\mathcal{Y}$. As we use hexagons, the localization of each hexagon in the grid can not simply be done by naming the lower left square (0,0) and add one to the first coordinate when going to the right and add one to the second coordinate when going up. In order to come up with a coordinate system, we first have to define the orientation of the hexagons. In this research, we arbitrarily chose to have two sides parallel to the x-axis. We name the center of the lower left hexagon (0,0). When going up, we add one to the second coordinate as we would in case of squares. However, when going to the right, we have two choices. We can either go up-right or down-right. In both cases, the first coordinate will increase with one. However, also the second coordinate might change. When going up-right, the second coordinate increases with 1 and when going down-right, the second coordinate remains the same. Figure 4.3 shows the coordinates relative to the middle hexagon named (0,0).

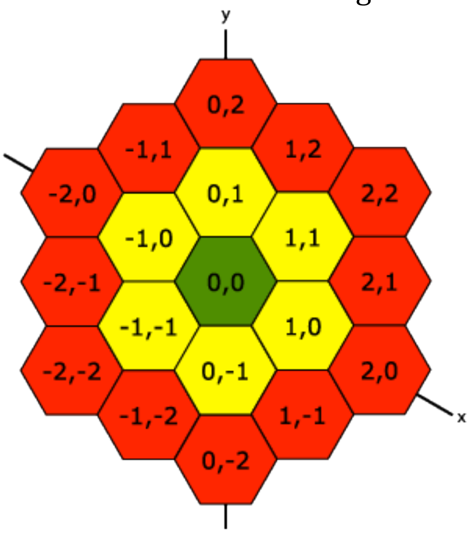

Figure 4.3 - The hexagonal coordinate system used in this research.

Although the exact location of a hexagon is not important for the optimization model, it is important for the forecasting model. An incident happens at a location in the Netherlands and should be placed in the correct hexagon for a correct forecast. The location of an incident at the KLPD is recorded using zip codes. There is no straightforward conversion possible from zip codes to our hexagonal coordinate system. However, tables are available to lookup the latitude and longitude of a zip code. As latitude and longitude are based on a sphere, while a flat representation will be given, we convert the latitude and longitude to coordinates of the Dutch *Rijksdriehoekstelsel* (RD). The Rijksdriehoekstelsel is a coordinate system for the Netherlands, which originally had its origin at the *Onze Lieve Vrouwetoren* in Amersfoort. This origin is moved, such that x-coordinates in the Netherlands are in the range [-7000;300000] and the y-coordinates are in the range [289000;629000]. The difference in coordinates is equal to the distance in meters. For example, a difference of 300 in the x-coordinates is a difference of 300 meters. The conversion from latitude and longitude to RD-coordinates is done using the conversion method of Schreutelkamp & Strang van Hees (2001).

The hexagon in which an incident with RD-coordinates (x^*, y^*) happens can be derived. We consider a hexagonal tiling as in Figure 4.3 with the height h equal to 3704 meters or two nautical miles. We define the radius r of a hexagon to be the distance between the center of a hexagon and a corner point. We use hexagons with a radius r of $\frac{h}{\sqrt{3}}$, as the distance between two centers and therefore the height of a hexagon is four nautical miles. We define point (0,0) at position (-7000; 289000), which is in a field next to the Airport of Lille. We chose for this point because it equals the lower left corner of the convex rectangle containing all border points of the area in which the RD-coordinates are valid.

Therefore, $x^*$and $y^*$are modified accordingly. The derivation to which hexagon an incident with coordinates (x^*, y^*) belongs is as follows.

$$a^- = \left\lfloor \frac{x^*}{\frac{3}{2}r} \right\rfloor$$
$$b^- = round\left(\frac{y^* + \text{h}\times a^-}{2\text{h}}\right)$$
$$a^+ = a^- + 1$$
$$b^+ \; analog \; to \; b^-$$

When the distance of the center of hexagon $(a^-, b^-) \in \mathcal{L}$ to (x^*, y^*) is smaller than the distance of the center of hexagon $(a^+, b^+) \in \mathcal{L}$ to (x^*, y^*), a is equal to a^-, else a is equal to a^+. Regardless the value of a, b is calculated analog to b^-. In the numerator of the formula for b, a correction is made for the tilted x-axis. A graphical representation is given in Figure 4.4.

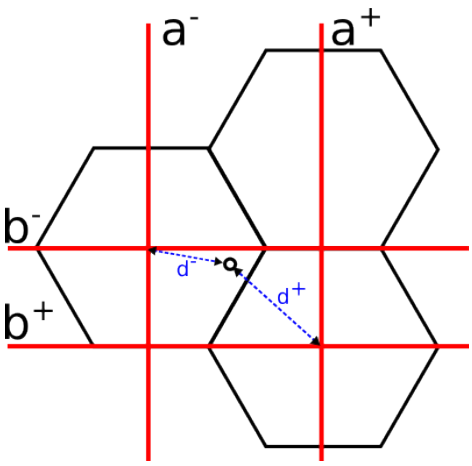

Figure 4.4 - Graphical representation of localizing a point in a hexagon

4.3 Forecasting model

Figure 2.3 shows that crime rates differ during the day. Making a single incident forecast for an entire day is therefore not suitable for use in our positioning model. Our positioning model uses time intervals of two minutes, as this equals the size of the areas. Therefore, we use these time intervals for our forecast. In addition to variations in time, crime rates also vary between regions as shown in Figure 2.5. Therefore, forecasts should be made for multiple smaller areas to get an accurate forecast. However, by decreasing the size of the forecast areas, fewer incidents will occur in a single forecast area. As a forecast with fewer incidents leads to a larger forecast error, this might lead to inaccurate forecasts. Furthermore, as we do not only differentiate in space but also in time, we have even fewer incidents per forecast area in time.

To overcome making forecasts based on too few incidents, we will use generalization to make forecasts for an area based on the number of incidents in that area at that time, as well as incidents that happened around that time in the neighborhood. This is based on the idea of Sutton & Barto (1998) that an event in an area also tells something about the neighboring areas. Example 4.1 gives an intuitive illustration of this concept.

Example 4.1: *When interested in the temperature in a room, one takes a look at the thermometer. Although this thermometer only gives the temperature at its own location, it does give information about the temperature on any location in the same room. Furthermore, it gives an indication of what the temperature in the nearby future might be.*

The KLPD does not have a unit specialized in forecasting on an aggregate level. A brainstorm session was organized to come up with a forecasting approximation method for each hexagon. Each hexagon represents an area at a time interval, as this research focuses on the dimensions time and space. This leads to an approximation with two steps. Before discussing these steps, let us first define an incident. An incident is an event that requires immediate attention from the KLPD, in a given time interval of two minutes on a given location. An incident is often an act of crime. For each type of crime, a different weight can be given to take differences into account as mentioned in section 2.3. An overview of the forecasting method is as follows:

1) Forecasting in space
   - Generalize incidents to their neighborhood
   - Take priority into account
   - Apply a forget factor to reduce the weight of old data
   - Convert months and weekdays to the target month and weekday
2) Generalize forecasted incidents of the first step in time

In the first step of the forecast approximation method, incidents only affect neighboring areas in the space dimension. In the second step, we smooth the made forecasts in time. In the brainstorm session, we defined what the rate is an incident occurred in neighboring areas. This rate has no unit, and represents how likely it is an incident would have happened in an area. We give the hexagon in which the incident happens a value of 1. The value of neighboring areas is determined based on the idea that the likeliness that an incident could have happened elsewhere decreases with the square of the distance. This yields the following formula, where h is the distance between two neighboring centers, and $d(xy, ab)$ the distance between the center of the hexagon in which the incident happened and the hexagon of which we want to get the forecast value:

$$forecast\ value = \frac{1}{\left(\frac{d(xy,ab)}{h} + 1\right)^2}$$

In this formula, $\frac{d(xy,ab)}{h}$ represents the distance in two-minute-units. The addition of 1 sets the value of the hexagon in which the incident happens to 1 instead of ∞. The forecast values are multiplied with the weight of the incident type. Given an incident with weight 1, this will roughly yield Figure 4.5 as we, for illustrative purposes, treat all hexagons in a ring around the center to be equally far away from the center. This is done for every incident and values are added up when two incidents have influence on the same hexagon. We recommend a detailed analysis on crime forecasting to be done within the KLPD for a better understanding of trends and a better forecast. However, this is outside the scope of this research.

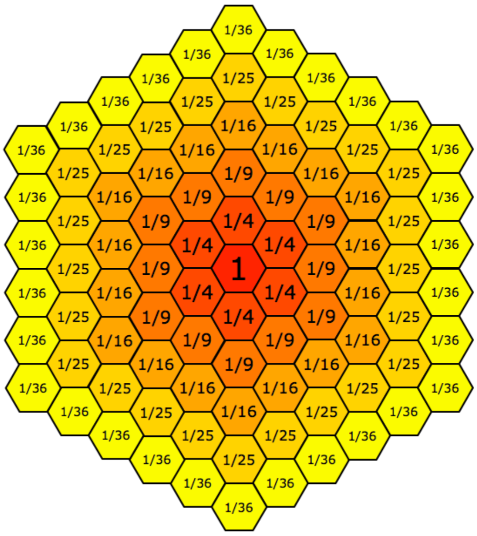

Figure 4.5 - Approximate effect of an incident on its neighboring area

Giving old data the same weight as new data leads to a slow adaption to changes in the incident distribution. An often proposed methodology to solve this is to a forget factor α. Every period, a fraction α is forgotten which means old data is multiplied by (1- α).

As discussed in section 2.3, crime rates vary between the months and days of the week. In addition, the distribution of crimes during a day differs between months and weekdays. Figure 4.6 and Figure 4.7 show the distribution in per month and weekday. The different colors depict different months and weekdays. As can be seen, these months and weekdays have different distributions, as lines cross each other repeatedly and have spikes at different times.

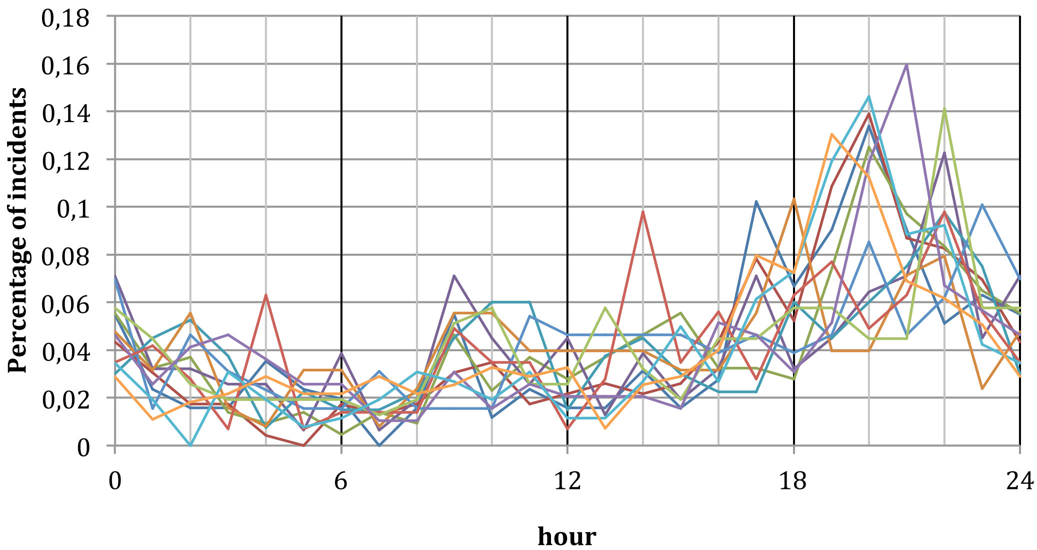

Figure 4.6 - Hourly incident distribution per month in 2011 (source: KLPD 2012c)

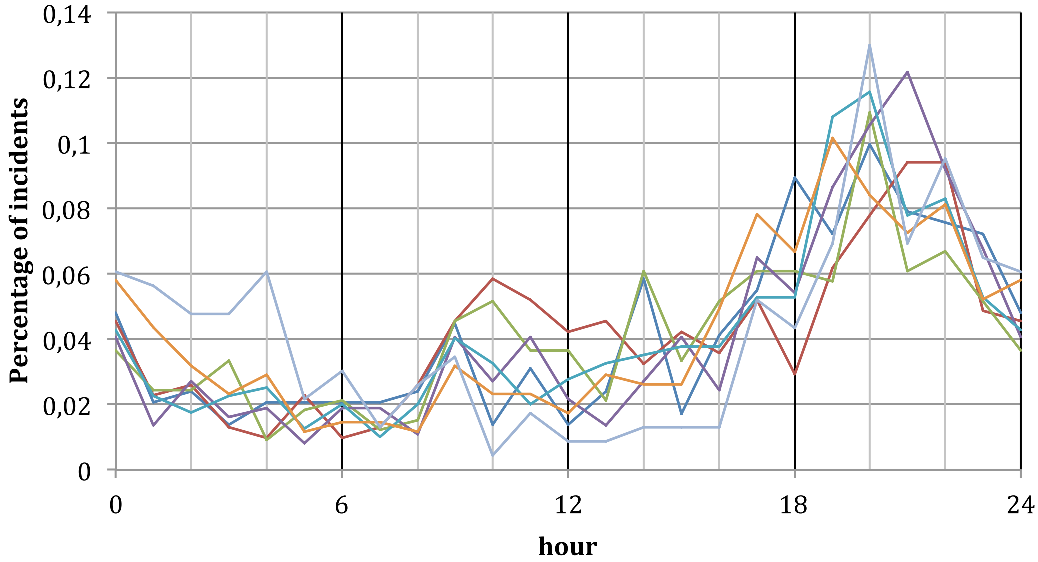

Figure 4.7 - Hourly incident distribution per weekday in 2011 (source: KLPD 2012c)

As more incidents reduce the forecast error, we want to use all data to forecast a single day. Therefore, we introduce a *factor month* to account for different distributions between months, and a *factor weekday* to account for different distributions between days of the week. The *factor month* is calculated as follows:

1. Define the target month as the month to which the day to be forecasted belongs.
2. Count the number of incidents for each hour of a day for each month.
3. Convert the number of incidents to a percentage by dividing the value for each hour by the total for the month it belongs to. This is the percentage of incidents that happen in during that hour of the day for a given month.
4. For each hour of each month, divide the value of the same hour of the target month by the value of that hour of the month it belongs to. For example, when converting the first hour on a day in December to a day in July, we divide the percentage of that hour in December by the percentage of that hour in July. The resulting fraction represents the conversion factor to apply to all incidents in December in the first hour to incidents in July during that hour.

This can be expressed in a formula, with the following notation:

- m_t Month for which the forecast is made
- m_i Month of the incident to be converted
- h_i Hour of the incident to be converted
- N_{m_t,h_i} Number of incidents in month m_t during hour h_i
- N_{m_i,h_i} Number of incidents in month m_i during hour h_i

This notation only applies to the following formula:

$$factor\ month = \frac{\left(\frac{N_{m_t,h_i}}{\sum_h (N_{m_t,h})}\right)}{\left(\frac{N_{m_i,h_i}}{\sum_h (N_{m_i,h})}\right)}$$

The *factor weekday* is calculated similar to *factor month*, where month is replaced by weekday in the method described above. These factors are used in the forecast by multiplying the priority value of an incident with the corresponding values of these factors. Applying these two factors reduces the forecast error to 71% compared to taking all incidents into account without correction for the month and weekday, based on the data of 2011 (source: KLPD 2012c).

After all incidents have been processed in the first step, we can now consider the effect on incidents in the dimension time. We assume the time between an actual incident and when it might happen in the future is normal distributed, and an incident is 95% likely have happened within thirty minutes before and thirty minutes after an incident happened. Therefore, we create a characteristic bell-shaped function around the time an incident happened and add the appropriate values to the same hexagon up to thirty minutes before and up to thirty minutes after the actual incident. Again, we recommended a detailed analysis for a better forecasting method, which is outside the scope of this research. A graphical representation of a forecast is given in Figure 4.8, where yellow indicates no expected incidents, and red indicates a relative high number of incidents.

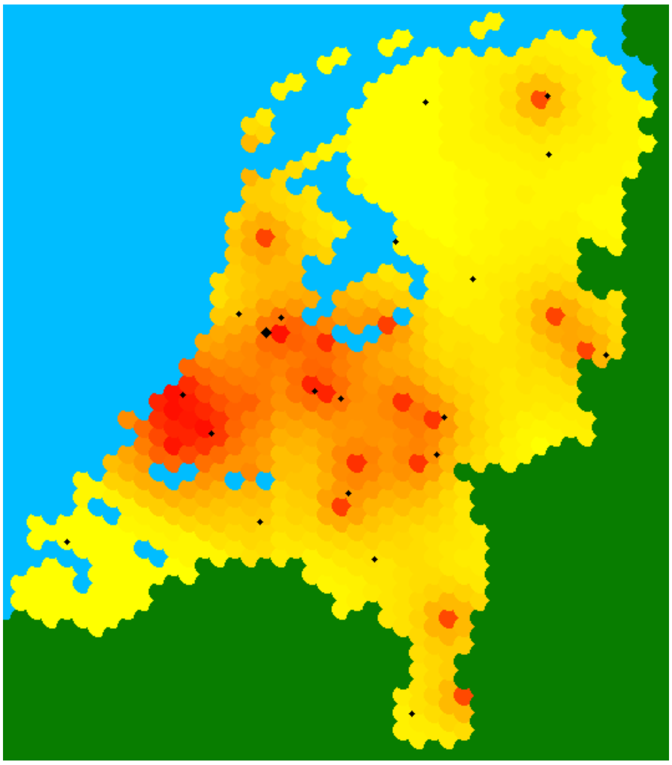

Figure 4.8 - Graphical representation of incidents around midnight in 2011 (source: KLPD 2012c)

4.4 Intelligence

Besides the use of historical data, the forecast model should also take intelligence into account. Since intelligence is about future events, it should not be based on historical incidents. When the result of a historical forecast is questioned, the method of forecasting based on historical data should be reviewed. This implies intelligence has to be added manually as it cannot be derived from earlier incidents. In this research, we do not discuss how to obtain such intelligence. However, we do discuss a few methods on how to combine historical data and intelligence. Those methods are as follows.

1. **Add incidents:** Adding additional incidents to the list of historic incidents gives additional weight to these areas and their neighborhood.
2. **Overrule the historic forecast:** By manually adjusting the historic forecast, intelligence can be taken into account in detail. Instead of the value given for a hexagon at a time, a different value is entered manually.
3. **Ignore intelligence during forecasting:** By taking intelligence into account during the positioning of helicopters, one can define the required action based on the intelligence. This implies it does not have to be taken into account in the forecast.

We propose to ignore intelligence in the forecast. As this allows defining the required action, it is more valuable than modifying the forecast. Furthermore, as adding incidents affects a larger area, this might lead to an incorrect representation of the intelligence. For example, if there is a festival and more incidents are expected at the festival area, this might not directly mean that more incidents are expected at a municipality five kilometers away.

4.5 Conclusion

In this chapter we searched for the answer to the forecasting part of the question 'How should a model for the operational positioning of police helicopters look like?'. We described the problem of positioning helicopters and why this is important for choosing forecasting method.

Furthermore, we discussed the use of a hexagonal grid for use in forecasting and positioning of helicopters. As the hexagon is the largest regular polygon that can produce a regular tiling, it is the best polygon we can use as a substitute for circles. Furthermore, we defined a coordinate system for the hexagonal grid and a method to convert zip codes into the correct hexagon.

We propose a forecasting method to overcome the issue of having either forecast areas that are too large to be useful or not enough data per forecast area to get sufficient small forecast errors. An incident does not only tell something about that place in that point in time but also about the neighboring area and time around it. Therefore, we can add some probability of an incident to its neighborhood. We advise to develop a more detailed forecasting method for even better performance of the positioning model. Furthermore, we discussed how to take intelligence into account. We propose ignore intelligence in the forecast and take it into account when routing the helicopters as this allows defining the required action.

5 Positioning model

In section 5.1, we discuss the basic positioning model. Section 5.2 contains the fuel extension, section 5.3 contains the tactical extension, and section 5.4 the extension that takes restrictions into account for grounded helicopters. In section 5.5, we propose two heuristic approaches for the positioning of the police helicopters. We end with the conclusions that can be made based on this chapter in section 5.6. Variables in this chapter are represented by a capital letter and parameters by a small letter to make the linearity of the constraints more clear.

5.1 Basic positioning model

With the forecasting method described in section 4, we are able to make forecasts for areas in which nothing or too few incidents have happened, without having to wait until enough crimes were committed. As we are now able to generate a forecast for every hexagon and every time interval, we can continue with the positioning in such a way that most forecasted criminal activity is covered. Figure 5.1 shows an example of a helicopter moving through time and space from one location to another.

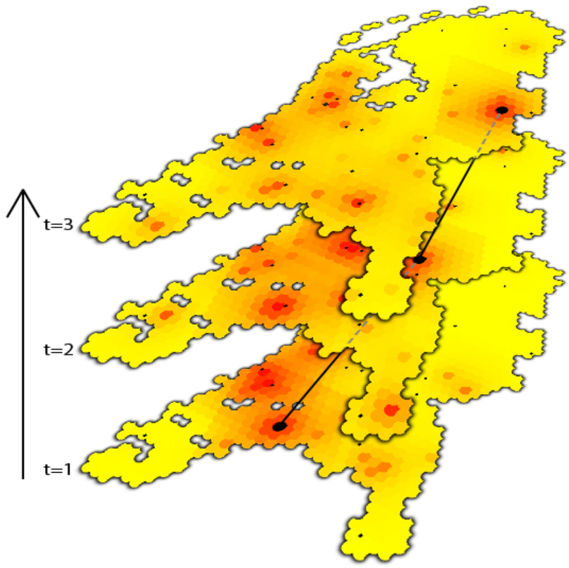

Figure 5.1 - Graphical representation of a helicopter moving through time and space.

Each helicopter gives coverage to the forecast-areas defined. This coverage is based on the distance between the helicopter and the forecast-area, using the formula defined in section 2.2. Given a point in time, the coverage-value of a forecast-area can be defined as the forecasted incident value multiplied by the coverage the forecast-area gets from each helicopter. The objective of maximizing the number of arrests can be reached by maximizing the sum over all forecast-areas for the given time horizon.

Using the coordinate system of section 4.2, we can define a basic helicopter routing model. This model does only take a few restrictions into account. It restricts a helicopter to move one hexagon at a time. Furthermore, it takes the coverage fraction into account with the nonnegative variable G_{xyt} and the forecasted incident value with nonnegative parameter i_{xyt}. The location (x,y) $\in (\mathcal{X},\mathcal{Y})$ of helicopter h $\in \mathcal{H}$ at time interval t $\in \mathcal{T}$ is represented by the binary variable L_{xyht}. A time interval t ∈ $\mathcal{T}'$ has a duration of two minutes. The coverage a location (x,y) ∈ ($\mathcal{X}$,$\mathcal{Y}$) gets from a location (a,b) ∈ ($\mathcal{X}$,$\mathcal{Y}$) is represented by the nonnegative parameter c_{xyab}. This basic model is as follows.

$$\max \sum_{xyt} \left(G_{xyt} \times i_{xyt}\right)$$

s.t.

(1) $$L_{xyht} \leq L_{xyh,t-1} + L_{x-1,y-1,h,t-1} + L_{x-1,y,h,t-1} + L_{x,y+1,h,t-1} + L_{x+1,y+1,h,t-1} + L_{x+1,y,h,t-1} + L_{x,y-1,h,t-1} \quad \forall x, y, t, h$$

(2) $$\sum_{xy} L_{xyht} = 1 \quad \forall t, h$$

(3) $$L_{xyht} = l_{xyh} \quad \forall x, y, h \quad t = 0$$

(4) $$G_{xyt} \leq \sum_{hab} \left(L_{abht} \times c_{xyab}\right) \quad \forall x, y, t$$

(5) $$G_{xyt} \leq 1 \quad \forall x, y, t$$

Constraints (1) restrict the movement of the helicopter. As the distance between the centers of two hexagons is two minutes, each helicopter is allowed to move one hexagon per time interval. Constraints (2) prevents a helicopter from being in no location or being in multiple locations at the same time. With constraints (3), every helicopter is set to its original location. Constraints (4) and (5) set the fraction of coverage a location (x,y) ∈ ($\mathcal{X}$,$\mathcal{Y}$) gets at any time interval t ∈ $\mathcal{T}'$ to be at most the minimum of 1 and the sum over all helicopters multiplied by there coverage. As the objective function maximizes the nonnegative variable G_{xyt} multiplied by a nonnegative parameter, G_{xyt} will be maximized. As G_{xyt} is bounded from above by constraints (4) and (5), it will be equal to the minimum of 1 and the sum over all helicopters multiplied by their coverage.

As this model only takes into account the movement restriction when airborne and assumes all helicopters to be airborne at all times, this model needs to be extended. However, this basic model can be used as the basis on which other more sophisticated models can be built. In sections 5.2-5.4, we extend this basic model such that it is able to deal with the following:

- Maximum flight duration due to fuel
- Force helicopters to be grounded when fueling
- Manage availability of helicopters
- Restrict total flight duration
- Adjust coverage according to time until airborne
- Start and end location
- Force a helicopter to be in a certain area at a time

5.2 Fuel extension

The basic model as described in section 5.1 lacks a number of constraints, which are critical for a good realistic plan. As helicopters only have a limited amount of fuel, they are not flying at all times. Therefore we define the nonnegative integer variable F_{ht} indicating the fuel level of a helicopter h ∈ $\mathcal{H}$ at time interval t ∈ $\mathcal{T}$. Furthermore, we define a nonnegative integer parameter f_h, which is the maximum duration helicopter h ∈ $\mathcal{H}$ has fuel for. The binary variable A_{ht} indicates whether a helicopter h ∈ $\mathcal{H}$ is airborne at time interval t ∈ $\mathcal{T}$. The duration added to helicopter h ∈ $\mathcal{H}$ per time period when fueling is represented by the nonnegative integer parameter g_h. As fuel trucks can be used to bring fuel to a helicopter, we assume fueling is allowed everywhere. Therefore, fueling is only restricted in being on the ground. Adding constraints (6)-(10) to the basic model takes into account the fuel restriction.

(6)	$F_{h,t+1} \leq F_{ht} - A_{ht} + g_h \times (1 - A_{ht})$	$\forall t, h$
(7)	$F_{ht} \leq f_{ht}$	$\forall t, h$
(8)	$F_{ht} = e_h$	$\forall h$ $t = 0$
(9)	$A_{ht} \leq F_{ht}$	$\forall t, h$
(10)	$L_{xyh,t+1} \geq L_{xyht} - A_{ht}$	$\forall x, y, t, h$

Constraint (6) manages the fuel level of the helicopters with the capacity limited by constraint (7). The fuel level is initiated by constraint (8). Constraint (9) restricts a helicopter from being airborne if the fuel level is 0. Constraint (10) in combination with constraint (2) only allows movement when airborne. When $A_{ht} = 1$, the helicopter is airborne and the right hand side of constraint (10) is either 0 or -1, allowing the left hand side to be 0 or 1. When $A_{ht} = 0$, the helicopter is not airborne and $L_{xyh,t+1}$ should be equal to L_{xyht}. When $L_{xyht} = 1$, the left hand side will be 1 as well, since it is either 0 or 1 and 0 is not allowed. When $L_{xyht} = 0$, constraint (10) allows $L_{xyh,t+1}$ to be 0 or 1. However, as (2) allows a helicopter to be in one position at a time, all other position will be 0.

5.3 Tactical extension

As police helicopters are not only used for ad-hoc dispatch, a helicopter is sometimes not available. For example, when the service Specialist Interventions makes an intervention, they might request a helicopter to give them an overview during the intervention. When this helicopter supports the service Special Interventions, the helicopter is not available. However, this might only be a portion of the time under consideration. Whether a helicopter h ∈ $\mathcal{H}$ is available at time interval t ∈ $\mathcal{T}$ is represented by the parameter d_{ht}. To account for helicopters being unavailable during the planning horizon, constraints (11)-(12) have to be added.

(11)	$L_{xyht} \geq l_{xyht}$	$\forall x, y, h, t$
(12)	$G_{xyt} \leq \sum_{hab} (L_{abht} \times c_{xyab} \times d_{ht})$	$\forall x, y, t$

Constraint (11) is an adjusted version of constraint (3). Instead of setting the location for the first time period, at every time interval t ∈ $\mathcal{T}$ a helicopter h ∈ $\mathcal{H}$ is either forced on a predefined location or free to go within bounds set by other constraints. In order to do so, the dimension time interval is added to the binary parameter l_{xyh}. This also allows letting helicopters fly from one base to another. Constraint (12) is a modified version of constraint (4). As a helicopter h ∈ $\mathcal{H}$ might not be available, this has to be reflected in the impact it has on the coverage. This is done through the binary parameter d_{ht}, which represents the availability of helicopter h ∈ $\mathcal{H}$ in time interval t ∈ $\mathcal{T}$.

Besides being unavailable for a given time period, helicopters are also limited in flight hours. For example, regular maintenance checks for the police helicopters are scheduled in advance. However, such a check should be done before a certain amount of hours have been flown. To avoid violating these rules and maintaining the maintenance schedule, flight hours of the helicopters are restricted. Adding constraints (13)-(14) add these rules. In these constraints, we use two new parameters to represent the limiting amount of flight hours. m_h is the allowed number of flight hours of helicopter h ∈ $\mathcal{H}$ and n is the allowed number of flight hours for all helicopters together.

(13) $$\sum_{t} A_{ht} \leq m_h \qquad \forall h$$

(14) $$\sum_{ht} A_{ht} \leq n$$

Constraint (13) restricts the flight hours for each helicopter h ∈ $\mathcal{H}$ and constraint (14) restrict the total number of flight hours for all helicopters together.

5.4 Grounded helicopter coverage extension

In the basic model we implicitly assumed all helicopters to be airborne. However, as discussed in section 5.2 and section 5.3, this assumption is not true. When a helicopter is not airborne, it is still able to get airborne and provide coverage. Furthermore, grounded helicopters are not able to get airborne immediately due to safety checks and other air traffic. We therefore modify the binary parameter c_{xyab}, by adding the state of a helicopter z ∈ $\mathcal{Z}$. The state z ∈ $\mathcal{Z}$ represents the time it takes for a helicopter to be airborne, which is naturally bounded by nonnegative integer parameter p_{xy}, which is the required time to get a helicopter airborne at a location (x,y) ∈ ($\mathcal{X}$,$\mathcal{Y}$). This yields the adjusted binary parameter c_{xyabz} indicating the coverage given to location (x,y) ∈ ($\mathcal{X}$,$\mathcal{Y}$) from a location (a,b) ∈ ($\mathcal{X}$,$\mathcal{Y}$) by a helicopter in state z ∈ $\mathcal{Z}$. We also adjust the binary variable L_{xyht} such that it includes state z ∈ $\mathcal{Z}$. This yields the binary variable L_{xyhtz}. We also introduce the binary variable S_{ht}, indicating whether a helicopter h ∈ $\mathcal{H}$ just landed at time interval t ∈ $\mathcal{T}$. Constraints (15)-(21) take these restrictions into account.

(15) $$L_{xyh,t+1,z} \leq \sum_{j=0}^{z+1} L_{xyhtz} \qquad \forall x, y, h, t, z$$

(16) $$1 - A_{ht} \geq \frac{1}{bigM} \times \sum_{z} \left(L_{xyhtz} \times z\right) \qquad \forall x, y, h, t$$

(17) $$\sum_{z} L_{xyhtz} = 1 \qquad \forall x, y, h, t$$

$$\sum_{z}(L_{xyhtz} \times z) \geq p_{xy} \times S_{ht} \qquad \forall x, y, h, t \tag{18}$$

$$S_{ht} \leq A_{h,t-1} \qquad \forall h, t \tag{19}$$

$$S_{ht} + A_{ht} \leq 1 \qquad \forall h, t \tag{20}$$

$$S_{ht} \geq A_{h,t-1} - A_{ht} \qquad \forall h, t \tag{21}$$

As state z ∈ $\mathcal{Z}$ is the time until a helicopter is airborne, the state can go down a step or increase any number of minutes, which is represented in constraint (15). A helicopter can only be airborne, when the time until airborne is 0. The right hand side of constraint (16) is either 0, when the helicopter is in state 0 or between 0 and 1 when in another state. When the right hand side is above 0, the left hand side has to be 1 due to A_{ht} being binary and therefore the helicopter h ∈ $\mathcal{H}$ cannot be airborne at time interval t ∈ $\mathcal{T}$. Constraint (17) only allows one state for each helicopter h ∈ $\mathcal{H}$ at any time interval t ∈ $\mathcal{T}$. Constraint (18) sets the state of a helicopter h ∈ $\mathcal{H}$ at time interval t ∈ $\mathcal{T}$ to the state z ∈ $\mathcal{Z}$ such that a helicopter always requires the takeoff time. When $A_{h,t-1} - A_{ht} = 1$, S_{ht} has to be 1 and 0 in all other situations. Constraint (19) sets S_{ht} to 0 when $A_{h,t-1} = 0$, constraint (20) sets S_{ht} to 0 when $A_{h,t} = 1$, and constraint (21) S_{ht} to 1 when $A_{h,t-1} - A_{ht} = 1$.

5.5 Heuristic approach

The basic positioning model described in section 5.1 and its extensions in sections 5.2 - 5.4 are too large to be used. The main decision variable L_{xyhtz} consists of five indices. Due to these indices, the number of variables will grow to the order of hundreds of millions of variables. As this requires significant computation time, we have to make smaller instances or use a heuristic approach. As smaller instances are in the order of a single helicopter and an area in which each hexagon will get some coverage at all times cannot be used to solve real-world problems, we developed two heuristics.

When we only consider a single helicopter and assume it becomes airborne at a given time interval t ∈ $\mathcal{T}$ and lands at a different time interval t ∈ $\mathcal{T}$. This reduces the binary variable L_{xyhtz} to L_{xyt} in which the set $\mathcal{T}$ can be considered significantly smaller. We propose a heuristic that makes use of this simplified model by positioning helicopters sequentially. This leaves the question when to schedule which helicopter. To overcome this issue, we propose scheduling helicopters in random order and at random times. By doing multiple iterations we improve the final schedule. Figure 5.2 shows a graphical representation of our heuristic.

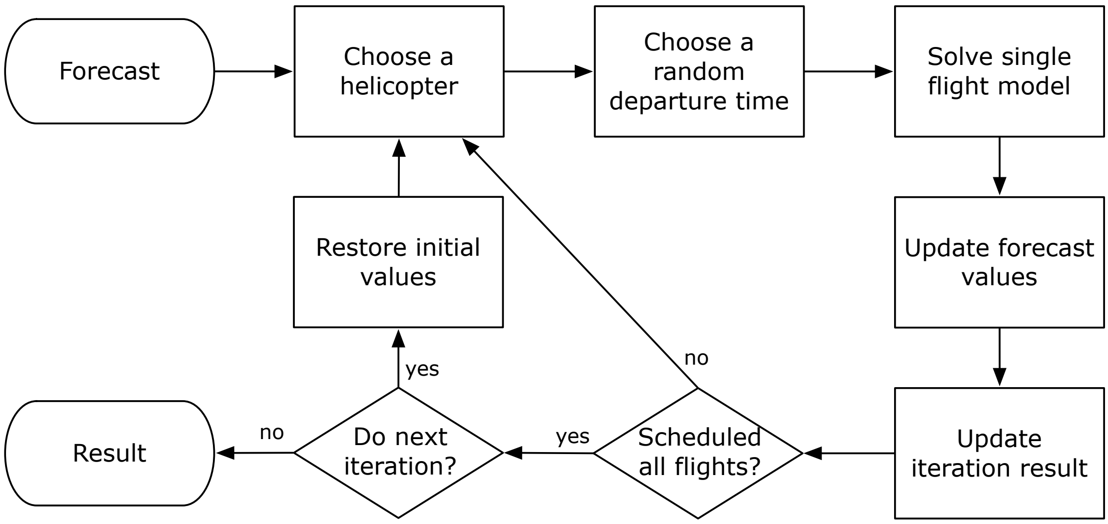

Figure 5.2 - Graphical representation of the heuristic.

The input in our heuristic is a copy of the forecast, which is made as described in section 4. We refer to a copy of the forecast as we will modify this copy during an iteration and require the original forecast for initialization of the next iteration. The first step of the heuristic is to pick a helicopter and a random start time and end time. This is done based on the number of incidents that happen, regardless of their location. This leads to a start time distribution comparable with Figure 2.3. The start time is chosen randomly as we do not know when each helicopter should fly. By giving more weight to times with relatively many incidents, we are more likely to fly at good hours, without excluding the possibility that a good moment to fly is when a few incidents happen.

The chosen helicopter and start time is given to the solver, which solves the positioning model to a given optimality gap. The result of this model is used to update the values of hexagons, as they are already partially covered by the chosen helicopter. This is done by keeping a copy of the real forecast and then decrease each hexagon with the amount it was covered. If not all flights have been scheduled, another helicopter is chosen, until all flights are scheduled. When all flights are scheduled and there is enough time left for another iteration, the initial forecast is restored and another iteration is done. After the last iteration, the schedule is given as output.

Solving the positioning problem for a single helicopter to proven optimality, obviously requires more computation than finding a feasible solution. Part of this computation time is proving the solution is optimal. Solvers such as CPLEX solve the Mixed Integer Linear Programs using branch-and-bound. The upper bound in each node is determined by solving the Linear Program in which the integer constraints are relaxed. As the solution space of a relaxed problem is larger, the optimal integer solution will be reached before sufficient constraints are added such that the linear relaxation of the problem yields an integer solution. Stopping a solver when there is still a gap between the upper bound and the current best integer solution leads to a solution that is in the worst-case equal to the gap but might be the optimal solution. The smaller the gap, the more likely it is the optimal solution is reached. As we use the result of the model in a heuristic that uses random search, we have to balance the result and the computation time of the model such that the overall solution after all iterations is as good as possible.

The trade-off between result and computation time does not have to be made in advance. For example, simulated annealing accepts any solution in the beginning and gradually continues to accept only better solutions. A similar approach can be used in this heuristic. When starting the heuristic, we can set the optimality gap quite large. This results in a larger number of results, but of potentially lower quality. When the overall best solution does not improve after a while, we can lower the optimality gap to get fewer solutions; however, potentially better. As we randomly determine flight times for helicopters, it is not recommended to get the optimal solution for a single flight, as the flight itself might be a poor decision.

The number of possible iterations that can be done decreases with the number of hexagons, the size of the time intervals, and the number of helicopters. Therefore, we propose a second approach that requires only a single iteration and is based on the assumption that it is most likely a helicopter should fly when most incidents happen in its vicinity. Figure 5.3 gives a graphical representation of the second heuristic.

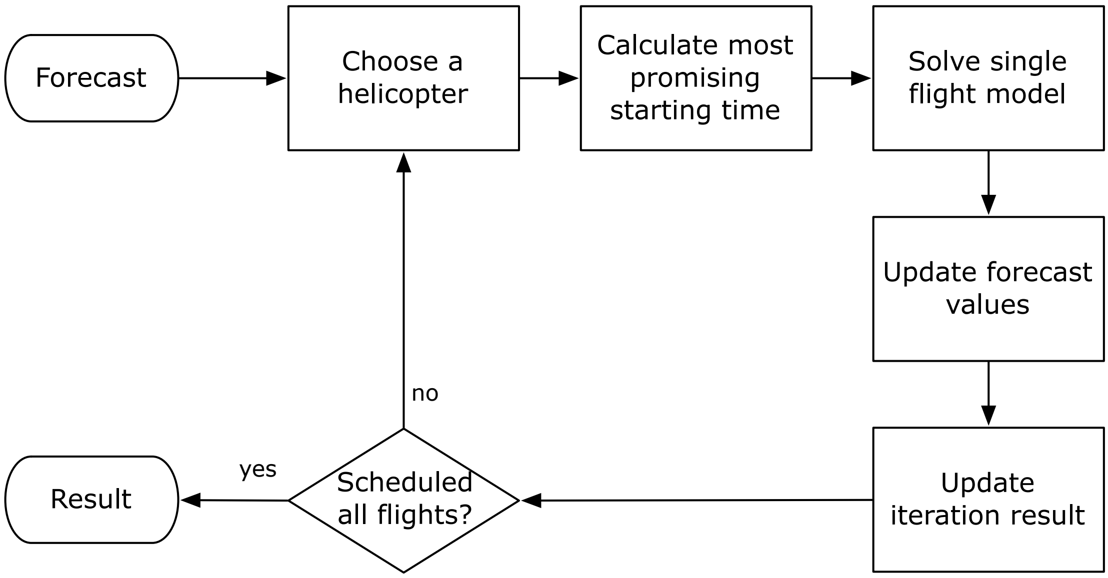

Figure 5.3 - Graphical representation of the quick heuristic

As can be seen, there are two differences between the two heuristics: the way the starting time is chosen and the number of iterations. As we now calculate the most promising starting time, it does not change between iterations and therefore we only iterate once. We calculate the most promising starting time based on the assumption that it is more likely to have a successful assist when more incidents happen. The calculation of the value for a single starting time is done with following formula with $\mathbb{V}(z)$ the set that contains all hexagons that can be reached from the starting location in z time and can reach the end location in the remaining time.

$$value_t = \sum_{z=t}^{t+flighttime} \sum_{xy \in \mathbb{V}(z)} i_{xyz}$$

The starting time is chosen such that the corresponding $value_t$ is the maximum value of all possible starting times. When the starting location is equal to the end location, this creates a cone through time from the starting location to the locations that can be reached in exactly half the flight duration. A second cone goes from all the location at half the flight duration to the end location. A graphical representation can be found in Figure 5.4.

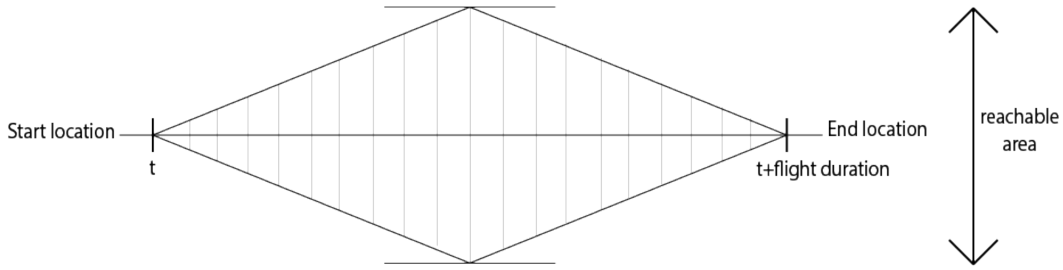

Figure 5.4 - Graphical representation of the areas that are reachable in a flight.

This starting time can be different for each flight as it is based on the modified incident forecast.

We compared the two heuristics using our instrument for the first week of 2012, using the historic incident data of 2011 as defined in *KLPD (2012c)*. Five helicopters were available, of which three were stationed at Schiphol with their crews available from 0.00-8.00, 8.00-16.00, 16.00-24.00. The other two helicopters were stationed at Rotterdam and Volkel with their crews available at respectively 15.00-23.00 and 9.00-17.00. Furthermore, we used a forget factor of 1%. Table 5.1 shows the results of this comparison.

	Heuristic 1	**Heuristic 2**	**Difference**
1 Jan 2012	103195	107435	+4.1%
2 Jan 2012	434658	456029	+4.9%
3 Jan 2012	307957	337612	+9.6%
4 Jan 2012	415742	423615	+1.9%
5 Jan 2012	1648512	1722670	+4.5%
6 Jan 2012	751551	764920	+1.8%
7 Jan 2012	851276	869265	+2.1%

Table 5.1 - Comparison result of the two proposed heuristics based on the data of KLPD (2012c).

As can be seen, the second heuristic outperforms the first heuristic on value covered with on average an additional coverage of 4.1%. Furthermore, the computation time of the first heuristic is on average between 23 and 24 hours, whereas the second heuristic is on average 652 seconds. Expectations before this experiment were that the first heuristic would outperform the second heuristic on value covered, as the first heuristic will ultimately try all possible solutions. However, it turned out the restriction of a maximum calculation time of 24 hours is not sufficient to outperform a smart guess for each starting time as done in the second heuristic. Furthermore, the calculation time of eleven minutes allows for more applications, such as:

- Experimenting with different number of flights and flight durations.
- Generating routes in the morning to take into account bad flight conditions in a part of the Netherlands.
- Generating new routes when a helicopter breaks down to optimize coverage under these new conditions.

5.6 Conclusion

We developed an optimization model with the objective of maximizing the expected number of successful assists. This model takes care of the movement restrictions. However, the model assumes helicopters are always airborne. Therefore we introduce fuel constraints. These constraints limit the consecutive time a helicopter can fly. Furthermore, helicopters are required to have maintenance after a number of flight hours. Therefore, the number of hours a helicopter is allowed to fly is restricted to preserve availability during a period, without violating regulations. These restrictions are taken into account as well as constraints for the availability of a helicopter during the day. Also, we discuss constraints for keeping track of the state of a helicopter. As helicopters cannot take off immediately, we have to take this time into account. Furthermore, the area a helicopter increases when it is in the process of taking off, as it is earlier airborne.

The described model is not a feasible solution for problems of practical size due to computation time. We therefore proposed two heuristics that are computationally more efficient. The cost of this computational efficiency is that these heuristics do not guarantee to find an optimal solution. However, as it is currently not possible to find a guaranteed optimal solution in time, these heuristics have more added value. Based on a comparison with 2011 incident data, heuristic 2 outperforms heuristic 1 on computation time as well as result. Furthermore, the computation time of eleven minutes allows for more applications.

6 Decision support instrument

In this chapter we discuss how the decision support instrument works. In section 6.1, we discuss how to feed the instrument with data. Section 6.2 describes how the forecast is generated and helicopters are positioned. Section 6.3 gives an impression of the instrument. In section 6.4, we discuss methods for validating our model. Section 6.5 contains the implementation plan for implementing our instrument at the LVP.

6.1 Data input

As time continues and priorities change, new incidents happen that should be incorporated in the forecast. The instrument allows the user to input a single comma-separated file containing information about the time and location of incidents. The format of this file should be as follows:

Zip code, hour, minute, weekday, day, month, year, priority

The line above should also be the first line of the file. The zip code should only be the four digits of the zip code as this gives sufficient detail; however, for user friendliness, the instrument converts six digit zip codes into four digit zip codes. The weekday is the day of the week, where Monday is 1 and Sunday is 7. Priority is the priority for that type of incident and the values of the priorities are considered relative. For example, an incident with priority 4.5 is considered to be 1.5 times as important as an incident with priority 3. The priority is used as a weight in the forecasting process. The total weight covered is maximized when routing the flights.

Besides loading the incidents, intelligence can be inputted. As we had to construct a time efficient heuristic, we had to comprise on the way intelligence will be taken into account. When intelligence shows an incident will happen, and air support is required, the LVP should assign a helicopter beforehand and give that helicopter a flight for the heuristic. When intelligence shows an incident might happen, the LVP can either assign a helicopter beforehand as if the incident is known, or choose a flight after the routes are calculated, input the location and time as a constraint, and have the flight rerouted to satisfy the intelligence constraints.

6.2 Algorithms

The processes of generating a forecast and positioning the helicopters require little human interaction. After the incident data is inputted, the instrument derives in which hexagon each incident happened. Furthermore, the instrument derives the weekday factor and the month factor. After specifying the target date for the forecast and setting the forget factor, the user can generate a forecast with a single click. This will start the forecasting methods described in section 4 to generate the forecast. The initial read data is stored to allow for parameter adjustments without the requirement of reloading the data.

After the forecast has been generated, the instrument will display a graphical representation of the forecast to the user. As AIMMS, the software environment in which our prototype instrument is developed, requires significant time for *Updating Pages*, we had to make sure this only happens when requested by the user. This required additional variables, to allow the user to change settings completely before the graphical representation is updated. An exception is the slider, which allows the user to scroll through time and the graphical representation is updated on release of the mouse button.

As the algorithms in this instrument are kept flexible, this allows the user some freedom to experiment with adjusted parameters. This helps the user in validating the instrument, which is discussed in section 6.4. Besides validation, the algorithms are made robust for variation in the data inputted by the user. For example, the instrument requires four digit zip codes (1234), however six digit zip codes (1234AB or 1234 AB) can be inputted by the user and will be converted to four digit zip codes. We believe it is essential for the success of an instrument that the user can interact with the instrument intuitively.

6.3 Demonstration

Although the instrument cannot be demonstrated in written form, this section attempts to give a similar experience as a real demonstration. When opening the instrument, it opens at the welcome page (Figure 6.1). On this page, a manual can be found as well as buttons for the three parts of the instrument:

- Heuristic for Expected Location of Incidents (HELI)
- Coverage Optimization Process (COP)
- Tool for Express Rerouting (TER)

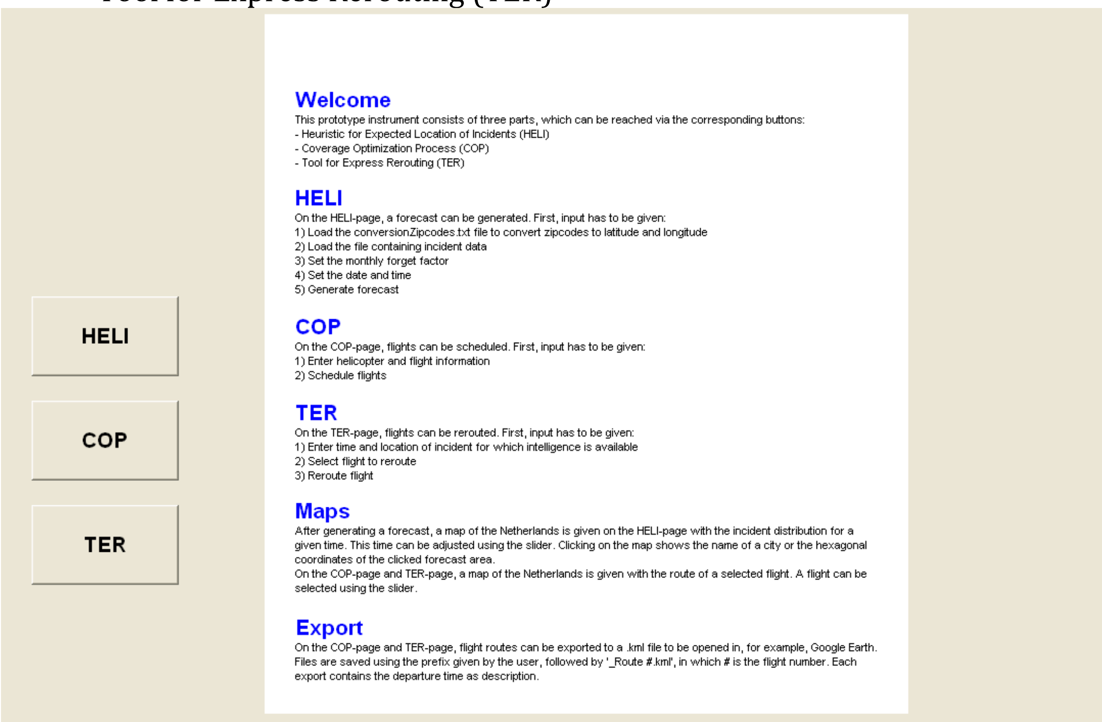

Figure 6.1 - Welcome screen with manual and buttons to the pages for HELI, COP, and TER.

When clicking on the HELI-button, the HELI-page (Figure 6.2) is shown to the user. In the upper left corner are two buttons: a button for loading the conversion file for converting zipcodes to latitude and longitude, and a button for loading the file with incident data. In the middle left, the user can set the target day, and adjust the forget factor. After setting these parameters, pressing the 'Generate forecast'-button in the lower left corner will generate a forecast.

After the forecast has been generated, a graphical representation is given to the user in the middle of the screen. Clicking on a black diamond on the map shows the name of the city. Clicking elsewhere on the map will give the hexagonal coordinates of the clicked hexagon. Changing the slider on the right adjusts the time of the forecast, and updates the graphical representation.

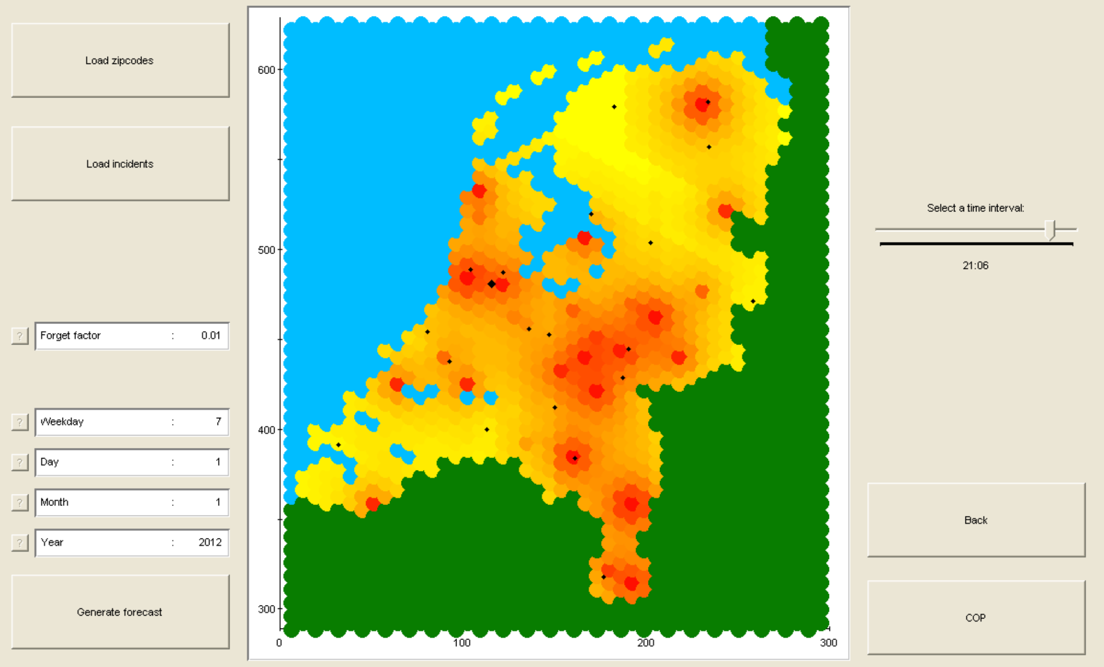

Figure 6.2 - The HELI page, which is the user interface for creating an incident forecast.

After a forecast has been made, the user can go to the COP-page by clicking on the COP-button in the lower right corner, or by going back to the welcome page and clicking the COP-button there. On the left of the COP-page (Figure 6.3), the number of flights and helicopter can be set. Pressing the 'Set helicopter data'-button allows setting the availability of each helicopter as well as starting location, end location, and helicopter belonging to a flight. The maximum number of time intervals a helicopter is allowed to fly above a location can be set on the left. Lowering this number leads to lower coverage; however, setting this helicopter to large might lead to a route where a helicopter flies to a nearby hotspot, waits there, and returns to the base. After all flights have been added, clicking the 'Schedule flights-button starts the coverage optimization process.

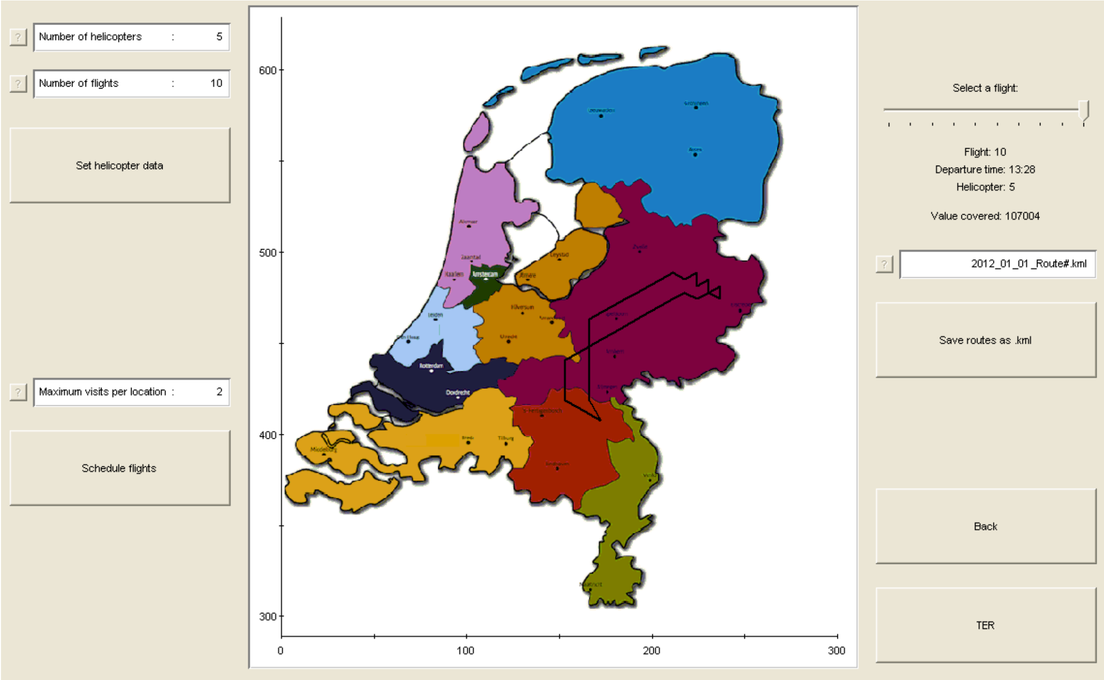

Figure 6.3 - The COP page, which is the user interface for the helicopter routing.

After the routes have been generated, the slider on the right side changes the flight for which the route is displayed on the map in the middle. Furthermore, the total covered value of all incidents and flight information are given on the right. The button 'Save routes as .kml' exports the routes as .kml files. The file is saved as "prefix"_Route#.kml, in which # is equal to the flight number and "prefix" can be specified by the user. These files can be used in, for example, Google Earth for a more detailed look on the routes as shown in Figure 6.4.

Figure 6.4 - Example of exported helicopter routes in Google Earth.

After the routes have been generated, the user can click on the TER-button to go to the TER-page (Figure 6.5), where helicopters can be rerouted to take intelligence into account. The slider on the left can be used to select a flight. Flight information is given below the slider, followed by input boxes to take intelligence into account. Clicking the Add-button adds the specified location at the specified time to the list of locations that have to be visited in the flight that will be rerouted. The Clear-button can be used to remove all previous entered intelligence. The intelligence can also be entered in the matrix in the lower left corner, by entering a 1 in the cell that represents the correct time interval as well as the correct x-coordinate and y-coordinate of the hexagonal coordinate system.

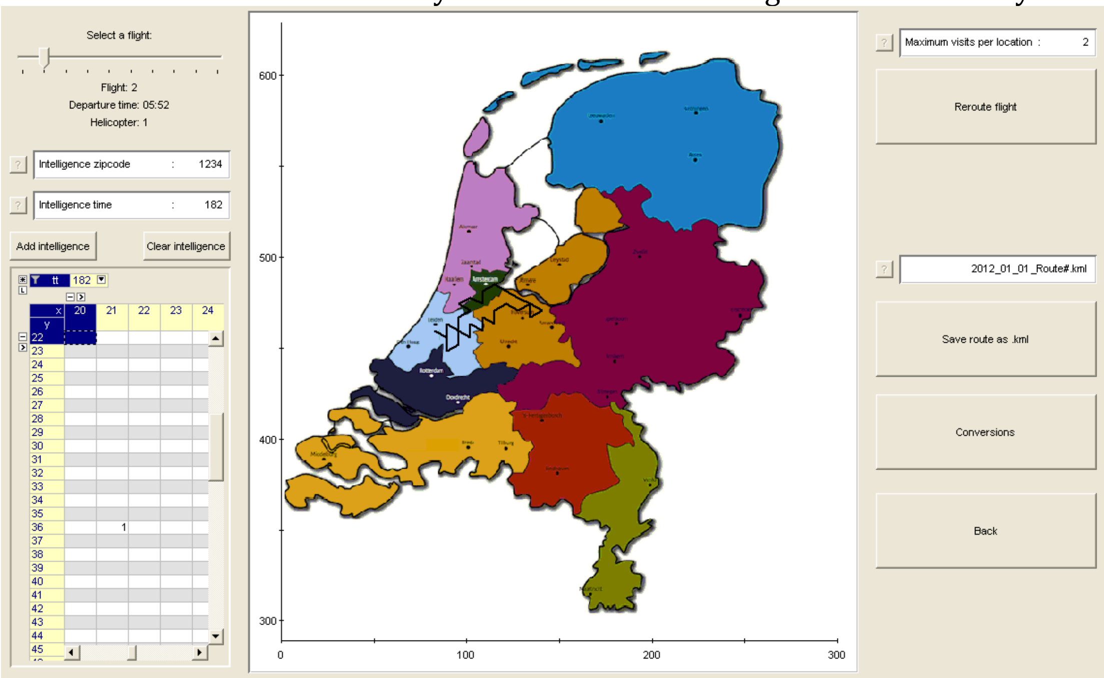

Figure 6.5 - The TER page, which is the user interface for rerouting flights.

After the intelligence has been inputted, clicking the 'Reroute flight'-button starts the rerouting process. The 'Save route as .kml'-button on the right can be used to save the adjusted route. It gets the file name given in the input box in a similar way as described for the COP-page.

6.4 Validation methods

As we have an exact model, the method to validate our heuristic seems obvious. However, as the exact model is too large to solve even the smallest representative situation, another validation method has to be used. As the LVP has data available on successful assists starting during the last DDO, we can pick a period in the past and use earlier data as input. We can then compare the result of the model with the historic results as achieved by the LVP.

As a complete validation requires significant amount of time, this is outside the scope of this research. Furthermore, a good validation should take intelligence into account, which is hard to use afterwards without using the result as intelligence as well. As the LVP would like to use the prototype instrument during the DDO, these six months can be used to validate the instrument. However, in order to give an indication about the performance of the prototype instrument, we did a small validation. We used the fast heuristic and used the historic data of 2011, as defined in KLPD (2012c), without the last seven days, to generate routes for these last seven days of 2011. We used the following settings:

- 5 helicopters are available for two flights each.
- Each helicopter has the following crew shifts:
  - Schiphol: 00:00-08:00
  - Schiphol: 08:00-16:00
  - Schiphol: 16:00-24:00
  - Rotterdam: 15:00-23:00
  - Volkel: 09:00-17:00
- Each flight starts and ends at the same base.
- Forget factor of 1% per month

After the routes were constructed, we compared these routes with the incidents that happened during the last seven days of 2011. This led to the performance as shown in Table 6.1. In this table, we distinguish between coverage from only airborne helicopters, and coverage from both airborne and standby helicopters.

	Incidents covered		
	Heuristic		Luchtvaartpolitie
	Airborne	All	
25 Dec 2011	0.4	0.4	0
26 Dec 2011	1	1	0
27 Dec 2011	0	2	1
28 Dec 2011	2.8	2.92	0
29 Dec 2011	4.6	7.59	0
30 Dec 2011	5.6	5.67	0
31 Dec 2011	0	1.07	0
Total	14.4	20.65	1

Table 6.1 - Comparison result of the heuristic and the actual result of the Luchtvaartpolitie

As can be seen, our small validation indicates that our heuristic outperforms the methods used by the LVP by 2065%. The single successful assist the LVP had, was part of fifteen assists in total in this week. This shows our heuristic had 138% more successful assists than the Luchtvaartpolitie had an assist, regardless of the outcome. However, a complete validation of this prototype is required as this is a small sample. There were 47 incidents during this week. The LVP had 15 assists in total, out of which a single successful assist. This indicates that the successful assist formula might be incorrect, or the dispatching rules used by the LVP do not take the probability of a successful assist into account.

When testing this prototype instrument in practice, one should be aware of human interaction with the model as the user can adjust the parameters *forget factor* and *maximum number of visits per flight*. Adjusting parameters each day does not give the model enough time to show its long-term performance. However, adjusting parameters after a couple of months will lead to poor results for a longer period.

6.5 Implementation plan

The prototype instrument has to be implemented into the organization in order to improve the performance of the LVP. This implementation plan describes the steps necessary to implement the prototype instrument such that it can be validated.

Like any instrument, our instrument is at most as good as its data. Therefore, the LVP should make sure the data they input in the instrument is correct and complete. The incident data should represent the type of incidents that should be covered by the LVP. This does not only apply to which type of incidents to use as input, but also the priority given to the incidents. This priority should include compensation for the degree to which the helicopter can have a successful assist.

Besides the incident data, the LVP also has to input some parameters as described in section 6.2. These parameters influence the behavior of the instrument and are not yet validated. These parameters should not be adjusted on a daily basis as the instrument is made to have a good performance on the long term and is subject to randomness. As the instrument has a quick heuristic, the LVP can calculate a theoretical number of successful assist by making routes with different parameters.

As solving the entire problem is too complicated, we had to resort to a heuristic. This heuristic cannot take intelligence into account. As the most promising starting time is solely based on the forecast, it is likely that taking intelligence into account for the Mixed Integer Linear Program will lead to an infeasible problem. Therefore we recommend using the rerouting functionality in the prototype instrument, or give a helicopter a flight less in the instrument and use that flight for the future incident associated with the intelligence. The rerouting functionality allows rerouting a flight such that intelligence is considered. When rerouting a flight, the starting time is already known, such that the LVP can add only the intelligence that will keep the problem feasible.

7 Conclusion and recommendations

Section 7.1 contains the conclusions that can be made based on this report. In section 7.2 we give our recommendations for the KLPD. We conclude with suggestions for further research (Section 7.3).

7.1 Conclusion

At the start of our research, the LVP already made significant progress since the research of Buiteveld (2011). However, they felt the need for a decision support tool for decision-making on the when and where to position the Dutch police helicopters. The decision support tool should use historical data, and allow intelligence to be taken into account. The output should consist of departure times and routes for the police helicopters.

In order to route the helicopters, we had to come up with a routing method. Although the police helicopter positioning problem could be described as a Dynamic Vehicle Routing Problem (DVRP), current solutions for DVRP cannot be applied to our problem. We therefore propose to define a new class within the field of DVRP with the name *Anticipatory Emergency Vehicle Routing Problem*. First we present an exact approach that would solve the problem to optimality. However, this approach is not suitable for real-world problems, as it requires too much computation time. We therefore propose the use of a heuristic that does not guarantee optimality, but does give a good result within reasonable time.

In order to use our heuristic, an incident forecast is required. The forecasting method we propose first generates a forecast in which generalization is used in the space dimension. In this forecast, we multiply the priority of an incident with a factor for the day of the week, a factor for the month, and a forget factor. The weekday factor and the month factor allow us to reduce the forecast error. The forget factor allows for giving more weight to recent incident data, as older data might not represent the current situation. This initial forecast is input for the second step. In the second step, we generalize in the time dimension. After generating a forecast, the heuristic we propose can be started.

We conclude that more incidents happen when it is dark outside. We believe this is due to less people on the streets when it is dark and therefore less potential witnesses. Our model and instrument takes this into account where possible. However, as our prototype instrument is restricted by the crew shifts, this observation should be considered in future crew schedules. Besides the difference in crime rates during day and night, we also observed a difference between days of the week and months. We recommend taking this into account on a tactical level as flying when more incidents are likely to happen leads to an increased probability of a successful assist.

To solve the positioning problem, we first modeled the problem as a Mixed Integer Linear Program. This model is too complicate to be used for problems of practical size. Therefore, we developed two heuristics that give a reasonable solution in a practical time. The first heuristic chooses random starting times for the helicopters and executes multiple iterations to increase the probability of finding the optimal solution. The second heuristic calculates the most promising starting, which makes the required computation time significantly smaller. Besides the smaller required computation time, the second heuristic also gives a better solution. This indicates that finding a good starting time requires much computation time when done randomly. We therefore propose the use of the second heuristic.

We implemented the proposed heuristic in a prototype instrument. We cannot give a definite conclusion on the performance improvement of this prototype instrument, as a complete validation is outside the scope of this research. However, based on an initial validation round, we believe using the prototype instrument will increase the number of successful assists, and therefore makes the Netherlands more secure. Furthermore, we described how to implement the prototype instrument at the LVP.

7.2 Recommendations

In this section we give our recommendations that do not require further research. Our first recommendation is to use the upcoming *Donkere Dagen Offensief* to validate the prototype instrument and implement it in the organization. If the results are satisfactory, we recommend having a software company develop a complete instrument that gets its data directly from the databases available at the Dutch police. In addition to those main recommendations, we also recommended the following:

- Continuously track the number of successful assists such that the performance is known at any time.
- Use multiple bases to have a larger base coverage of the Netherlands, as proposed by Buiteveld (2011), and to ensure air support when a basis is not operational due to, for example, fire.
- Mention successes. Everyone in the organization has a role in the performance, so share successes for example in a weekly bulletin to let everyone in the organization know that they make a difference.
- Make regional departments aware of the importance of complete data. When they do not enter all incidents, they appear to perform better and will receive less air support.

7.3 Further research

During this research, we encountered several issues that we believe require further research. In this section we describe these issues.

Cooperation with Belgium and Germany

As police helicopters can freely move in any direction, they cover areas in a circular shape. In Limburg and other border areas, this leads to either no coverage or a great part of the covered area is in foreign areas. By cooperating with Belgium and Germany, the LVP can share the cost of covering these areas.

Probability of successful assist

As we mentioned in section 2.2, the probability of a successful assist has not been thoroughly researched. As this is closely related with the efficiency of the LVP, we recommend researching it. We expect this will lead to different formulas for different types of incidents. After this has been researched, the LVP can make guidelines on when to deploy a police helicopter.

Preventive effect

Police helicopters may have a preventive effect on incidents. After an incident has taken place, the damage is already done. If police helicopters flying over an area prevent part of the incidents, this leads to a more favorable situation. When researching this possible effect, we notice that criminals might postpone their criminal activity when they notice a police helicopter. Therefore, researching the preventive effect of police helicopters should focus on prevention due to helicopters and postponement of incidents.

Forecasting

In this research, we forecasted based on location, date, and time of historical incidents. However, more variables can be used to forecast future incidents as mentioned in section 3.2. Besides forecasting when incidents will happen, forecasting escape routes might lead to an increased success probability. This requires analysis of modus operandi of criminals.

Integral scheduling approach

In this research, we focused on the LVP; however, this research can be extended to have an integral approach for all police vehicles and policemen. For example, if all units of the Dutch police would make similar decisions, this would likely lead to overcapacity at hotspots, whereas other areas lack capacity. Furthermore, we recommend extending this research to cover all hierarchical planning levels of the model of Hans et al. (2007). This would lead to a balanced approach of crew scheduling, maintenance scheduling, and helicopter routing.

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List of abbreviations

AEVRP	Anticipatory Emergency Vehicle Routing Problem
AMEXCLP	Adjusted Maximal Expected Covering Location Problem
AW139	Agusta Westland helicopter
C182	Cessna airplane
DDO	*Donkere Dagen Offensief*, Dark Days Offense
DOS	Dienst Operationele Samenwerking, Service Operational Cooperation
DVRP	Dynamic Vehicle Routing Problem
EC135	Eurocopter helicopter
FIC	Flight Information Center
KLPD	*Korps Landelijke Politiediensten*, National Police Services Agency
LSCP	Location Set Covering Problem
LVP	*Luchtvaartpolitie*, Air Support & Aviation Police
MCLP	Maximal Covering Location Problem
MEXCLP	Maximal Expected Covering Location Problem
RD	Rijksdriehoekstelsel
STAC	Spatial and Temporal Analysis of Crime
TIMEXCLP	Maximal Expected Covering Location Problem with time variation
VRP	Vehicle Routing Problem

List of mathematical notations

Sets

$\mathcal{H}$ Helicopters

$\mathcal{T}$ Time

$(\mathcal{X},\mathcal{Y})$ Locations

$\mathcal{Z}$ State

Parameters

$bigM$ A large number, used for integer linear programming tricks

c_{xyabz} The coverage a location (x,y) ∈ $(\mathcal{X},\mathcal{Y})$ gets from a location (a,b) ∈ $(\mathcal{X},\mathcal{Y})$ for an airborne helicopter in state z ∈ $\mathcal{Z}$

d_{ht} Whether helicopter h ∈ $\mathcal{H}$ is available at time t ∈ $\mathcal{T}$

e_h Initial duration helicopter h ∈ $\mathcal{H}$ has fuel for

f_h Maximum duration helicopter h ∈ $\mathcal{H}$ has fuel for

g_h Duration added to h ∈ $\mathcal{H}$ per time period when fueling

i_{xyt} Forecasted incident value at location (x,y) ∈ $(\mathcal{X},\mathcal{Y})$ at time t ∈ $\mathcal{T}$

l_{xyht} Whether helicopter h ∈ $\mathcal{H}$ is at location (x,y) ∈ $(\mathcal{X},\mathcal{Y})$ at time t ∈ $\mathcal{T}$

m_h Maximum allowed flight hours for helicopter h ∈ $\mathcal{H}$

n Maximum allowed total flight hours

p_{xy} Take-off time at location (x,y) ∈ $(\mathcal{X},\mathcal{Y})$

r Radius of a hexagon

Variables

A_{ht} Whether helicopter h ∈ $\mathcal{H}$ is airborne at time t ∈ $\mathcal{T}$

F_{ht} Duration helicopter h ∈ $\mathcal{H}$ has fuel for at time t ∈ $\mathcal{T}$

G_{xyt} Percentage location (x,y) ∈ $(\mathcal{X},\mathcal{Y})$ is covered at time t ∈ $\mathcal{T}$

L_{xyhtz} Whether helicopter h ∈ $\mathcal{H}$ is in state z ∈ $\mathcal{Z}$ at location (x,y) ∈ $(\mathcal{X},\mathcal{Y})$ at time t ∈ $\mathcal{T}$

S_{ht} Whether helicopter h ∈ $\mathcal{H}$ landed at time t ∈ $\mathcal{T}$

W_{htz} Whether helicopter h ∈ $\mathcal{H}$ is in state z ∈ $\mathcal{Z}$ at time t ∈ $\mathcal{T}$

Appendix A (Organizational structure)

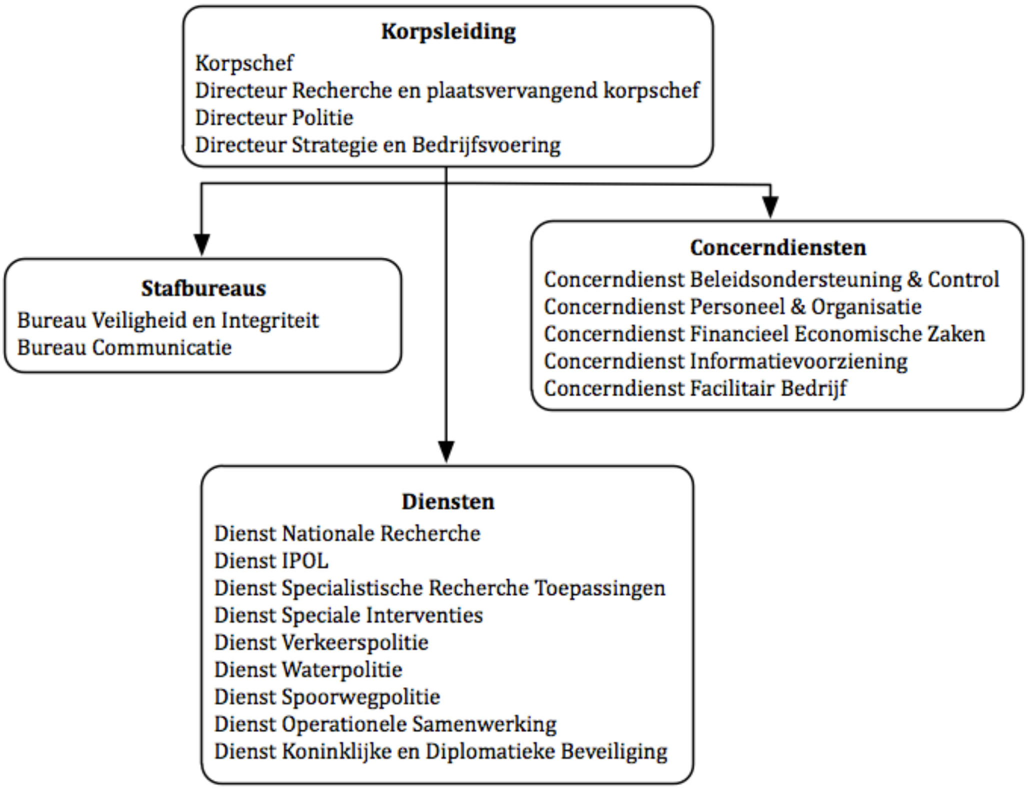

Figure A.1 Organizational structure of the Korps Landelijke Politiediensten. (KLPD 2012a)