Concentration of major trauma centres

What will be the effects?

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This report is intended for Acute Zorg Euregio and my supervisors of the University of Twente. In this public version, some parts are left out and rewritten or replaced by *[Restricted]*.

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This report was written as part of the master thesis of the Industrial Engineering and Management educational program.

PREFACE

'For from him and through him and to him are all things. To him be glory forever.'
- Rom. 11:36 (ESV)

Before you lies my master thesis 'Concentration of major trauma centres: What will be the effects?', which is the result of the study I performed for Acute Zorg Euregio. This study is the final piece of my time of being a student in the Industrial Engineering and Management programme at the University of Twente. During this time, I learned a lot, not only in my courses, but also during my side jobs and my graduation project. I learned about mathematical modelling, planning and scheduling, change management and operations research in healthcare environments. I learned from working together with my fellow students and got inspired by our teachers. Additionally, during my graduation project, I learned a lot about the trauma care system and what it involves to keep providing a high quality of care.

I thank Nancy ter Bogt for her supervision from within Acute Zorg Euregio. Thank you for all our weekly meetings. I liked that you were always interested in the progress of my project, that you gave useful feedback and that you indicated when a meeting with Manon and Ralph or once with Ambulance Oost would be useful. I also thank Manon, Ralph and Johan for these meetings. Thank you for thinking along with my study and for providing me with some new insights once in a while.

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Nynke Meijer
Enschede, June 2022

MANAGEMENT SUMMARY

Problem definition

Since 1998, trauma care in the Netherlands is concentrated in specialised major trauma centres (MTCs). Currently, there are thirteen of these MTCs. However, the National Committee Trauma Surgery envisioned further concentration to improve the quality of care. This could also contribute to meeting the minimum volume norm, which currently not all MTCs meet. However, before possible further concentration can be considered, research should be performed to provide insight into the effects on the transportation of patients, the usage, capacity and location of the ambulance and helicopter services, and the fraction of multitrauma patients that are brought to an MTC. This fraction should be at least 90% but is currently only 69%. All in all, the core problem is the following:

The multitrauma healthcare organisations in the Netherlands cannot yet decide on logistical improvements to the multitrauma care chain, because they have little insight into the relationship between further concentration of MTCs and the use of Emergency Medical Services (EMSs) for patient transportation.

Method

To provide the missing insights, in this study, we model the prehospital trauma care system and analyse the effects of changing the number and locations of the MTCs and the use of the EMSs for patient transportation. To do this, we use two models. First, we develop a multi-objective binary linear programming model to determine which MTCs should be opened to maximise the coverage of patients and to minimise the transportation by helicopter given that the number of MTCs to open is known. We base this model on the maximal covering location problem (MCLP) of Church and Revelle (1974) and extend this model by considering two transportation modes, e.g., ambulances and helicopters, of which one is prefered over the other. The outcomes of this model are the combinations of MTCs that we expect to perform well from a logistical perspective.

To further evaluate these outcomes, we develop a Discrete Event Simulation model of the Dutch trauma care system. In this simulation model, we consider the capacity of the EMSs, approximate the real-time decision processes of medical staff, and take into account the stochasticity of among others the prehospital times and emergency calls. Additionally, we take into account that multitrauma patients should be managed differently than other patients. Furthermore, we not only evaluate the performances of the combinations of open MTCs with the currently available HEMS stations, but also with a possible additional HEMS station and/or without the possibility to use the German HEMSs. Next to this, we evaluate the impact of forcing the trauma care system to meet the norm of bringing at least 90% of the multitrauma patients to an MTC. Finally, we perform a sensitivity analysis to evaluate the performances of the suggested combinations of opened MTCs in a situation with more patients.

Results

Applying the mathematical model to the Dutch trauma care system, we find several combinations of nine to twelve MTCs that perform as good as the current situation with thirteen MTCs when considering the fraction of the multitrauma patients that reach a hospital within 45 minutes and the fraction of multitrauma patients that are brought to an MTC instead of another hospital. This holds for both the coverage and the fraction of patients that are transported by helicopter. Additionally, for

several combinations of opening only eight MTCs, the coverage decreases by at most 2 percent points, while the fraction of patients that are transported by helicopter increases by at most 2 percent points. So, the coverage is only slightly worse and the increase in the fraction of patients that are transported by helicopter is not unreasonably high. Therefore, we focus on the options of opening eight or nine MTCs when applying our simulation model and we compare the outcomes of these options to the option of opening all thirteen MTCs. Additionally, we compare the results to three combinations of open MTCs that follow from a more pragmatic approach to choosing which MTCs to open. In the first two of these approaches, the choice of which MTCs should be opened is based on the number of multitrauma patients the MTCs treated in the past year or past three years. In the third approach, we base our choice on the prediction of the number of multitrauma patients that the MTCs will treat next year given all MTCs are open.

Using the simulation model, we find that independent of the Helicopter EMS (HEMS) stations that can be used, opening all thirteen MTCs results in the highest fraction of multitrauma patients reaching a hospital within 45 minutes after the emergency call. This fraction is 1 to 5 percent points higher than when only nine MTCs are opened. Additionally, opening all thirteen MTCs results in the highest fraction of multitrauma patients going to an MTC. Depending on which HEMS stations are open, this fraction is 4 to 8 percent points higher than when only nine MTCs are opened. In the other three best-performing scenarios, four or five specific MTCs are closed. This reduces the number of multitrauma patients that go to an MTC from 60-63% to 54-58% depending on which HEMS stations can be used. The differences between these three runner-up scenarios are small, although when the number of patients increases, the scenario in which nine MTCs are open seems to perform slightly better in terms of the fractions of multitrauma patients that go to an MTC and that have a prehospital time of at most 45 minutes. In general, the scenario with nine MTCs will perform better than the scenarios with eight MTCs, because it has one additional open MTC.

Conclusion and discussion

In conclusion, when trauma care should be concentrated in fewer MTCs, from a logistics perspective, we recommend closing four specific MTCs. However, this would reduce the score on the 90% norm by 4 to 8 percent points and it would decrease the fraction of multitrauma patients that reach a hospital within 45 minutes by 1 to 5 percent points, depending on which HEMS stations could be used. If we would let the trauma care system bring 90% of the multitrauma patients to an MTC, the prehospital times and the busyness of the HEMSs would increase by 5 to 5.5 minutes and by 0.3 to 1.2 percent points, respectively. The busyness of the ambulances would hardly be affected. However, if more patients are brought to MTCs, more capacity will be needed in these hospitals. This is not included in our study but would be a useful addition in further research. Furthermore, we recommend further investigating the decision processes of medical staff on where to bring a patient and which transportation mode to use. That way the simulation model can be improved to better represent reality. Another useful research direction is to incorporate the busyness of EMSs in the mathematical model to more accurately calculate the values of the KPIs and thereby support decision-makers in choosing which combinations of open MTCs should be further evaluated using the simulation model.

Next to this, we want to remark that because of the long computation time of our simulation model, we only simulated thirty days of the prehospital trauma system, which means that the results only include multitrauma patients of 9% of the postcodes. Nonetheless, these postcodes are spread across the whole country.

Finally, we note that we performed our study using public data. Therefore, sometimes the lack of granularity of the data required us to make assumptions or use pragmatic approaches to derive probability distributions for our simulation model. We realise that this might affect the validity of our results. Additionally, we could not draw valid conclusions on a hospital level, which is also because more research is needed on the real-time decision processes. However, the main results about the closing of which MTCs would reduce the performance on the logistical KPIs the least are clear and can also be logically explained. So, we believe that these conclusions can be drawn. Additionally, if in further research more data is available, this can be used in the model to increase the validity of the results and to draw conclusions on a hospital level.

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GLOSSARY

90% norm	Norm that states that at least 90% of the multitrauma patients in the trauma region should be transported directly to an MTC
A1 dispatch	Dispatch with high urgency in which the ambulance should reach the scene within 15 minutes after the emergency call
A2 dispatch	Dispatch with lower urgency in which the ambulance should reach the scene within 30 minutes after the emergency call
AZE	Acute Zorg Euregio
B dispatch	Planned ambulance dispatch to for instance transport a patient from one hospital to another.
Dispatch time	Time between an emergency call and the departure of an EMS.
EMS	Emergency Medical Service (includes ambulance care and MMTs)
HEMS	Helicopter Emergency Medical Service *(Dutch: Helikopter-MMT)*
ISS	Injury Severity Score
LNAZ	National Network of Acute Care *(Dutch: Landelijk Netwerk Acute Zorg)*
MMT	Mobile Medical Team (includes ground-based MMT and HEMS)
MTC	Major trauma centre
Multitrauma patients	Patients with an ISS > 15
Post-landing time	Time it takes a HEMS team to get from the helicopter's landing location to the scene.
Primary dispatch	Dispatch of an MMT upon receiving an emergency call
RAV	Regional ambulance service *(Dutch: Regionale ambulance voorziening)*
Secondary dispatch	Dispatch of an MMT upon request of the ambulance staff at the scene
Trauma care	Care for patients that got injured during an accident
Volume norm	Norm that states that each MTC should accommodate at least 240 multitrauma patients per year

1. INTRODUCTION

In this chapter, we introduce the topic of the study. First, we provide background information on the concentration of care in the Dutch healthcare system, and we elaborate on this regarding trauma care. Second, we further analyse the problem and describe our approach to solving it.

1.1. Background information

The healthcare system in the Netherlands is known to be one of the best healthcare systems in the world. However, the costs are increasing and so is the workload for people working in this sector. Therefore, it is important to manage healthcare cleverly. Commissioned by the Dutch Minister of Medical Care, the Dutch Healthcare Authority (NZa, Dutch: Nederlandse Zorgautoriteit) and the National Health Care Institute (ZIN, Dutch: Zorginstituut Nederland) (2020) have proposed several measures to do this, one of which is the concentration of complex, low frequency and expensive care. This should increase the quality of care in the Dutch healthcare system.

Concentration of healthcare is not a new phenomenon. Already in 1998, the Dutch Ministry of Health, Welfare and Sport proposed concentrating the trauma care and especially the multitrauma care (Borst-Eilers, 1998). Trauma care entails care for patients that got injured during an accident. The severity of injuries is measured using the Injury Severy Score (ISS) and patients with an ISS above fifteen are called ‘multitrauma patients’. Since 1999, the care for these patients is concentrated in hospitals that are specialised in trauma care, the so-called ‘major trauma centres’ (MTCs) These hospitals are also called level I hospitals (Landelijke Beraadsgroep Traumachirurgie, 2015; Zorgverzekeraars Nederland, 2013). Currently, there are thirteen of them in the Netherlands.

Another example of concentration in the past is the introduction of minimum volume norms for hospitals for several treatment categories, such as specific oncological or cardiological treatments. This was done in 2003 with the purpose to concentrate those specialisms more (den Engelsen et al., 2019). Furthermore, a recent development regarding concentration is the presentation of plans to concentrate pediatric cardiological surgeries in two instead of four hospitals (de Koning, 2021).

1.1.1. Trauma care

In this study, we focus on trauma care. In 2015, the National Committee Trauma surgery (LBTC, Dutch: Landelijke Beraadsgroep Traumachirurgie) envisioned further concentration of the trauma centres at a regional as well as a national level, especially for the multitrauma patients (Landelijke Beraadsgroep Traumachirurgie, 2015). The progression of this concentration is reflected in the increase of the minimum volume norm for the number of multitrauma patients each trauma centre needs to treat per year. This norm used to be 100 patients but has been increased to 240 (Nederlandse Vereniging voor Traumachirurgie, 2020). Currently, not all of the MTCs meet the new minimum volume norms as, in 2019 and 2020, respectively seven and six out of the thirteen MTCs treated fewer than the required 240 multitrauma patients (Landelijk Netwerk Acute Zorg, 2020; Zorginstituut Nederland, 2020, 2021).

Before possible further concentration can be considered, research should be performed on the effects it has on the performance of the trauma centres (Landelijke Beraadsgroep Traumachirurgie, 2015). Additionally, the consequences for the transportation of patients and the usage, capacity and location of the ambulance and helicopter services need to be investigated (Ministerie van Volksgezondheid Welzijn en Sport, 2020). In this study, we contribute to this need.

1.1.2. Terminology

Before continuing with describing the identification of the problem we address in the study, we first present some terminology on the trauma care system. A more detailed description of the system can be found in Chapter 2. The main components of the trauma care system are the MTCs and the Emergency Medical Services (EMSs). The MTCs are the thirteen hospitals that are specialised in proving care to multitrauma patients. The EMSs are the Emergency Medical Services that transport medical staff and equipment to the patient, provide first aid at the accident site and transport the patient to the hospital. In **Figure 1**, the different types of EMSs are shown. First, we see the ambulance services, which are the first to be dispatched and are the main service to transport the patient to the hospital. If the patient needs specialist care or if the accident scene is hard to reach by ambulance, a Mobile Medical Team (MMT) can be dispatched. This team among others includes a trauma surgeon or anesthesiologist, who can provide specialist care, which is the main purpose of the MMTs. In the Netherlands, four MMTs are permanently at the ready to assist the ambulance staff. These four operational teams have a helicopter at their disposal and are therefore called Helicopter Emergency Medical Services (HEMSs). Only in 7% of the cases that a helicopter comes to the scene, it is used to transport the patient to the hospital (Landelijk Netwerk Acute Zorg, 2015). Next to using this helicopter, HEMSs can choose to use a car, for instance, if the weather conditions are insufficient. Apart from these four HEMSs, there are two ground-based MMTs, which are called Ground-based Emergency Medical Services. These Ground-based EMSs need a short preparation time before they can be used and they do not have a helicopter. They are only deployed in case of large accidents with more than ten patients (Instituut Fysieke Veiligheid, 2021). Furthermore, in the regions near the Dutch border, the Dutch HEMSs collaborate with the German and Belgian ones to be able to reach those areas more quickly.

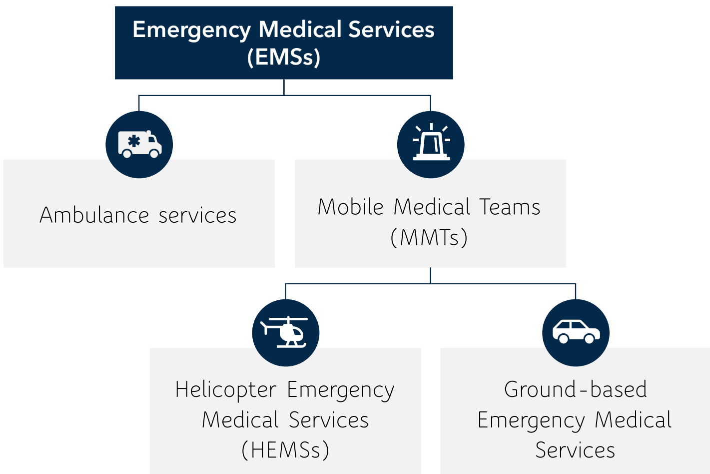


Figure 1 Structure of the EMS modes

1.2. Problem identification

In **Figure 2**, the problems and challenges observed in the Dutch trauma care system, as well as the relationships between them, are mapped. We see that the problems are related to two norms that are not met. The first norm is the minimum volume norm, which states that each MTC should accommodate at least 240 patients per year. The second one is the 90% norm, which specifies that 90% of the multitrauma patients in the trauma region should be transported directly to an MTC (Nederlandse Vereniging voor Traumachirurgie, 2019). These two norms ensure a good quality of care. Therefore, they must be met. However, several causes impede this.

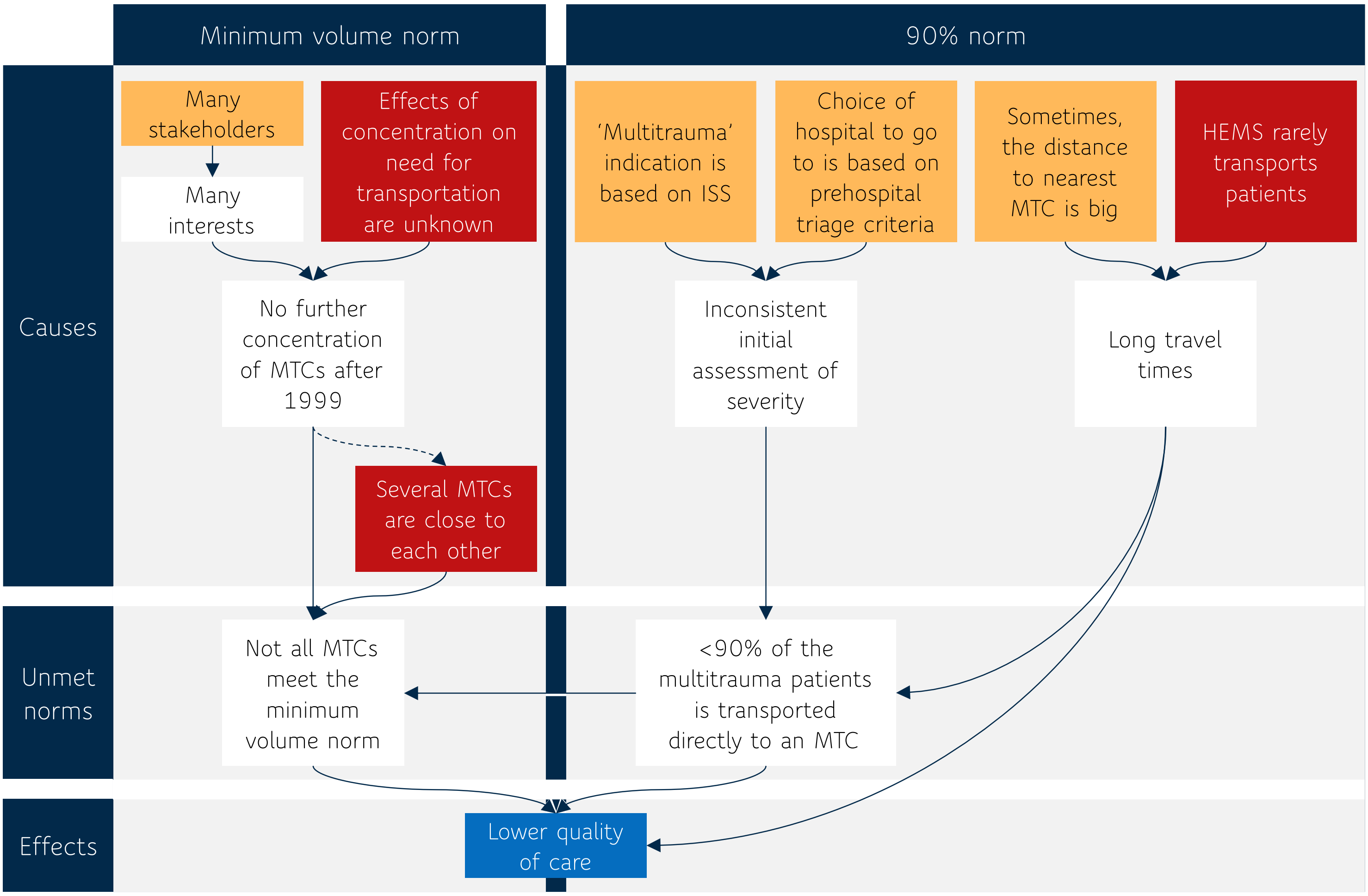


Figure 2 Problem cluster

1.2.1. The minimum volume norm

When considering the minimum volume norm, we observe that some MTCs are close to each other. This is the case for Trauma Centre West, which comprises three level I hospitals in Leiden and The Hague, as well as for the two trauma centres in Amsterdam. This density of MTCs might cause their low volumes. Probably, further concentration would have altered this. However, reducing the number of MTCs has not happened after the concentration of 1999 (Borst-Eilers, 1998). One of the reasons for this is that there are many stakeholders that all have different interests. Patients might prefer an MTC close to their city, health insurers might aim for concentration to keep healthcare affordable, medical scientists might want concentration to optimise quality of care and hospitals might not want to lose their MTC status, because it allows them to use their expertise to provide the best care to their patients (Nieuwenhuis et al., 2021).

Another reason that further concentration has not occurred is that the effects of concentration are unknown, whereas the norms regarding timely accessibility still need to be met (Ministerie van Volksgezondheid Welzijn en Sport, 2020). This means that patients still need to be transported to the right hospital on time.[1] Regarding the 'right hospital', the 90% norm should be met. This implies that, if the distances to the MTCs increase because of the reduced number of MTCs, other means of transportation might be needed, such as transporting patients by a helicopter instead of just using it to bring the medical team and equipment to the patient (Mommsen et al., 2012). It might also be necessary to increase the transportation capacity by increasing the number of ambulances or HEMSs. For the latter, a plan already exists, because this could improve the timely accessibility of the eastern part of the Netherlands (Megens, 2021; Timmers, 2021). Before decisions can be made regarding possible further concentration, the impact on transportation and the potential need for change need to be clear.

1.2.2. The 90% norm

The second norm that is currently not met, is the 90% norm. Instead of 90%, only 69% of the multitrauma patients are brought to an MTC (Landelijk Netwerk Acute Zorg, 2020). As can be seen in **Figure 2**, this again has multiple causes. First, the inconsistent initial assessment of the severity of the injury. The ambulance staff performs this assessment based on the prehospital triage criteria of the National Ambulance Care Protocol (LPA, Dutch: Landelijk Protocol Ambulancezorg). Based on these criteria, they decide to which hospital they will transport the patient. Later, in the hospital, further examination, using the Injury Severy Score (ISS) results in a final indication of whether the patient is a multitrauma patient. However, because the 90% norm is based on the ISS, which differs from the criteria that are used to decide to which hospital the patient will be transported, patients are often transported to the wrong hospital (ter Bogt et al., 2017). For instance, a patient who at first seems to be moderately injured might be transported to a hospital that is not an MTC, whereas there it might turn out that he is severely injured and should have been transported directly to an MTC.

Another cause of not meeting the 90% norm is that travel times to the nearest MTC are sometimes perceived to be too long. Ambulance staff can then transport the patient to another, closer hospital, which decreases the score at the 90% norm. These long travel times are caused by big distances and by transportation modes that are not fast enough. To illustrate the latter, most of the patients (about 88%) are transported by ambulance and only 3% are transported by helicopter (Sturms et al., 2021). One of the reasons the helicopter is not used more often to transport the patient is that providing care during the flight is difficult. For instance, due to the small space, resuscitation is challenging and communication with the patient is difficult because of the noise (Werkgroep Landelijke Richtlijnen MMT-NL, 2013).

1.2.3. Core problem

When looking for the underlying causes of the causes that we discussed till now, seven root causes emerge which are marked orange and red in **Figure 2**. The first cause, which is the high number of stakeholders, is something we cannot influence. Additionally, the ISS and prehospital triage criteria are out of scope for this study because we focus on logistical rather than medical aspects. Furthermore,

[1] The exact norm for timeliness is subject to research. Currently, in case of an A1 dispatch, the norm is to bring the patient to the MTC within 45 minutes after the emergency call (van Ark, 2020). However, experts agree on a norm of 60 minutes before the start of the treatment in an MTC (Gezondheidsraad, 2020).

the big distances to the nearest MTCs are unsolvable, because concentration will naturally not decrease, but increase the distances. So, there are three core problems left that we could influence: the lack of insights into the effects of concentration on the need for transportation, the density of part of the MTCs, and the fact that helicopters rarely transport patients. These are all related to the absence of insights into the relationship between concentration and transportation. Namely, further concentration might reduce the number of MTCs that are close to each other. Additionally, for concentration, it might be needed that helicopters more frequently transport patients. But before these decisions can be made, it should be predicted how many MTCs are needed to serve the patients, how much transportation capacity is needed and what this means for the performance regarding the minimum volume norm and the 90% norm. Therefore, the core problem we address in this study is:

The multitrauma healthcare organisations in the Netherlands cannot yet decide on logistical improvements to the multitrauma care chain, because they have little insight into the relationship between further concentration of MTCs and the use of EMSs for patient transportation.

1.3. Problem approach

To solve the problem, multiple steps need to be taken. Hence, we define several research questions and define the scope of the study.

1.3.1. Research questions

The steps we take are reflected in six research questions, which we cover in the body of our report.

1. *How is the multitrauma care chain currently organised?*
    1.1. How are the MTCs organised?
    1.2. How is the ambulance care organised?
    1.3. How are the Mobile Medical Teams (MMTs) organised?
    1.4. What does the prehospital care path for the multitrauma patient look like?

Before improvements to the current situation can be developed, we first should understand the current situation. This is reflected in the first research question. We describe and map this situation considering the four major stakeholders (MTCs, ambulance care, specialised MMTs and patients) in Chapter 2.

2. *What can we learn from literature regarding concentration and patient transportation?*
    2.1. Which models are suitable for evaluating the positioning of healthcare facilities?
    2.2. Which models are suitable for evaluating the positioning of EMS stations?
    2.3. Which EMS types are recommended for patient transportation in which situations?

Once the current situation is clear, we explore the existing body of knowledge. It is useful to employ this because this way we exploit the work and expertise of multiple parties. This contributes to the completeness, level of detail and validity of the model, and thus to the conclusions regarding possible concentration, and prevents us from reinventing the wheel. Therefore, in Chapter 3, we describe the knowledge and models that are already existing.

3. *How can we integrate the available relevant information regarding MTCs and patient transportation into a mathematical model to determine which MTCs should be opened?*
    3.1. Which assumptions and simplifications are needed?
    3.2. How should the model be formulated?

After examining the existing knowledge and models, in Chapter 4, we answer the third question by explaining how we integrate the available information on MTCs and patient transportation into one mathematical model. Additionally, we extend the model to be able to evaluate the concentration of MTCs and the adapted use of EMSs for patient transport.

4. *Which combinations of open MTCs perform best according to our mathematical model?*
    4.1. Which case data do we use?
    4.2. What are the results of the mathematical model?

In Chapter 5, we apply the model we described in Chapter 4 to the Dutch trauma care system to determine which combination of open MTCs we expect to be able to provide care to the most patients while considering that for patient transportation ambulances are preferred over helicopters.

5. *How can we determine which combinations of open MTCs perform best when including stochasticity and finite EMS capacity?*
    5.1. Which type of model should we use?
    5.2. Which assumptions and simplifications are needed?
    5.3. Which logistical KPIs are relevant?
    5.4. How do we validate the results?
    5.5. Which combinations of open MTCs should we evaluate?
    5.6. Which combinations of open HEMS stations should we evaluate?

The model we describe in Chapter 4, is a mathematical model which assumes infinite EMS capacity. To further evaluate the performances of the combinations of open MTCs, we need to consider stochasticity and finite EMS capacity. In Chapter 6, we describe which type of model we use for this evaluation, which Key Performance Indicators (KPIs) we evaluate and how we can use this model to answer the fifth research question.

6. *What are the effects of the concentration of multitrauma care on the logistical KPIs?*
    6.1. How can we approximate real-time decision processes?
    6.2. Which combination of open MTCs performs best on the logistical KPIs?
    6.3. What are the effects of the concentration on the minimum volume norm?
    6.4. What are the effects of the concentration on the 90% norm?
    6.5. What are the effects of the concentration on the busyness of the EMSs?

Using the model, we describe in Chapter 6, we evaluate the effects of several concentration options that result from the analysis of Chapter 4 and from reality. Before doing this, we calibrate the approximations of the real-time decision processes in the model to increase validity. Thereafter, we evaluate the performances of the combinations of open MTCs on the KPIs we defined in Chapter 6. We describe these results in Chapter 7.

1.3.2. Scope

This study considers the trauma patients in the Netherlands, as well as the parties that are responsible for their care between the emergency call and the arrival in the hospital. We focus on the existing or planned locations for MTCs and EMSs and we leave the ambulance stations in their current positions. For our study, we use public data, which means that in the implementation of our models we do not use historic patient-specific information, but we approximate postcode-specific information using less granular data. However, when more granular data is available, it can be used in our models without needing to change them.

This study focuses on the logistical aspects of the concentration and transportation, rather than on the medical aspects. Hence, measures of the quality of care are out of scope. Additionally, the costs are out of scope. Of course, costs are relevant for the decision-making, however, whereas prehospital costs might increase if helicopters are used more to respond to the concentration of the MTCs, hospital costs might decrease because of the greater efficiency. This trade-off should be evaluated, but it goes beyond the objective of this study because it belongs to another field of knowledge and medical expertise should be employed for this as well.

1.4. Conclusion

In the Netherlands, trauma care is concentrated in specialised major trauma centres (MTCs). To ensure the quality of care, these MTCs should meet a minimum volume norm of 240 patients per year, which currently not all of them do. To improve the quality of care, the National Committee Trauma Surgery envisioned further concentration, which contributes to meeting the minimum volume norm. However, before possible further concentration can be considered, research should be performed to provide insight into the effects further concentration has on the performance of the MTCs. Additionally, the consequences for the transportation of patients and the usage and capacity of the ambulance and helicopter services need to be investigated. In this study, we contribute to this need by modelling the prehospital trauma care system to analyse the effects of changing the number and locations of the MTCs and the use of the EMSs for patient transportation.

2. CONTEXT

In this chapter, we elaborate on the context of this study. We start by explaining more about the historical context. Further, we give a short description of the organisation that initiated the current study. Thereafter, we specify the stakeholders of the topic and finally, we show how they cooperate in the care process for the trauma patients.

2.1. National historical context

In 1998, the Dutch Ministry of Health, Welfare and Sport proposed to designate ten hospitals as MTC. These MTCs should also coordinate and register the care for trauma patients and facilitate the establishment of agreements on the assignment of the patients to the hospitals in the region, based on the patient's level of injury (Borst-Eilers, 1998). Later, an eleventh trauma region was added, and the coordinating and research facilities were transferred to eleven networks for acute care (Landelijk Netwerk Acute Zorg, 2020). These networks now coordinate the acute care, which also incorporates trauma care, for their region. Each region still has at least one MTC that provides care for multitrauma patients. The region of Leiden and The Hague (Trauma Centre West) has three MTCs. Of the eleven trauma regions, four also function as helicopter centres. In **Figure 3**, the trauma regions and MTCs are shown.

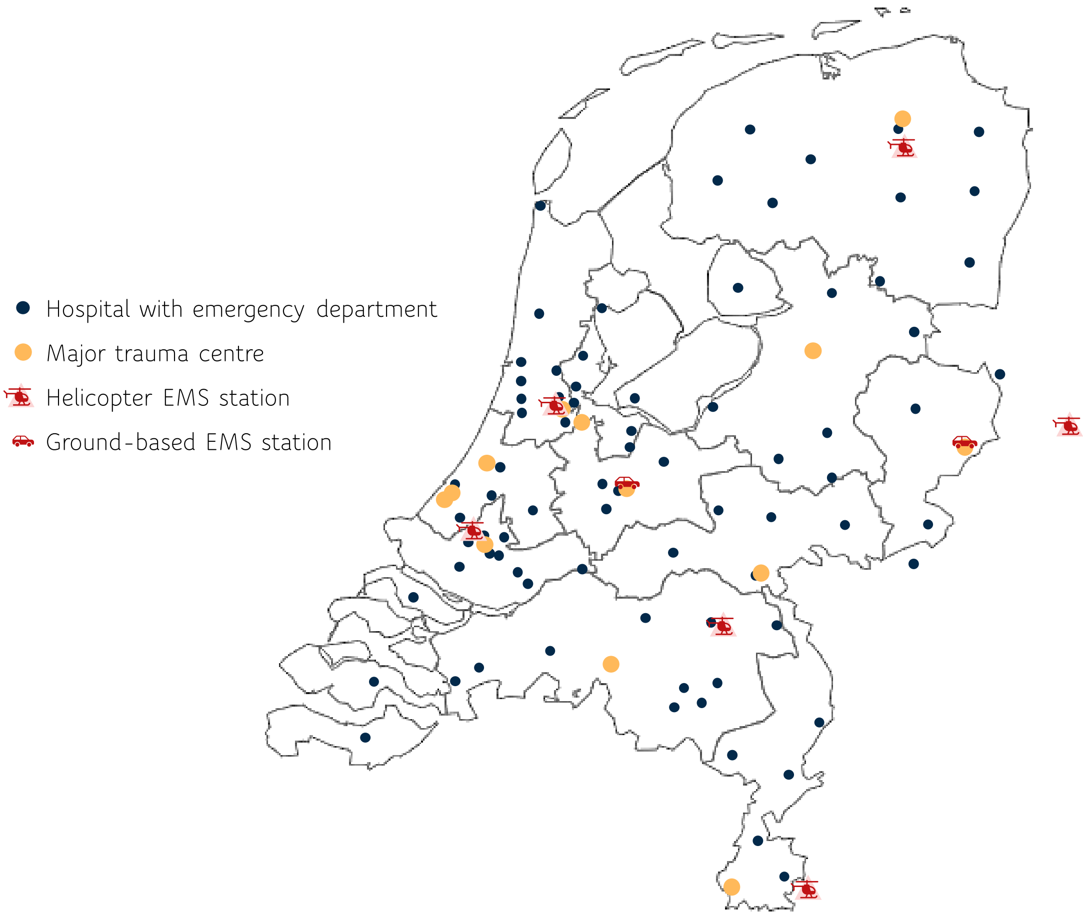


Figure 3 Trauma regions, hospitals and MMT stations
(Adapted from Landelijk Netwerk Acute Zorg (n.d.-d))

2.2. Organisational context

The acute care network that initiated our current study is Acute Zorg Euregio (AZE), which is responsible for the coordination of acute care, part of which is trauma care, in the Euregio region. This region is a cross-border region covering the Dutch regions Twente and the eastern part of the Achterhoek, as well as parts of the German states Niedersachsen and Nordrhein-Westfalen. The MTC of this region is the Medisch Spectrum Twente hospital in Enschede, which treats approximately three hundred multitrauma patients per year (Medisch Spectrum Twente, 2022). The goal of AZE is to coordinate and improve the acute care in this region to enable care to be delivered on time and by the right people or organisations. It does this by training organisations, studying improvement possibilities, and facilitating inter-organisational communication. AZE also collaborates with other acute care and trauma regions and bodies of the National Network of Acute Care (LNAZ, Dutch: Landelijk Netwerk Acute Zorg). Hence, this study is not limited to the Euregio region but aims at providing insights into the national trauma care system.

2.3. Stakeholders

The trauma care system is a network of several stakeholders. The main stakeholders are the patients, the MTCs, the ambulance care, the MMTs, and the ambulance dispatching centres. Next to these parties, also the government, the health insurers and the research and advisory bodies of the LNAZ are involved.

2.3.1. Major trauma centres and other hospitals

The thirteen MTCs of the Netherlands are listed in **Table 1**. These trauma centres have a level I status and are responsible for the care of the multitrauma patients. The level I status means, among others, that these hospitals have at least 12 Intensive Care beds, of which one is always available for an acute trauma patient. Furthermore, they should meet the volume norm and the 90% norm and they should meet requirements regarding the certification of their medical staff (Nederlandse Vereniging voor Traumachirurgie, 2019).

Table 1 Major trauma centres in the Netherlands (* = This MTC operates a HEMS)

Major trauma centre	Short name	City
Academisch Medisch Centrum	AMC	Amsterdam
Elisabeth Tweesteden Ziekenhuis	ETZ	Tilburg
Erasmus Medisch Centrum*	Erasmus MC	Rotterdam
Haaglanden Medisch Centrum	HMC	The Hague
HagaZiekenhuis	HagaZiekenhuis	The Hague
Isala Zwolle	Isala Zwolle	Zwolle
Leids Universitair Medisch Centrum	LUMC	Leiden
Maastricht Universitair Medisch Centrum+	Maastricht UMC+	Maastricht
Medisch Spectrum Twente	MST	Enschede
Radboud Universitair Medisch Centrum*	Radboud UMC	Nijmegen
Universitair Medisch Centrum Groningen*	UMC Groningen	Groningen
Universitair Medisch Centrum Utrecht	UMC Utrecht	Utrecht
Vrije Universiteit Medisch Centrum*	VUmc	Amsterdam

Next to the level I hospitals (the MTCs), there are also level II and III hospitals. These hospitals also need to meet certain level criteria. However, the norms for these criteria are more easily achievable. Level III hospitals are therefore meant to only treat less severely injured patients. Level II hospitals can also treat vitally endangered patients. However, they are not obliged to have all equipment and staff that a level I hospital needs to have (Landelijk Netwerk Acute Zorg, n.d.-a).

2.3.2. Ambulance care

Other important stakeholders are the organisations that are responsible for the ambulance care. These organisations are the 25 regional ambulance services (RAVs, Dutch: Regionale ambulance voorzieningen). Since 2013, the RAVs are responsible for operating an ambulance dispatching centre (MKA, Dutch: Meldkamer Ambulancezorg) and for providing ambulance care within their RAV region (Ambulancezorg Nederland, 2021a). The RAVs are united in a national organisation for ambulance care (AZN, Dutch: Ambulancezorg Nederland). The goal of this organisation is to achieve a cooperative acute care system in which the patient is central. The latter implies that they want to provide the right care at the right moment and in the right place (Ambulancezorg Nederland, 2017).

To provide care, the RAVs nationally have 881 ambulances at their disposal. They are located at 240 ambulance stations, which are spread over the country in such a way that approximately 95% of the Dutch population can be reached within 15 minutes in case of an emergency. Yearly, ambulances are used for over a million accidents across the country (Ambulancezorg Nederland, 2021b).

2.3.3. Mobile Medical Teams

Next to the ambulances and ambulance staff, the Dutch EMSs also consist of more specialised Mobile Medical Teams (MMTs)(**Figure 1**). In the Netherlands, four teams are permanently at the ready to assist the ambulance teams. These operational MMTs have a helicopter at their disposal to get to the accident quickly and to be able to reach locations that are hard to reach by car. Therefore, they are called HEMSs, Helicopter Emergency Medical Services. If, on the contrary, the location of the accident cannot be reached by helicopter or if the weather conditions are insufficient, the HEMSs go to the accident by car (Landelijk Netwerk Acute Zorg, n.d.-e). This happens in 24% of the MMT dispatches. The helicopters are mainly used for the transportation of the team and the equipment. Only in 7% of the cases that a HEMS comes to the scene, it is used to transport the patient to the hospital (Landelijk Netwerk Acute Zorg, 2015).

The permanently ready MMTs are the HEMSs that are operated by the MTCs of Amsterdam, Groningen, Nijmegen, and Rotterdam. These MMTs can depart within 2 minutes during the day and 5 minutes at night, after they are dispatched (Radboud UMC Mobiel Medisch Team, n.d.). Additionally, two ground-based MMTs are located in Enschede and Utrecht. These are not permanently ready but can be utilized after a short preparation time in case more than ten patients are expected in an accident (Instituut Fysieke Veiligheid, 2021). Furthermore, in the regions near the Dutch border, the Dutch HEMSs collaborate with the German and Belgian ones to be able to reach those areas more quickly. The German helicopter that is stationed in Rheine is used for accidents in a large part of the Dutch region Overijssel and some smaller parts of the regions Drente and Gelderland. Additionally, the German helicopter from Würselen is used for accidents in the soutern part of the Dutch region Limburg (Landelijk Netwerk Acute Zorg, n.d.-e). These two HEMSs can only be used during the daytime (ADAC Luftrettung, n.d.-a, n.d.-b). To ensure collaboration between the four Dutch HEMSs, they are all represented in the National Network of MMT Care (LNMZ, Dutch: Landelijk Netwerk MMT-Zorg) which facilitates the synchronisation of their procedures and provides recommendations to the LNAZ (Landelijk Netwerk Acute Zorg, n.d.-b).

2.3.4. Ambulance dispatching centres

The stakeholders that coordinate the dispatch of ambulances and MMTs are the regional ambulance dispatching centres. These centres answer the emergency calls and decide whether to dispatch an ambulance and possibly an MMT. Additionally, if ambulance staff at the scene asks for the assistance of an MMT, the ambulance dispatching centres take care of this. The regional ambulance dispatching centres cannot all dispatch the MMTs themselves but will request the ambulance dispatching centres of the regions that have an MMT to do so (Venticare, n.d.).

2.3.5. Other stakeholders

Apart from the stakeholders that take care of the patient, other stakeholders are related to the trauma care system as well. One of these stakeholders is the government, which legislates for an affordable and qualitatively good healthcare system. Especially the Ministry of Health, Welfare and Sport is involved in this. This ministry also initiated the concentration of trauma care. Related governing bodies are the Dutch Healthcare Authority (NZa, Dutch: Nederlandse Zorgautoriteit) and the National Health Care Institute (ZIN, Dutch: Zorginstituut Nederland), which have similar objectives and conduct research to give recommendations to the Ministry of Health, Welfare and Sport. Additionally, they set rules regarding maximum tariffs and monitor health insurers and healthcare providers (Nederlandse Zorgautoriteit, n.d.; Zorginstituut Nederland, n.d.).

Other research and advisory bodies are the bodies related to the LNAZ. For instance, the National Committee Trauma surgery (LBTC, Dutch: Landelijke Beraadsgroep Traumachirurgie), which provides recommendations on the medical aspects of trauma care, and the National Network of MMT Care (LNMZ, Dutch: Landelijk Netwerk MMT-Zorg). Further, the parties that are concerned with the National Trauma Register are stakeholders as well. They manage the quality of the trauma data and report on this data (Landelijk Netwerk Acute Zorg, n.d.-b).

2.4. The emergency care process

The stakeholders all aim for providing the patients with the right care at the right moment and in the right place. To do this, they all have their own role in the emergency care process. To show these roles, as well as the collaboration between the stakeholders, we now describe the emergency care process in which we focus on the prehospital care.

When an accident occurs, a bystander or the patient calls the emergency number 112. The emergency control room operator forwards the call to the right regional ambulance dispatching centre. The operator at this centre estimates the severity of the injury and the degree of urgency based on the information the caller tells him. If needed, he dispatches an ambulance. If it is very urgent, the operator classifies this dispatch as an A1 dispatch. In that case, the ambulance drives at high speed to arrive at the scene within 15 minutes. If it is less urgent, the operator classifies the dispatch as an A2 dispatch and the ambulance aims for reaching the scene within 30 minutes. In that case, the ambulance does not use sirens (Veiligheidsregio Gelderland-Zuid, n.d.). The time between the emergency call and the departure of an EMS is called the 'dispatch time'. In some cases, the operator also dispatches an MMT. This for instance happens if the injury is very complex or severe, if the ambulance cannot reach the severely injured patient in time or if the accident is of a hazardous type, such as drowning or a fall from a height. If the dispatching centre operator decides to dispatch an MMT, this is called a primary dispatch. When no MMT is dispatched, the ambulance staff may decide to ask for the assistance of an MMT when they arrive at the scene. This is called a secondary dispatch (Christiaans et al., 2013).

If a HEMS is dispatched, it will fly to either a location near the scene or it will meet the ambulance with the patient halfway at a so-called 'rendezvous' location. If it flies to a location near the scene, it takes some time to get from the landing location to the scene. We call this time 'post-landing time'. When arrived at the scene, the ambulance and/or MMT staff assesses the injuries and provides the needed first aid. Furthermore, they assess to which hospital type they should bring the patient. This can be a level I, II, or III hospital. After performing the first aid, the ambulance, or occasionally the helicopter, transports the patient to the hospital. If an MMT was collaborating, the physician of the MMT can stay with the patient during the transportation. In that case, the helicopter also flies to the hospital to pick up the MMT physician. At the same time the patient is transported, an emergency team in the hospital prepares for the arrival of the patient. When the patient arrives, the ambulance or MMT staff hand the patient over to the hospital's emergency team. This team performs further examination and treatment and the ambulance and MMTs are again available for new dispatches (Landelijk Netwerk Acute Zorg, n.d.-c).

2.5. Conclusion

In 1998, the Dutch Ministry of Health, Welfare and Sport started the concentration of the trauma care. Currently, there are thirteen MTCs which meet high standards regarding the quality of care they are able to provide. Before a patient reaches such an MTC or another hospital, there is a prehospital process. This process starts with the emergency control room receiving an emergency call. Upon that call, an ambulance, and possibly also an MMT, is dispatched. Most of the time the dispatched MMT is one of the permanently ready helicopter MMTs (HEMSs) of which there are four in the Netherlands. In some regions, a Belgian or German HEMS is used instead. When the EMSs arrive at the scene, they provide care and decide to which hospital they will transport the patient. Most frequently, this transportation is done by ambulance, but it can also be performed by helicopter. In both cases, if an MMT is at the scene, the MMT physician can accompany the patient during transportation. When the patient is handed over to the hospital's emergency team, the EMSs are available for new dispatches.

3. RELATED LITERATURE

In this chapter, we show which studies are already performed in the field of positioning healthcare facilities and EMS stations. First, we review studies that position healthcare facilities in an isolated way. Second, we elaborate on studies that position them simultaneously with EMS stations. Finally, we present studies that investigated the difference in transportation times between ambulances and helicopters.

3.1. Positioning healthcare facilities

Much research is performed on the positioning of healthcare facilities. The studies aim at determining how many healthcare facilities need to be established, and where they need to be placed. These results are useful in many contexts, not only for improving the normal healthcare system, but also for establishing temporary facilities for humanitarian aid or COVID care (Hassan et al., 2021; Loree & Aros-Vera, 2018; Oksuz & Satoglu, 2020) or for locating emergency care facilities (Ishii & Lee, 2013; Mohri et al., 2020; Pacheco et al., 2008). The objectives of most of the developed models are to minimise the costs for creating and maintaining the facilities and/or to minimise the costs for transportation of patients and/or to maximise the coverage, which is the fraction of the patients that can reach a healthcare facility within a certain time or distance. The latter is often achieved by solving a maximal covering location problem (MCLP), which was introduced by Church and ReVelle (1974). This model maximises the number of patients that are covered by locating a fixed number of facilities.

3.1.1. Extensions to traditional facility location models

Over the past decades, many studies continued to build on the MCLP model of Church and ReVelle (1974). Daskin (1983) adapted the model to include a so-called 'busy probability', which is the probability that a facility or vehicle is already busy or not operational and thus cannot cover a patient. Hereby, he addresses the limitation of the MCLP in that it assumes all facilities or EMSs are always available. Goldberg and Paz (1991) add to this maximum expected covering location problem (MEXCLP) by addressing another limitation of the MCLP, namely that it fails to consider the stochasticity of the response times of the EMSs. They do this by using coverage probabilities, reflecting the probability that the response time is below a certain limit. Goldberg and Paz solve their model using pairwise interchange heuristics. Ingolfsson et al. (2008) also use busy and coverage probabilities, but instead of equal probabilities for all stations, they use station-specific busy probabilities. Additionally, they show that incorporating the stochasticity of pre-trip delays is important. Furthermore, in contrast to the model of Goldberg and Paz, their model is solvable without needing to use heuristics. Erkut et al. (2009) compared the adapted models that implemented either busy probabilities or coverage probabilities or both, as well as the model of Ingolfsson. Erkut et al. show that this last model performs best while needing only a short computational time. They suggest that it could possibly be improved by for example a pairwise exchange method.

Another limitation of the MCLP that could be addressed by using coverage probabilities is that in real-life, coverage is often not a boolean variable. Demirtas (2016) addresses this in her study on the positioning of automatic external defibrillators (AEDs). A patient is not simply covered or not covered by an AED, because although a patient is covered, the distance does still matter. Coverage probabilities can be used to deal with this partial coverage. Additionally, in her study, Demirtas distinguished between three scenarios. In the first scenario, multiple bystanders went to search for an AED. In the second and third scenarios, only one bystander would search for an AED and that bystander would either find the covering AED that was the furthest away or the closest to the patient. By using this scenario-based approach, Dermitas dealt with the uncertainty regarding bystanders' behaviour. Metrot et al. (2019) also applied the MCLP to AED positioning, but they used real-time distances, considering the expected traffic intensities during various times of the day.

Li et al. (2018) used an MCLP as well, but they combined it with the Double Standard Model (DSM) of Gendreau et al. (1997). The DSM maximises the number of locations that are covered by at least two ambulances, given that all patients can be reached within a certain time and that a predetermined fraction of the patients can be reached within a shorter predetermined time. Li et al. combined the MCLP and the DSM and included busy probabilities. Next to uncertainty in the availability and response times of facilities or EMSs, also the benefit of opening a facility can be uncertain. Coco et al. (2018) deal with this uncertainty by combining the MCLP with a min-max regret objective. Using this objective, they aim to minimise the maximal regret, in which regret is the difference between the chosen solution and the optimal solution for a certain scenario that reflects a realisation of the benefits per opened facility. Further, several studies dealt with multi-objective MCLPs. Mrkela and Stanimirovic (2020) created a bi-objective model to maximise the weighted sum of the covered demand, in which the weights are determined by the preference of the patients, and to minimise the uncovered demand. They solve this model using three multi-objective evolutionary algorithms to obtain a Pareto-optimal front. Atta et al. (2021) solve their bi-objective model using a Pareto-based multi-objective harmony search algorithm and Ibarra-Rojas et al. (2020) solve their multi-objective MCLP by assigning weights to the several objectives using the Linear Best Worst method. Another difference between the model of Ibarra-Rojas et al. and the traditional MCLP is that Ibarra-Rojas et al. allow for two types of coverage. Patients can either be within the coverage area of the hospital or the hospital can be within the mobility radius of the patients.

3.1.2. Specific contexts

To apply mathematical models to specific situations, it is important to consider the particular circumstances of the situations. For instance, Lauree et al. (2018) wanted demand after a humanitarian disaster not to be covered by only one facility, but by multiple facilities. This way, human suffering could be reduced, even though the costs might be higher. Using a heuristic that randomly opens facilities and uses a swapping operation to improve the solution, they created possible solutions to their mixed-integer nonlinear problem. Then, they chose to open the facilities that were opened in all the best solutions and repeated the process for the remaining facilities. This way, they determined which facilities should be opened. Another study that addressed locating healthcare facilities after a humanitarian disaster, is the study of Oksuz and Satoglu (2020). In their stochastic two-stage model, they took into account the probable damage to roads and facilities after the disaster. Additionally, they distinguished between several levels of injury to use the scarce resources as efficiently as possible. They did this by including a constraint limiting the distance that patients with the highest priority level need to travel. Vaishnav et al. (2019) took this one step further and did not only distinguish between levels of injury but also included the tendency to undertriage or overtriage traumatic injuries. They did this by making assumptions on prehospital time limits below which the EMS staff would choose to send a multitrauma patient to an MTC and another trauma patient to a hospital that is not an MTC. This is a relevant topic considering the 90% norm in the Dutch trauma care system.

3.1.3. Long-term situations

Other studies focussed on long-term instead of temporary situations and included a prediction of future demand. Ouyang et al. (2020) did this to determine the location of healthcare facilities to minimise costs. Additionally, they analysed several scenarios. In the first scenario, patients would always go to the nearest healthcare facility, whereas in the third scenario, patients could always go to all healthcare facilities that were within reach. The second scenario was a mixed one, currently, patients could go to all facilities within reach and only in the future, they would only go to the nearest one. Another study that took into account future demand, is the study of Meskarian et al. (2017). They estimated the demand for the next three to five years but did not treat different periods differently. However, they chose to compare two scenarios for choosing locations. In the first scenario, they could only choose currently existing facilities and in the second scenario, they could also choose other locations. They solved the problem by using a greedy algorithm, which keeps adding the locations with the highest coverage of unmet demand until all demand is met.

3.1.4. Other focal points

Whereas most studies aim for cost minimisation or coverage maximisation, Pourrezaie-Khaligh et al. (2022) and Tavakkoli-Moghaddam et al. (2019) added social objectives to these goals. Pourrezaie-Khaligh et al. aimed for equity regarding the accessibility of care and Tavakkoli-Moghaddam et al. pursued maximising the social impact of the facilities, for instance by creating jobs. Pacheco et al. (2008) had an alternative objective as well. They used the maximal covering location problem, but instead of maximising the coverage or minimising the number of not-covered patients, they adapted the model to minimise the permanent negative effects of a diabetic coma. So, they did not just count the covered and not-covered patients but took into account the time it took to reach the hospital and the resulting risk of permanent negative effects.

Additional considerations were implemented by Ye and Kim (2016), who took into account the capacity of the facilities and used real distances instead of the often used Euclidean ones. Furthermore, Song et al. (2021) considered that children and elderly people prefer to visit a hospital nearby, whereas other people are willing to travel a little further.

3.1.5. Research gap

Most of the studies on the positioning of healthcare facilities focus mainly on the geographical distances to determine whether a facility covers the demand. However, in the case of trauma care, patients usually need to be transported to the hospital by ambulance or helicopter. Therefore, it is important to take the locations, capacity and busyness of these transportation modes into account as well. Erkut et al. (2009) already showed the relevance of including capacity and occupation in the model. Furthermore, for instance, using helicopters to transport patients could possibly contribute to achieving a similar coverage with fewer MTCs (Vaishnav et al., 2019). We review the literature on the simultaneous positioning of healthcare facilities and these transportation modes in the next section. Additionally, apart from the studies of Oksuz and Satoglu (2020), and Vaishnav et al. (2019), the studies mentioned above did not take into account different injury severities, whereas this is important in trauma care. For, multitrauma patients need to be managed differently than patients that are only slightly injured.

3.2. Simultaneous positioning of healthcare facilities and EMS stations

To establish a healthcare network in which all patients have the best possible access to healthcare considering the available resources, it is important to align the positioning of the healthcare facilities with the positioning of the EMS stations. Therefore, simultaneous positioning of healthcare facilities and EMS stations is important. Cho et al. (2014) also mention this in their study on maximising the coverage of trauma care. To address the simultaneous positioning, they create a mixed-integer nonlinear programming (MINLP) model which they solve by using various relaxations and restrictions. Their objective is to position MTCs and HEMS stations simultaneously to maximise the number of patients that are transported without delay while assuming that the ambulance capacity is unlimited. To determine the delay, they include the busyness of the HEMSs in the model and whereas other studies do this by introducing busyness as a parameter, Cho et al. include it as a variable, because it depends on the positioning of the MTCs and HEMS stations. Next to solving the MINLP model, they use a simulation model to evaluate the performance of its results taking into account real-time decision-making regarding the choice of transporting the patient by ambulance or helicopter. A more recent study by Mousavi et al. (2021) addresses the simultaneous positioning of healthcare facilities and HEMS stations as well, but instead of maximising the coverage, they aim at minimising the costs, the transfer times, and the waiting times at the MTC. To measure the performance of their model regarding the third objective, they use a simulation model to train an artificial neural network. Just as Cho et al., they assume the ambulance capacity is infinite. This is an assumption that we cannot make in our current study on the Dutch trauma system because we want to predict the effect that reducing the number of MTCs has on the busyness of the ambulances. So, we need to consider the capacity of the EMSs.

3.2.1. Humanitarian disasters

Three other studies that are performed on the topic of simultaneous positioning of healthcare facilities and EMS stations are performed in the context of humanitarian disasters. In two of these studies, the questions are where to locate temporary on-site healthcare facilities and which helicopters and ambulances to use to transport the patients to the temporary or general hospitals. Sun, Wang, Zang, et al. (2021) do this to minimise the increase in the ISS, whereas Sun, Wang, and Xue (2021) aim to minimise the total ISS as well as the total costs. The situations of both studies differ from the trauma care system, because during humanitarian disasters EMSs are not only used to care for patients and transport them, but also to deliver emergency supplies to the disaster area. Another difference between the use of the EMSs in the two humanitarian disaster models and the trauma care system is that Sun, Wang, Zang, et al. assume that severely injured patients are always transported by helicopter and always go to a general clinic, whereas less severely injured patients are transported to an on-site clinic by an ambulance. Additionally, they assume that each vehicle transports patients from only one demand location, whereas in trauma care, vehicles can serve various locations. Further, Sun, Wang, and Xue assume that all patients are first transported to an on-site clinic by helicopter. If needed, they can thereafter be transported to a general hospital by ambulance. This differs from trauma care, because in trauma care there are fewer patients at the same accidence site and transportation by helicopter is not common in the Netherlands.

The third study that is related to healthcare after humanitarian disasters is performed by Wang et al. (2020). They do not consider the use of helicopters but solely determine the number and positioning of ambulance stations and ambulances. They do not do this simultaneously with determining the locations of healthcare facilities, but suggest adding healthcare facilities in areas where the waiting time for the ambulances is long. Further, they assume that each demand location can only be served by one ambulance team.

3.2.2. Compensate for the closing of a healthcare facility

A final study that addresses the dependency between the locations of healthcare facilities and EMS stations is the study of Andersson et al. (2020). They examine how the effects of closing a local healthcare facility can be compensated by using an additional ambulance and possibly also an additional ambulance station. They evaluate the time it takes an ambulance to reach the patient and the time it takes to bring the patient to the nearest healthcare facility. They conclude that in their Norwegian case, just adding an ambulance does not solve the longer times. However, adding both an ambulance and an ambulance station does. That solution results in a little longer time to the nearest healthcare facility, compared to the old situation, but it also slightly reduces the time to reach the patient.

3.2.3. Research gap

Having reviewed this literature, we conclude that there exist some studies that address the topic of simultaneously locating healthcare facilities and EMS stations, but the literature on this topic is limited and in most studies, the study-specific assumptions and contexts differ considerably from the Dutch trauma care system. Additionally, to the best of our knowledge, no studies are performed that, while maximising the coverage, included several transportation modes (e.g., ambulances and HEMSs) of which one is prefered over the other.

3.3. Patient transportation modes

When determining appropriate locations for ambulance and helicopter stations, it is also relevant to have some indications on when it is appropriate to dispatch an ambulance and when a helicopter can be more beneficial. This decision should be made based on medical and time considerations. In this report, we limit ourselves to the latter. Nonetheless, we believe it is good to shortly mention that several studies studied the combination of medical and time considerations. Using historical data, most of them found that transportation times were longer when a helicopter instead of an ambulance was used for transportation. This might be caused by the patients that were transported by helicopter being more severely injured and therefore needing more prehospital care (Aiolfi et al., 2018; Brown et al., 2010; Buchanan et al., 2016; Carr et al., 2006; Stowell et al., 2019). Another cause of the longer transportation times might be that the helicopter is used more often when the distance to the hospital is larger (Stowell et al., 2019). Whether the longer transportation times have a negative medical result is debated. Some studies suggest that, even though the helicopter's transport times are longer, the medical results are better (Aiolfi et al., 2018; Brown et al., 2010; Buchanan et al., 2016; Kim et al., 2015; Nasser & Khouli, 2020). Others did not find differences in the medical results (Butler et al., 2010; Chappell et al., 2002).

3.3.1. Guidelines based on distance

While reviewing the studies that primarily focussed on the time and distance differences between transport by ambulance or by helicopter, we found that not many studies have been performed on this topic. However, the studies that are performed did give some indications for which transportation mode to use when. Using historical data, Diaz et al. (2005) evaluated the time between receiving the emergency call and delivering the patient to the hospital. When the distance from the scene to the hospital was less than 10 miles, which corresponds to 16 kilometres, ambulances were the quickest option. When the distances were bigger than 10 miles, the fastest option was to dispatch a helicopter at the same time as the ambulance, which is always dispatched, and transport the patient by helicopter. In some cases, the helicopter is only dispatched after the ambulance arrived at the scene and requested a helicopter dispatch. In these cases, transporting the patient by helicopter was only quicker when the distance from the scene to the hospital was greater than 45 miles (72 kilometres). In this study, medical considerations, such as just dispatching a HEMS to be able to provide emergency care at the scene, were not considered. Additionally, the distance from the HEMS station to the scene was not included. Therefore, the generalisability to the Netherlands is limited, because the distances between the station and the scene are significant as in the Netherlands we only have a few HEMS stations.

Stowell et al. (2019) found different bounds for the usage of ambulances and helicopters. Just as Diaz et al. (2005), they used historical data to evaluate the time between the emergency call and the delivery of the patient to the hospital. However, they observed that the helicopter was faster if the distance from the hospital to the scene was more than 35 kilometres. Additionally, they mentioned that, compared to the ambulance, the helicopter was used more often if the patient was severely injured or if the accident site was poorly accessible.

3.3.2. Usage of geographic information systems

While most researchers used historical data on helicopter and ambulance transports, a few authors exploited geographic information systems (GISs) to estimate this data. The advantage of using GIS data is that you can compare the two transportation modes without the conclusions being biased by for example the differences in severity of the injuries. Jang et al. (2021) used historical data on military medical helicopter transports and used a GIS to predict the time it would have taken an ambulance to transport the same patients. They concluded that transportation by helicopter is faster and that the time savings increase when the distance to the hospital increases. Widener et al. (2015) also applied GIS data, but they used it for both helicopter and ambulance transports. They suggest that using GIS data can assist dispatchers to decide which transportation mode to dispatch.

3.3.3. Research gap

The literature on logistical guidelines on when to use an ambulance for patient transport and when to use a helicopter is very limited. Additionally, the conclusions are varying, which suggests that they are situation-dependent. Therefore, we cannot copy them to the situation in the Netherlands which we are focussing on in our current study. Furthermore, a limitation of the studies mentioned above is that the guidelines they provide on when to use a helicopter instead of an ambulance are averages, whereas, next to the distance to the hospital, the location of the accident scene also impacts which transportation mode is quicker. For, if an ambulance can reach the accident scene via highways, it can reach the scene faster than if it should drive the same distance via smaller roads. Therefore, in our study, we include GIS data per origin and destination pair instead of using averages.

3.4. Conclusion and our study

3.4.1. Summary of the literature

Much research is performed on the positioning of healthcare facilities, out of which a small part of the studies combined this with the positioning of EMS stations. When the objective for the positioning of healthcare facilities is to maximise the coverage, this is often achieved by solving an MCLP. To make the model more realistic, busy probabilities and coverage probabilities could be added to reflect that the EMSs are not always available and that the response times are stochastic. Additionally, when the modelled processes were not fully predictable, some studies used scenarios and when the positioning of EMS stations was part of the study, several studies included a simulation model to determine the waiting times at the hospital or to include a real-time decision-making process.

3.4.2. Research gap

When determining the coverage, most studies mainly focus on the geographical distances, ignoring the capacity and busyness of the transportation modes. Furthermore, although one study included an approximation of a real-time decision-making process to decide which transportation mode to use, to the best of our knowledge no such studies are performed in which one transportation mode is prefered over the other. Additionally, we found only a few studies that considered different injury severities, whereas in the trauma system, multitrauma patients need to be managed differently than other patients. Furthermore, the literature on logistical guidelines as to which transportation mode to use for which distance is limited and context-dependent and the studies that used historical or GIS data to find these guidelines did provide average guidelines, whereas, in reality, which transportation mode is best, does not only differ per distance, but per origin-destination pair.

3.4.3. Our study

Considering what we described above, we choose to use an MCLP to determine which combinations of opened MTCs result in the best coverage. In this MCLP, we consider that the use of ambulances for patient transport is preferred over the use of helicopters. We do not have data on the busyness of the EMSs, so we do not use busy probabilities in the model. However, we evaluate the output of the MCLP using a simulation model in which we can simulate the busyness of the EMSs and the stochasticity of the prehospital times. Additionally, in the simulation model, we take into account that multitrauma patients should be managed differently than other patients and we use several scenarios to approximate the real-time decision processes regarding the transportation mode to use and the hospital to go to.

4. MATHEMATICAL COVERING MODEL

In this chapter, we formulate a mathematical model based on the maximal covering location problem. This model determines which MTCs should be opened to maximise the coverage given that you know how many MTCs you want to open, while minimising the fraction of patients that are transported by helicopter.

4.1. Assumptions and simplifications

The assumptions and simplifications that we use to build the model are among others related to the locations and capacity of MTCs and EMSs and the use of MMTs.

4.1.1. Locations and capacity

1. The locations of the HEMS and ambulance stations are fixed and all open.
2. All open MTCs, HEMS stations and ambulance stations have infinite capacity.

Statement 1 reflects our decision that locating EMS stations is out of the scope of this study. The reason we use Statement 2 is that we assume that when we reduce the number of MTCs, the capacity of the open MTCs can be increased. However, we do not have data on the possible size of this increase. Regarding the EMS stations, the capacity depends on their busyness, which is stochastic and depends on the opened MTCs. Therefore, we assume infinite capacity in our mathematical model and include the stochasticity in our next model.

4.1.2. MMTs

3. HEMSs only use their helicopter, not their bus.
4. We exclude the ground-based MMTs.
5. We exclude the Belgian HEMS.
6. The German HEMSs can only be used during the daytime.

Regarding the MMTs, we use several simplifications. First, we exclude the possibility for HEMSs to use their bus. The reason for this is that the primary transportation mode of the HEMS is the helicopter (76% in 2015) (Landelijk Netwerk Acute Zorg, 2015). Additionally, the use of the bus would hardly change the coverage, because they perform quite similar to ambulances. We also exclude the ground-based MMTs, because they are only used in case of large accidents with more than ten patients (Instituut Fysieke Veiligheid, 2021). The third simplification regarding the MMTs is that we exclude the Belgian HEMS, because in reality it is only used for a small part of the Netherlands, i.e., Zeeuws-Vlaanderen (Landelijk Netwerk Acute Zorg, n.d.-e). Finally, we take into account that German HEMSs can only be used during the daytime, due to a lack of night vision equipment (ADAC Luftrettung, n.d.-a, n.d.-b).

4.1.3. Other

7. All parameters are deterministic.
8. All multitrauma patients are transported directly to an MTC.
9. Average dispatch times are equal for all RAV regions.
10. Driving times are equal during all times of the day.
11. The number of patients as a fraction of the population size of a postcode is equal for all postcodes in a RAV region.

12. The fraction of multitrauma patients relative to all patients is equal for all postcodes.
13. Each patient belongs to a separate accident.
14. Coverage by ambulance is prefered over coverage by helicopter.

In our model, we assume that all parameters are deterministic. Additionally, we assume that multitrauma patients are transported directly to an MTC because we do not consider operational decisions, while we focus on maximising the number of patients that could be covered by a certain set of MTCs. Additionally, as represented in Statement 9, we assume that the average dispatch times are equal for all RAV regions because the average dispatch times of all RAV regions differ less than one minute from the national average and the distribution of which RAV region has a higher or lower dispatch time than the others differs per year (Ambulancezorg Nederland, 2020, 2021c). Further, because of a lack of data, we assume that driving times are equal during all times of the day. We expect that this is reasonable because the distances are relatively small and often ambulances get priority. Regarding the number of patients, we need to apply Statements 11 and 12, because we could not obtain more granular data. Additionally, we assume that each patient belongs to a separate accident. In reality, in for instance car accidents, it is likely that there are multiple patients in one accident. However, we do not have data on the number of patients that are dispatched per accident. Therefore, we use Statement 13. Finally, we assume that coverage by ambulance is prefered over coverage by helicopter, because most of the time, patients are transported by ambulance.

4.2. Notation

4.2.1. Sets

The definitions of the sets are given below. The main sets are the locations of the MTCs, ambulance and HEMS stations and the accidents. Additionally, we use a set of time periods. The time period can either be 'day' or 'night', in which 'day' is from 7 AM to 7 PM and 'night' is from 7 PM to 7 AM. These time periods are relevant because the dispatch, flight and landing times of the HEMSs differ per time period.

$MTCs$	The MTCs	with index m
$AmbuStations$	The ambulance stations	with index a
$HEMSStations$	The HEMS stations	with index h
$Postcodes$	The four-digit postcodes in the Netherlands	with index i
$PatientPcs$	The four-digit postcodes in the Netherlands with a nonzero population size	with index p
$RAVs$	The RAV regions in the Netherlands	with index r
$TimePeriod$	Part of the day ('day' or 'night')	with index t

4.2.2. Parameters

In our model, we use several parameters. These are the following:

n	Number of MTCs to open
w	Weight of the first term in the objective function
$\lambda_{p,t}$	Number of multitrauma patients at postcode p during time period t
$s^A_{p,m,a}$	$\begin{cases} 1, \text{ if accidents at postcode } p \text{ can be covered by MTC } m \text{ and ambulance station } a \\ 0, \text{ otherwise} \end{cases}$

$s^H_{p,m,h,t}$ $\begin{cases} 1, \text{ if accidents at postcode } p \text{ can be covered by MTC } m \text{ and HEMS station } h \text{ during time period } t \\ 0, \text{ otherwise} \end{cases}$

$BigM$ A big, positive number

First, we let n represent the number of MTCs to open and w represent the weight that is put on the first term of the objective function. Second, let $\lambda_{p,t}$, be the number of multitrauma patients at postcode p during time period t. When the values of this parameter are not given, we can approximate them. To do this, we need some additional parameters:

q^{multi}	Fraction of the patients that are multitrauma patients
q^T_t	Fraction of the accidents that occur during time period t
λ^R_r	Number of ambulance dispatches in RAV region r
k^R_r	Population size of RAV region r
k^P_p	Population size of postcode p
R_p	RAV region to which postcode p belongs

We denote q^{multi} as the fraction of the patients that are multitrauma patients, and q^T_t as the fraction of the accidents that occur during time period t. Additionally, we denote λ^R_r as the number of ambulance dispatches in RAV region r, k^R_r as the population size of RAV region r, k^P_p as the population size of postcode p, and R_p as the RAV region to which postcode p belongs. Using these parameters, we calculate the number of trauma patients at postcode p by weighing the number of multitrauma patients in the RAV region the postcode belongs to by the fraction of the population of the RAV region that lives at postcode p. This is done in equation [1].

$$\lambda_{p,t} = q^{multi} \cdot q^T_t \cdot \lambda^R_r \cdot \frac{k^P_p}{k^R_{R_p}} \qquad \forall(p,t) \quad [1]$$

Third, we use $s^A_{p,m,a}$ and $s^H_{p,m,h,t}$ which indicate whether postcode p can be covered by MTC m and ambulance station a or HEMS station h. For the coverage by HEMS stations, this also depends on the time period t. A postcode p can be covered by MTC m and ambulance station a if a patient can be transported from postcode p to MTC m with an ambulance of station a within the maximum allowable prehospital time, given that the MTC and station are open. Similar reasoning holds for the coverage by MTC m and HEMS station h. This means that $s^A_{p,m,a}$ and $s^H_{p,m,h,t}$ equal 1 if the expected prehospital time is smaller or equal to the maximum allowable prehospital time. This is represented in formulas [2] and [3].

$$s^A_{p,m,a} = \begin{cases} 1, \text{ if } T^A_{p,m,a} \le T^{max} \\ 0, \text{ otherwise} \end{cases} \qquad \forall(p,m,a) \quad [2]$$

$$s^H_{p,m,h,t} = \begin{cases} 1, \text{ if } T^H_{p,m,h,t} \le T^{max} \\ 0, \text{ otherwise} \end{cases} \qquad \forall(p,m,h,t) \quad [3]$$

In these formulas, we define the expected prehospital time and the maximal allowable prehospital time as follows:

$T^A_{p,m,a}$ Expected prehospital time (minutes) in case of transport of a patient from postcode p by an ambulance of station a to MTC m

$T^{H}_{p,m,h,t}$ Expected prehospital time (minutes) in case of transport of a patient from postcode p by a helicopter of station h to MTC m during time period t

T^{max} Maximum allowable prehospital time (minutes)

We calculate the expected prehospital times by summing the elements of the prehospital times. We now first define these elements. In all cases, we use T^{S}, which denotes the expected on-scene time of a vehicle. In case of transportation by ambulance, we additionally use the expected dispatch time T^{CA}, and the expected driving time $T^{DA}_{i,j}$ from postcode i to postcode j. In case of transportation by helicopter, we use the expected dispatch time T^{CH}_{t}, the expected flight time $T^{FH}_{i,j,t}$ from postcode i to postcode j, the expected landing time T^{LH}_{t}, and the expected post-landing time T^{PLH}_{t} during time period t. Using these parameters, we apply formulas [4] and [5] to calculate the expected prehospital times.

$$T^{A}_{p,m,a} = T^{CA} + T^{DA}_{a,p} + T^{S} + T^{DA}_{p,m} \qquad \forall (p,m,a) \quad [4]$$

$$T^{H}_{p,m,h,t} = T^{CH}_{t} + T^{FH}_{h,p,t} \cdot 60 + 2 \cdot T^{LH}_{t} + T^{PLH}_{t} + T^{S} + T^{FH}_{p,m,t} \cdot 60 \qquad \forall (p,m,h,t) \quad [5]$$

In our model, the flight time $T^{FH}_{i,j,t}$, in hours, follows the flight time model of Zwakhals et al. (2008). Using historic data on HEMS flights, Zwakhals et al. found that an exponential relationship exists between the distance and the speed of a helicopter. This relationship is shown in formula [6a]. F^{1}_{t} and F^{2}_{t} are parameters that Zwakhals et al. estimated using historic data. Parameter F^{2}_{t} can be interpreted as a delay before acceleration, while parameter F^{1}_{t} is a scaling factor. In their model, Zwakhals et al. set a minimum speed of 30 km/h and a maximum speed of 220 km/h. Additionally, in the original formula, the plus sign in the operator was a minus sign, but the results of Zwakhals et al. reflected that they actually used the formula as shown here. Therefore, we use this formulation. To use it in formula [5], where we need the flight time given a certain distance, we rewrite formula [6a] to derive formula [6b]. The derivation can be found in Appendix A.

$$d_{i,j} = e^{\frac{Speed + F^{2}_{t}}{F^{1}_{t}}} \text{ with } 30 \leq Speed \leq 220 \quad [6a]$$

$$T^{FH}_{i,j,t} = \frac{d_{i,j}}{\min\left(220, \max\left(30, F^{1}_{t} \cdot \ln\left(d_{i,j}\right) - F^{2}_{t}\right)\right)} \quad [6b]$$

4.2.3. Variables

The variables below are determined by the model.

$$M_m = \begin{cases} 1, \text{ if MTC } m \text{ is open} \\ 0, \text{ otherwise} \end{cases}$$

$$X^{A}_{p,m} = \begin{cases} 1, \text{ if an ambulance is assigned to cover postcode } p \text{ by bringing the patients to MTC } m \\ 0, \text{ otherwise} \end{cases}$$

$$X^{H}_{p,m,t} = \begin{cases} 1, \text{ if a HEMS is assigned to cover postcode } p \text{ during time period } t \text{ by bringing the patients to MTC } m \\ 0, \text{ otherwise} \end{cases}$$

$Y_{p,t}$ = Auxiliary variable

4.3. The model

The model we use to determine which MTCs to open is based on the maximal covering location problem of Church and ReVelle (1974).

$$\text{Maximise } w \cdot \sum_p \sum_t \lambda_{p,t} \sum_m (X^A_{p,m} + X^H_{p,m,t}) - (1-w) \cdot \sum_p \sum_t \lambda_{p,t} \sum_m X^H_{p,m,t} \qquad [7]$$

$$\text{S.t.} \quad \sum_m (X^A_{p,m} + X^H_{p,m,t}) \leq 1 \qquad \forall(p,t) \qquad [8]$$

$$X^A_{p,m} \leq M_m \cdot \sum_a s^A_{p,m,a} \qquad \forall(p,m) \qquad [9a]$$

$$X^H_{p,m,t} \leq M_m \cdot \sum_h s^H_{p,m,h,t} \qquad \forall(p,m,t) \qquad [9b]$$

$$\sum_m M_m = n \qquad [10]$$

$$\sum_m X^A_{p,m} + \sum_m \sum_h M_m \cdot s^H_{p,m,h,t} \leq BigM \cdot Y_{p,t} \qquad \forall(p,t) \qquad [11a]$$

$$1 - \sum_m (X^A_{p,m} + X^H_{p,m,t}) \leq BigM \cdot (1 - Y_{p,t}) \qquad \forall(p,t) \qquad [11b]$$

$$M_m, X^A_{p,m}, X^H_{p,m,t}, Y_{p,t} \in \{0,1\} \qquad \forall(m,p,t) \qquad [12]$$

The objective [7] is the weighted sum of two terms. The objective of the first term is to maximise the number of multitrauma patients that are covered. The objective of the second term is to minimise the number of transportations by helicopter. The objective is subject to several constraints. First, [8] states that each postcode in which accidents occur is assigned to at most one MTC. The reason for this is that we want to maximise the number of postcodes that are covered. Therefore, in our model, it does not matter how many MTCs cover the postcode. Church and ReVelle (1974) use a similar constraint, but they introduce an additional auxiliary binary variable representing whether or not a postcode is covered. However, in our study, we do not need to store information on *which* MTC covers a postcode. We just need to know *if* a postcode is covered. So, we can limit the number of MTCs that are assigned to covering a postcode to 1, although more MTCs might be able to cover the postcode. Therefore, we use constraint [8] and do not need the additional variable.

Second, [9a,9b] state that a postcode can only be assigned to an MTC if the MTC is open and at least one of the EMSs can realise a prehospital time of at most T^{max}. In the original MCLP, Church and ReVelle (1974) use subsets that only contain the facilities that can cover a postcode and apply the other constraints only to these subsets. Therefore, they do not include constraints [9a,9b]. This approach could also be applied to our model if the computation time should be reduced. Third, [10] ensures that the right number of MTCs are opened. This constraint is also included in the model of Church and ReVelle because in MCLPs the number of facilities to open is always fixed. Fourth, [11a, 11b] prevent the model from making the operational decision of not dispatching a HEMS when it is the only transportation mode that covers a patient. This is an extension to the original MCLP. The reason for these constraints is that the model is a tactical model. Therefore, operational decisions should be prevented. If only a HEMS can cover postcode p during time period t, then [11a] forces $Y_{p,t}$ to get a value of 1 and therefore [11b] assigns a HEMS to the postcode. Finally, [12] are the sign constraints. There is no constraint regarding meeting the minimum volume norm because that involves real-life decision-making. Therefore, we evaluate the norms later using simulation.

4.4. Conclusion

In this chapter, we formulated a binary linear programming model to determine which combination of MTCs should be opened to maximise the coverage and minimise the transportation by helicopter given the number of MTCs to open. This model is based on the MCLP of Church and ReVelle (1974), but we created a multi-objective version in which we use two possible transportation modes in which one is prefered over the other. Additionally, if the least prefered option is the only transportation mode which can cover a postcode, the constraints prevent the model from making the operational decision not to cover that postcode, because in reality, you will also always cover a patient if it is possible, independent of the transportation mode you need to use.

5. RESULTS OF THE MATHEMATICAL MODEL

In this chapter, we apply the mathematical model to the Dutch trauma care system, present the results and show which MTCs the model suggests opening.

5.1. The Dutch case

We apply the mathematical model to the trauma care system of the Netherlands. For the locations of the hospitals, MTCs and ambulance and HEMS stations, we used the four-digit postcodes, which are publically available (Kommer et al., 2020; Landelijk Netwerk Acute Zorg, n.d.-d; Zorginstituut Nederland, 2021). These postcodes have an average area of 10.2 km^2. For the locations of the accidents, we used all four-digit postcodes with a nonzero population, except for six postcodes, accommodating 0.03% of the Dutch population, of which the RAV region was not known. To be able to calculate the straight-line distances between the centres of the four-digit postcodes, we used the PDOK Geocoder spreadsheet (Baltussen & Tadema, 2021) to get the coordinates of the centres of the postcodes following the Dutch national grid system (Dutch: Rijksdriehoek coördinaten). Further, to acquire the estimated real driving times, we use the impedance matrix of Object Vision (2019), which is publically available under a Creative Common licence (n.d.). This matrix gives the driving times for cars between postcodes i and j. In Appendix B, we explain how we adapt these driving times to apply them to ambulances instead of normal cars.

Next to this data, we use data about the other elements of the prehospital time, as well as data on the number of accidents. Regarding the ambulance data and the number of ambulance dispatches, we use the data of 2019 (Ambulancezorg Nederland, 2021c), because that is the most recent data in which the COVID-19 pandemic plays no part. Additionally, we obtain the data on the prehospital times using HEMSs from a report by Zwakhals et al. (2008).

Furthermore, data on the population size per postcode is obtained from Statistics Netherlands (Centraal Bureau voor de Statistiek, 2021). Finally, we calculated the fraction of the patients that are multitrauma patients by dividing the number of multitrauma patients in 2019 (Zorginstituut Nederland, 2020) by the number of ambulance dispatches in that year.

5.2. The MTCs to open

The mathematical model has two Key Performance Indicators (KPIs). The first one is the coverage of the multitrauma patients. The second one is the fraction of patients that are transported by helicopter. In this section, the values of these KPIs are shown for the scenarios of opening one to thirteen MTCs when w ranges from 0.1 to 1. We exclude $w = 0$, because that would result in a very small coverage. Additionally, in presenting the fraction of patients that are transported by helicopter, we exclude $w = 1$, because in that case the fraction of patients that are transported by helicopter is not minimised and therefore, it does not give meaningful results regarding the use of the helicopter.

We run the model using a maximum allowable prehospital time of 60 minutes. In **Figure 4**, we see that, approximately up to opening nine MTCs, the more open MTCs, the higher the coverage. Opening more than nine MTCs hardly increases the coverage further. In **Figure 5**, we see that the fewer MTCs are opened, the stronger the fraction of patients that are transported by helicopter depends on w. This is because, when opening few MTCs, the choice of the MTCs to open strongly affects which HEMS stations can cover patients. Therefore, the model selects different MTCs for low than for high values of w. Whereas, when many MTCs are opened, the exact choice of MTCs to open has a smaller impact on the fraction of patients that can be covered by a HEMS station, because all HEMS stations can already be used. The reason the fraction of patients that are transported by helicopter is not always decreasing if an additional MTC is added is that adding more MTCs can result in opening an MTC which is relatively close to a HEMS station. In that case, that HEMS station can increase the coverage because the HEMS can reach the new MTC more quickly than other MTCs and can therefore cover a larger range of postcodes. So, in that case, the transportation by helicopter increases.

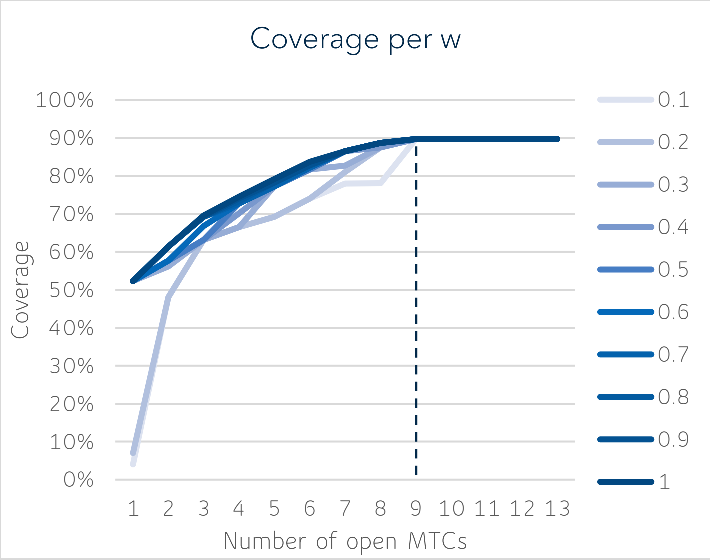


Figure 4 Coverage for w from 0.1 to 1

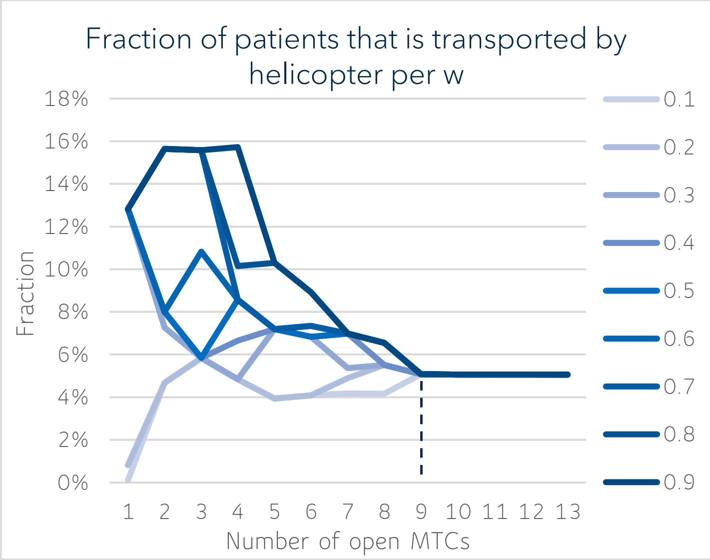


Figure 5 Fraction of patients that are transported by helicopter for w from 0.1 to 0.9

The objective is to maximise the coverage and minimise the fraction of patients that are transported by helicopter. Therefore, opening at least nine MTCs seems to be the best choice. Hence, we further investigate the performance of this option in Chapter 6, where we include stochasticity and consider finite capacity. Additionally, we investigate the options of opening eight or thirteen MTCs, to compare the option of opening nine MTCs to these options. The option to open thirteen MTCs is relevant because it is the best performing and current option. The option to open eight MTCs is relevant because, for most values of w, it scores at most 2 percent points worse on both KPIs when comparing it to opening nine MTCs. So, the coverage is only slightly worse, while the increase in the fraction of patients that are transported by helicopter is not unreasonably high.

5.3. Performance maps

In this section, we present the results for the options of opening eight, nine or thirteen MTCs in more detail. For most numbers of MTCs to open, there are several best-performing combinations, depending on w. For instance, when opening eight MTCs, for a low value of w ($w = 0.1$), one option performs best, whereas for $0.2 \leq w \leq 0.4$ and for $0.5 \leq w \leq 1$ other combinations are the best-performing options. However, when opening eight MTCs, using $w = 0.1$ results in a significantly worse coverage than when using $w \geq 0.2$, so we exclude the option of $w = 0.1$, because coverage is the main objective.

In **Figure 6**, we see that the difference in coverage between opening nine or thirteen MTCs is indeed negligible, as **Figure 4** and **Figure 5** already indicated. The difference in coverage between these two options and the alternative of opening eight MTCs with $0.5 \leq w < 1$ is also small, but when opening only eight MTCs, the transportation by helicopter increases. This can be decreased when lowering $\boldsymbol{w}$. However, that causes an additional uncovered spot in the regions Twente and the Achterhoek.

5.4. Conclusion

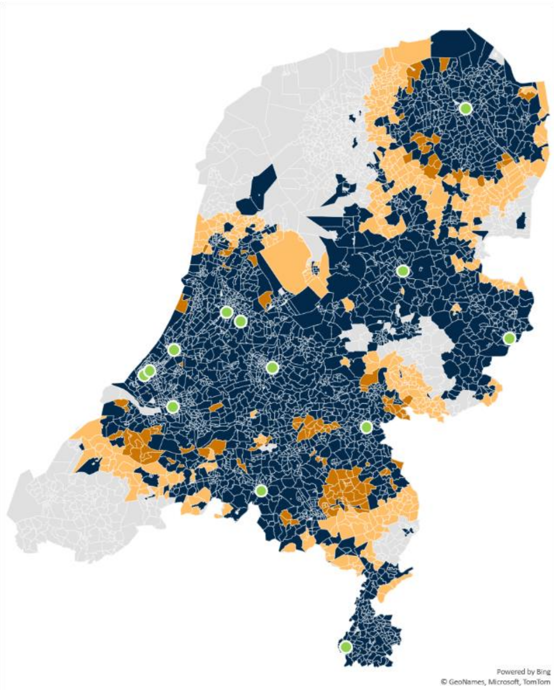
To summarise, when we apply the mathematical model to our case of the Dutch trauma care system, we find that opening nine to twelve MTCs seems to perform as good as the current situation with thirteen MTCs. This holds for both the coverage and the fraction of patients that are transported by helicopter. Therefore, in the next chapters, we further investigate the options to open nine and thirteen MTCs. Additionally, we further investigate the option to open eight MTCs, because it performs only slightly worse than opening nine MTCs. For opening eight MTCs, we have two possible combinations of MTCs, because the best combination depends on the relative weight that is put on maximising the coverage on the one hand and on minimising the transportation by helicopter on the other hand.

Covered by ambulance
Covered by HEMS (day and night)
Covered by HEMS (only day)
Uncovered
Open MTC
Closed MTC

Fraction of patients that are covered: 87.6%
Fraction of patients that are transported by HEMS: 5.5%
(a)

Fraction of patients that are covered: 88.7%
Fraction of patients that are transported by HEMS: 6.5%
(b)

Fraction of patients that are covered: 89.7%
Fraction of patients that are transported by HEMS: 5.1%
(c)



Fraction of patients that are covered: 89.8%
Fraction of patients that are transported by HEMS: 5.1%
(d)

Figure 6 Coverage when opening 8 MTCs with $0.2 \leq w \leq 0.4$ (a), or $0.5 \leq w \leq 1$ (b), or 9 MTCs (c), or 13 MTCs (d)

6. SIMULATION MODEL

Using the mathematical model, we found several combinations of open MTCs that possibly perform well. In this chapter, we explain our approach to further investigate these options by evaluating the effects of the busyness of EMSs and the stochasticity of the patient arrivals and the prehospital times on the performance of the trauma care system. We state our assumptions, define the KPIs, and explain the scenarios that we evaluate. More information about the logic we implemented in the simulation model and the way the model generates patients can be found in Appendices F and G.

6.1. The model choice

In our mathematical model, we assumed all variables to be deterministic. For instance, we assumed the on-scene times to be equal to the average on-scene times. Additionally, we did not yet consider the busyness of the EMSs. To make the model more realistic, we include stochasticity, so uncertainty, in the model. There are several options to do this. First, we could use a stochastic mathematical model. Such a model incorporates stochasticity by including several scenarios that occur with certain probabilities. A second option is to use a Discrete Event Simulation model, which evaluates a solution and includes stochasticity by for instance generating an on-scene time per patient from a certain probability distribution.

In our case, there are several stochastic variables and the values of these variables differ per patient, and per ambulance, etc. If we would use a stochastic mathematical model, we would need to combine these variables into aggregated variables such as (ambulance-station-specific) busy probabilities as introduced by Daskin (1983) and Ingolfsson et al. (2008) and (ambulance station and patient-specific) coverage probabilities as used by Goldberg and Paz (1991). The reason for this is that creating scenarios for all possible combinations and including these in a stochastic model is unworkable because, even if we would evaluate only three values per variable, there would be at least billions of scenarios. However, aggregating variables takes away some variability. Therefore, Discrete Event Simulation is a more suitable method. This way, we can evaluate the options that we chose based on the mathematical model. Additionally, we can use simulation to perform a sensitivity analysis of our results. For these reasons, we choose to use Discrete Event Simulation, to which we will from now on refer with 'simulation'.

6.2. Assumptions and simplifications

For the simulation model, we again need assumptions and simplifications. The assumptions and simplifications that remain unchanged in the simulation model are:

6.2.1. Locations and capacity

1. The locations of the ambulance stations are fixed and all open.
2. All open MTCs have infinite capacity.

6.2.2. MMTs

3. HEMSs only use their helicopter, not their bus.
4. We exclude the ground-based MMTs.
5. We exclude the Belgian HEMS.
6. The German HEMSs can only be used during the daytime.

6.2.3. Other

7. Average dispatch times are equal for all RAV regions.
8. Average driving times are equal during all times of the day.
9. The number of patients as a fraction of the population size of a postcode is equal for all postcodes in a RAV region.
10. The fraction of multitrauma patients relative to all patients is equal for all postcodes.
11. Each patient belongs to a separate accident.

The adapted and additional assumptions and simplifications in the stochastic model are related to the patients, their urgency levels, the EMSs and the choices of the transportation mode to use and the hospital to transport the patient to. These assumptions and simplifications are the following:

6.2.4. Patients

12. The arrival of patients follows a Poisson distribution, which is equal for all days of the week.
13. Severely burned patients are not managed differently than other (multi)trauma patients.

Regarding the arrival of patients, we assume that it follows a Poisson distribution, because we do not have data on the real arrivals. We base the Poisson distribution on the total number of patients per year. Additionally, we use the simplification to not manage burned patients differently than other (multi)trauma patients. In reality, severely burned patients should go to a burn centre instead of an MTC to get specialist care for their burns. However, yearly, only 900 severely burned patients are treated in these centres (Nederlandse Brandwonden Stichting, n.d.). This is less than 0.1% of the emergency calls. Therefore, we do not manage them differently.

6.2.5. Urgency levels

14. Multitrauma patients always get assigned an A1 urgency level.
15. HEMSs are only dispatched in case of an accident with an A1 urgency level.
16. We treat planned ambulance dispatches as A2 dispatches.

As we do not have data on the correlation between the urgency levels and the patient types, we make some assumptions. We assume that multitrauma patients are always assigned an A1 urgency level, because they are severely injured. Additionally, HEMSs are only used for patients with an A1 urgency level, because in those cases speed is important and additional care might be needed.

Furthermore, next to A1 and A2 dispatches, ambulances are also used for, so-called 'B dispatches', which are planned dispatches to for instance transport a patient from one hospital to another. The B dispatches are responsible for 24% of the ambulance dispatches, so they do impact the availability of the ambulances (Ambulancezorg Nederland, 2021c). Therefore, we need to include them in our model. However, we do not have much data on these dispatches. Therefore, in our model, we replace them with A2 dispatches, because both A2 and B dispatches have a relatively low urgency level.

6.2.6. EMSs in general

17. HEMS and ambulance stations have finite capacities.
18. EMSs are occupied from the moment they are dispatched to the moment they either deliver the patient to the hospital or, in case they do not transport the patient, depart from the scene. While they are occupied, they are not reassigned to another patient.

19. To calculate the location of a moving EMS, we assume a straight-line path between the previous location and the destination.
20. If at an emergency call no EMS is available, the patient is not treated.
21. All dispatches are primary dispatches.

In contrast to our mathematical model, our simulation model takes into account the stochastic capacity of the HEMS and ambulance stations. Namely, in our simulation model, EMSs are occupied as long as they are travelling to, treating or transporting a patient. This way, the model is a more realistic representation of reality. When an EMS is travelling back to its station, it can be reassigned to a new patient. We will then approximate its location at the moment by assuming it follows a straight-line path between its previous location and original destination. Using its real location is too complex because then we would need to use the real road maps. Furthermore, we assume that if at an emergency call no EMS is available, the patient is dropped from the system. In reality, an ambulance would be dispatched as soon as it becomes available or the patient would be brought to the hospital by a bystander, but we exclude these possibilities to reduce the complexity of the model. However, to measure the performance of the possible solutions, we do store the number of patients that are dropped.

A final assumption on EMSs in general is that we assume that all dispatches are primary dispatches. In reality, additional EMSs can be dispatched if an arrived EMS asks for it, but due to a lack of data, we do not include this possibility.

6.2.7. Ambulances

22. Ambulances are evenly distributed over the stations per RAV.
23. The number of available ambulances per day equals the average of the number of available ambulances over a week.
24. To almost every accident, exactly one ambulance is dispatched, as long as there are available ambulances. This is independent of whether a HEMS is dispatched. Only when resuscitation is needed, two ambulances are dispatched.

We assume that the ambulances are evenly distributed over the stations per RAV, because we do not have this data at a more granular level than per RAV. Additionally, we assume the number of available ambulances equals the average of the number of available ambulances over a week. In reality, the number of available ambulances differs per day of the week. During the weekend, for instance, the number of available ambulances is smaller (Kommer et al., 2021). However, because we assume that the number of patients is equal for all days of the week (Assumption 12), we also average the available ambulance capacity.

Further, we assume that in most cases exactly one ambulance is dispatched. In reality, in some cases, multiple ambulances might be dispatched to make sure that medical assistance is provided as quickly as possible. This for instance happens in case of a resuscitation or in case it is expected that the accident has many and/or severely injured patients. We know that yearly, 8000 out-of-hospital resuscitations take place (Hartstichting, n.d.). However, we do not have data on the number of ambulances that are dispatched in cases other than resuscitation and we assume that each patient belongs to a separate accident. Therefore, we assume only one ambulance is dispatched per accident, except for when resuscitation is needed.

6.2.8. HEMSs

25. Which HEMS stations are open depends on the scenario.
26. If a HEMS is dispatched, it meets the ambulance at the accident scene.
27. If next to an ambulance, a HEMS is demanded for medical assistance, the HEMS is only dispatched if it can reach the scene within 30 minutes.

In the mathematical model, we assumed all six current HEMS locations (four Dutch and two German locations) were open. However, to improve the timely accessibility of the eastern part of the Netherlands, the hospitals of Nijmegen, Groningen, Zwolle and Enschede presented a plan to open an additional HEMS station at Teuge Airport (Brouwer, 2022). We evaluate the impact of this additional station by running the simulation both with and without opening a HEMS station at Teuge Airport. Furthermore, the German HEMSs may be relocated in the future, meaning that they cannot cover the eastern part of the Netherlands anymore (Brouwer, 2022). To consider this, we run the simulation both with and without the German HEMSs. We create several scenarios to evaluate the different combinations of open HEMS stations.

Next to this, in all scenarios, we assume that a dispatched HEMS always goes to the accident scene to meet the ambulance. So, we exclude the possibility of meeting the ambulance at a rendezvous location because we have no data on rendezvous locations, and it would make the model too complex. Additionally, we assume that, if a HEMS is demanded for medical assistance, so not just to save time, the HEMS is only dispatched if it can reach the scene within 30 minutes, because then it can have added value (Hoogervorst, 2006).

6.2.9. Destination and transportation mode

28. The medical staff at the scene decides to which hospital they transport the patients.
29. If a HEMS is at the scene, multitrauma patients are always transported to the closest MTC.
30. If a HEMS is at the scene with the purpose to provide specialist care, the MMT physician always accompanies the patient to the hospital.

In the mathematical model, we assumed that all multitrauma patients are transported directly to an MTC. However, in reality, the medical staff at the scene decides where to bring the patient. This means they can also decide to bring a multitrauma patient to a closer hospital that is not an MTC. This for instance happens if this saves time for the patient, or if there are many patients in the region and the ambulance should quickly go to a new patient. We use several scenarios to incorporate this choice in the model. If a HEMS is at the scene, we assume the staff always chooses to transport the patient to the closest MTC, because in that case it is likely that the patient is severely injured. After all, otherwise a HEMS would most probably not have been dispatched. Also in reality, when a HEMS is at the scene, most of the time the patient is brought to an MTC (R. de Wit, personal communication, 2022). Additionally, if the HEMS is at the scene with the purpose to provide specialist care, we assume the MMT physician always accompanies the patient during transportation, independent of the used transportation mode, because it is likely that he wants to be able to provide care during transportation as well. So, also in cases in which the patient is transported by ambulance, the helicopter that was at the scene flies to the hospital to pick up the MMT physician.

6.3. Stochastic variables

In this section, we explain for which variables we include stochasticity and which probability distributions we use for this. Before doing this, we introduce an additional set:

$DispatchLevel$ Dispatch level of an ambulance ('A1' or 'A2') with index l

The durations of the prehospital activities are stochastic, but we only know their average values. To approximate the stochasticity, we use normal distributions around the average values of the data of 2019 with standard deviations of 5%. We do this for dispatch, landing and post-landing times of HEMSs during time period t as well as for the dispatch times of ambulances with dispatch level l and for the duration of the on-scene treatment. For the driving and flight times, we also use normal distributions with standard deviations of 5%, but for these variables, we use the origin-destination pair dependent averages. An explanation of the choice of these probability distributions can be found in Appendix D.

6.4. Key Performance Indicators

To evaluate the performance of the possible solutions, we compare the solutions using several Key Performance Indicators (KPIs), which we explain in this section.

Fraction of multitrauma patients that are in the hospital on time

To measure the coverage of the possible solutions, which we want to maximise in this study, we store the fraction of multitrauma patients that arrive at the hospital within a prehospital time which is within T^{max}.

Fraction of multitrauma patients that are transported directly to an MTC

To measure the effect of a possible solution on the performance on the 90% norm, we measure the fraction of multitrauma patients that are transported directly to an MTC.

Fraction of patients that are transported by helicopter

Next to maximising the coverage of the multitrauma patients, we want to minimise the number of patients that are transported by helicopter. The latter is measured in this KPI.

Average prehospital time

To provide the best care for the patients, it is important to minimise the prehospital time. Therefore, this KPI calculates the average prehospital time of all treated patients.

Average prehospital time for multitrauma patients

In our study, we focus on the multitrauma patients, therefore, we use a separate indicator showing the average prehospital time for the treated multitrauma patients.

Fraction of MMT requests for specialist care that are not satisfied

The HEMSs are not just meant to reduce the prehospital time, but they also serve to provide specialist care at the scene. However, if the use of HEMSs to transport patients increases, this affects the availability of HEMSs to provide care. Therefore, in this KPI, we measure which fraction of HEMS requests with a medical purpose cannot be satisfied.

Fraction of untreated patients
Of course, in reality, we want to treat all patients. When at an emergency call, no EMS is available, the call operator will dispatch an EMS as soon as it becomes available. However, in our model, if no ambulance is available, the patient is ignored to reduce complexity. Therefore, this indicator calculates the fraction of patients that are not treated.

Busyness of the ambulances
Closing MTCs is likely to cause ambulances to be busier than currently. To check whether the busyness is still acceptable we track the fraction of the time that ambulances are occupied with driving to, treating or transporting a patient.

Busyness of the HEMSs
Closing MTCs is also likely to cause HEMSs to be busier than currently. To check whether the busyness is still acceptable we track the fraction of the time that HEMSs are occupied with flying to, treating or transporting a patient. We only include the Dutch HEMSs in this KPI, because including the German HEMSs would reduce the busyness, because we do not consider their flights to German patients, causing that it would seem that they are less busy than they really are.

6.5. Experiments for validation

In reality, the dispatching centre operator decides whether to dispatch a HEMS. Further, if a HEMS is at the scene, the care providers need to decide which transportation mode to use. Additionally, if no HEMS is at the scene, the ambulance staff needs to decide to which hospital to bring the patient. These decisions are partly based on time considerations and partly on the injury and the needed treatment during transportation. They are not fully predictable. Therefore, to find how to approximate these decision processes best, we evaluate several scenario combinations and compare them to reality to check which scenario combination resembles reality most closely. We then use that scenario combination for our other experiments.

6.5.1. Choice of whether to dispatch a HEMS

When an emergency call comes in, the dispatching centre operator dispatches an ambulance and possibly also a HEMS. Reasons to dispatch a HEMS are that the operator expects that the patient needs specialist care or that the HEMS can reach the scene faster than the ambulance. Regarding the second reason, we use several scenarios to approximate the decision process of the operator. In all scenarios, a HEMS is only dispatched if the ambulance is expected not to be able to reach the scene within the maximum allowable prescene time (15 minutes).

Scenario HDFaster: Only dispatch a HEMS if it is faster than the ambulance
In the first scenario, if the HEMS is expected to reach the scene faster than the ambulance, the operator dispatches the HEMS.

Scenario HD15: Only dispatch a HEMS if it is at least 15 minutes faster than the ambulance
The second scenario increases the required time difference between the arrival of the ambulance and the HEMS. The operator only dispatches a HEMS if it saves at least 15 minutes.

6.5.2. If no HEMS is at the scene: Choice of the hospital to go to

After the treatment at the scene is finished, the medical staff decides which hospital to bring the patient to. If a HEMS is at the scene, we assume they always decide to transport the patient to an MTC. However, if no HEMS is at the scene, the decision process is less predictable. Therefore, we evaluate three scenarios to find the one that approximates the real decision process best.

Scenario Nearest: The patient always goes to the nearest hospital
The first scenario is a scenario in which the patient is always brought to the nearest hospital, independent of whether this is an MTC or not.

Scenario Right: The patient always goes to the right hospital
In the second scenario, the patient is always brought to the right hospital. This means that multitrauma patients are always brought to the nearest MTC and that other trauma patients are always brought to the nearest hospital, independent of whether this is an MTC or not.

Scenario TimeDependent: The destination depends on the prehospital time
The third scenario is in between the first and second scenarios. When at the end of the on-scene treatment the expected prehospital time when transporting the patient to the right hospital is within the maximum allowable prehospital time T^{max}, the patient is transported to the right hospital. Otherwise, the patient is brought to the nearest hospital.

6.5.3. If a HEMS is at the scene: Choice of the mode of transportation

In the mathematical model, patients are only transported by helicopter if the prehospital time in case of transportation by ambulance is longer than T^{max}, while the prehospital time in case of transportation by helicopter is within T^{max}. However, in reality, if the difference in prehospital time is small, the medical staff might still decide to transport the patient by ambulance although T^{max} will be exceeded. The decision of the transportation mode is not fully predictable. Therefore, we evaluate several scenarios. In all scenarios, the patient will be transported by ambulance if that is possible within T^{max}. If that is not possible, the scenarios follow the decision rules below.

Scenario HTFaster: Only transport the patient by helicopter if it saves time
In the first scenario, if the expected prehospital time when transporting the patient by ambulance is too long, and the expected prehospital time when transporting the patient by helicopter is shorter, the patient is transported by helicopter.

Scenario HT15: Only transport the patient by helicopter if it saves at least 15 minutes
Transportation by ambulance has advantages regarding the treatment possibilities during transportation. Additionally, transportation by helicopter is more expensive than transportation by ambulance. Therefore, if the difference in prehospital time is small, transportation by ambulance is preferred. Thus, in the second scenario, the patient is only transported by helicopter if the expected prehospital time of transportation by ambulance is longer than the T^{max} and transportation by helicopter saves at least 15 minutes compared to transportation by ambulance.

Scenario HT30: Only transport the patient by helicopter if it saves at least 30 minutes
The third scenario increases the required time difference between transportation by ambulance and by helicopter. The patient is only transported by helicopter if that saves at least 30 minutes.

6.5.4. Maximum allowable prehospital time

The choices of the hospital to go to and the transportation mode to use depend on T^{max}. As mentioned in Section 1.2.1, the value of T^{max} is subject to research. Currently, in case of an A1 dispatch, the norm is to bring the patient to the MTC within 45 minutes after the emergency call (van Ark, 2020). However, experts agree on a norm of 60 minutes before the start of the treatment in an MTC (Gezondheidsraad, 2020). Therefore, within the scenarios of choosing the hospital to go to and the transportation mode, we use two scenarios for the value of T^{max}. The scenarios are:

Scenario Max45: The maximum allowable prehospital time for A1 dispatches is 45 minutes
Scenario Max60: The maximum allowable prehospital time for A1 dispatches is 60 minutes

6.6. Main experiments

In this section, we define the experiments that we perform. For all stochastic variables, we use probability distributions to generate their values. Next to this, we use scenarios to consider the impact of other uncertain factors that we explain below. For the HEMS stations and MTCs to open, we evaluate all scenario combinations.

6.6.1. HEMS stations to open

As explained in Section 6.2.2, there is a plan to open an additional HEMS station at Teuge Airport and there is a possibility that we cannot use the German HEMSs anymore in the future (Brouwer, 2022). To consider these possibilities, we run the simulation both with and without the German HEMSs and the HEMS station at Teuge Airport. The opening or closing of HEMS stations affects the results of the mathematical model. Therefore, we also run the mathematical model for each of the scenarios to find out which MTCs to open.

Scenario CurrentHEMSs: Do not open a HEMS station at Teuge Airport and use the German HEMSs
This scenario reflects the current situation in which there is no HEMS station at Teuge Airport and we do use the German HEMSs of Rheine and Würselen.

Scenario NoGerman: Do not open a HEMS station at Teuge Airport and do not use the German HEMSs
This scenario neither opens a HEMS station at Teuge Airport nor uses the German HEMSs.

Scenario AddTeuge: Open a HEMS station at Teuge Airport and use the German HEMSs
This scenario adds a fifth Dutch HEMS station at Teuge Airport to the current situation.

Scenario AddTeuge+NoGerman: Open a HEMS station at Teuge Airport and do not use the German HEMSs
This scenario does not use the German HEMSs anymore, but it does open a HEMS station at Teuge Airport.

6.6.2. MTCs to open

Using the mathematical model, we determined that it would be useful to evaluate the options of opening eight, nine or thirteen MTCs. Regarding opening eight MTCs, the mathematical model makes three suggestions, depending on w and on whether or not a HEMS station at Teuge Airport is opened. Therefore, the scenarios that we run regarding the number of MTCs to open are the following:

Scenario 8MTCsLowW: Open the eight MTCs the mathematical model suggests with $0.2 \leq w \leq 0.4$ *and no HEMS station at TeugeAirport*
Scenario 8MTCsHighW: Open the eight MTCs the mathematical model suggests with $0.5 \leq w \leq 1$ *and no HEMS station at TeugeAirport*

Scenario 8MTCsAddTeuge: Open the eight MTCs the mathematical model suggests when using a HEMS station at Teuge Airport
Scenario 9MTCs: Open the nine MTCs the mathematical model suggests
Scenario 13MTCs: Open all thirteen MTCs

Additionally, we run some scenarios that are more similar to the current practice of choosing which MTCs to open. For, in reality, the MTCs are inspected periodically to check whether they meet the requirements to be an MTC. One of these requirements is the minimum volume norm. In the next three scenarios, we only open the MTCs that meet the requirements of being an MTC, so, in this case, the MTCs that meet the minimum volume norm.

Scenario LastYearMTCs: Open the MTCs that met the minimum volume norm last year
In this scenario, we only open the MTCs that met the current minimum volume norm in 2020.

Scenario Last3YearsMTCs: Open the MTCs that met the minimum volume norm in each of the last three years
In this scenario, we only open the MTCs that met the current minimum volume norm during each of the last three years. These hospitals are the same hospitals that met the current minimum volume norm when averaging the volumes of the last three years.

Scenario NextYearMTCs: Open the MTCs that are expected to meet the minimum volume norm next year
For this scenario, we use linear regression to predict the volume per MTC for the year 2021. We open the MTCs that are predicted to meet the volume norm.

6.6.3. Performance on the 90% norm

As explained before, the norm is that 90% of the multitrauma patients should be brought to an MTC. To evaluate the effect that actually meeting the 90% norm has on the busyness of the EMSs, we also run two scenarios in which the 90% norm is more likely to be met. We only run these scenarios for the current situation with 13 MTCs and the currently operational HEMS stations.

Scenario 90%norm: 90% of the multitrauma patients are transported directly to an MTC.
In this scenario, we use the 90% norm as an input instead of output of our simulation model. This means that each multitrauma patient is transported directly to an MTC with a probability of 90%, independent of the location or prehospital time and whether or not a HEMS is at the scene.

Scenario 90%norm+Overtriage: Overtriage the trauma patients to meet the 90% norm
In this scenario, we evaluate a solution that is suggested to improve the performance on the 90% norm. This solution is to overtriage the trauma patients (van Rein et al., 2019). This means that medical staff is motivated to bring trauma patients of which it is not clear that they are multitrauma patients to an MTC to increase the number of multitrauma patients that are brought to an MTC directly. We evaluate the effect of this measure on the busyness of the EMSs by applying Scenario 90%norm and additionally doubling the fraction of the patients that are multitrauma patients, because with an overtriage of 50% an undertriage of 11% could be achieved, meaning that the 90% norm could be approximately met (van Rein et al., 2019).

6.7. Experiments for sensitivity analysis

When the experiments are performed, it is useful to analyse the sensitivity of the solution to changes in the real trauma system. We focus on the sensitivity of the solution to the number of patients. In 2018 and 2019, the number of patients increased by 0.7% and 1.8% respectively. It is also realistic to assume that the number of patients will increase further, because of the ageing population. So, we investigate the impact of a further increase of 2%, 5%, and 10% compared to 2019.

Scenario Plus2%patients: The number of patients increases by 2%
Scenario Plus5%patients: The number of patients increases by 5%
Scenario Plus10%patients: The number of patients increases by 10%

6.8. Conclusion

In this chapter, we presented the experimental design of our simulation model. We explained our assumptions and simplifications, which show that our simulation model includes stochasticity that our mathematical model did not yet cover. Additionally, we defined our KPIs, which we use to evaluate the coverage and the use and busyness of the EMSs. Furthermore, we listed the three phases of our experiments, which are validation, experimentation and sensitivity analysis. In the validation phase, we test how we can approximate the uncertain decision processes of the EMSs to dispatch, the hospital to go to, and the transportation mode to use. In the experimentation phase, we evaluate the performance of several combinations of open MTCs in several situations of open HEMS stations. Additionally, we evaluate the effect of meeting the 90% norm in the current situation. In the sensitivity analysis phase, we evaluate the effect of an increasing number of patients.

7. RESULTS OF THE SIMULATION MODEL

In this chapter, we present the performance of several combinations of opened MTCs when considering the stochasticity and busyness of the EMSs. These performances follow from our simulation model. We also show the results of our sensitivity analysis.

7.1. Warm-up period and run characteristics

Before performing our experiments, we need to determine the warm-up period, run length and number of runs to execute (Appendix H). Using Welch's graphical procedure (Law, 2015), we choose a warm-up period of 1 day, which corresponds to approximately 3700 patients. Additionally, we choose a usable run length which is ten times as long as the warm-up period, so a run length of 11 days. Finally, using the replication/deletion approach with a 95% confidence interval (Law, 2015), we find that performing 3 replications per experiment would result in a confidence interval which is small enough. So, we perform 3 replications per experiment.

7.2. Validation

To ensure that our model correctly approximates the decision processes which are not fully predictable, we first run several combinations of the scenarios that we described in Section 6.5 to find how we could best model the choices of whether to dispatch a HEMS, to which hospital to transport the patient, and which transportation mode to use.

Table 2 Target values for validation

KPI name	Target value for validation	Source
Average prescene time (mm:ss)	12:27	(Ambulancezorg Nederland, 2021c)
Average prehospital time (mm:ss)	Unknown, but 56:00 for trauma patients	(Landelijk Netwerk Acute Zorg, 2020)
Average prehospital time for multitrauma patients (mm:ss)		
Fraction of multitrauma patients of which the prehospital time $\leq T^{max}$	Unknown	
Fraction of multitrauma patients that are transported directly to an MTC	69%	
Fraction of patients for which a HEMS is dispatched	0.7%	(Landelijk Netwerk Acute Zorg, 2015)
Fraction of HEMS dispatches that resulted in transportation by helicopter	3.5%	
Fraction of MMT requests for specialist care that are not satisfied	Unknown	
Fraction of patients that are not treated	0%	-
Busy fraction of ambulances	Max. 60%	(Kommer et al., 2020)
Busy fraction of HEMSs	Unknown	-

7.2.1. Target values

To check which scenarios reflect the real decision processes the best, we need to know the real values of the KPIs in 2019. These values are shown in **Table 2**. As can be seen in the table, the busy fraction of ambulances should be at most 60%. We want to remark that this target value only takes into account A1 and A2 dispatches, whereas our model also includes B dispatches (which we treat as A2 dispatches). Therefore, the busy fraction of the model may be a little above 60%. In the table, we added two variables that are not KPIs, but that we use to validate the model because we know the real data. These are the average prescene time for all patients and the fraction of patients for which a HEMS is dispatched.

7.2.2. Varying the method to choose the hospital to go to

First, we run the scenarios of choosing a hospital to go to with a T^{max} of 60 minutes without varying the other two scenario types. Namely, we expect that the method of choosing the hospital to go to has a big impact while being the least dependent on the other variables compared to the other two variables, because the other two variables both are closely related to the use of HEMSs. While varying the method of choosing the hospital, for dispatching a HEMS we use the scenario that a HEMS is only dispatched if the expected prescene time of the ambulance is too long and the HEMS is expected to reach the scene faster than the ambulance (Scenario HDFaster). For transportation by helicopter, we use the scenario that the helicopter only transports the patient if the ambulance cannot do that within T^{max} and the helicopter is expected to be at least 15 minutes faster than the ambulance (Scenario HT15).

We find that for most KPIs the results are quite similar for all three methods of choosing a hospital. However, the average prehospital time for multitrauma patients and the fraction of multitrauma patients that are transported directly to an MTC strongly differ, which is logical considering that choosing the hospital to transport multitrauma patients to is the main difference between the three scenarios. As can be seen in **Figure 7**, always going to the nearest hospital results in 34% of the multitrauma patients being transported directly to an MTC, always going to the right hospital of course results in 100% of the multitrauma patients going to an MTC and when letting the choice of the hospital be time-dependent, 86% of the patients is brought to an MTC. The target value for this variable is 69%. Therefore, the scenario to let the choice be time-dependent dominates the scenario to always go to the right hospital. Additionally, the performances on this KPI of the options of always going to the nearest or right hospital will not change, when changing the other scenario types, because the choice of the hospital to go to is fixed in these cases. Therefore, we do not further investigate the scenarios of always going to the right or nearest hospital. Instead, we choose to use the scenario of letting the choice of the hospital to go to be time-dependent.

Furthermore, we find that the fraction of patients for which a HEMS is dispatched is 0.5% in all of the three scenarios. This value is relatively close to 0.7% and running the scenario of only dispatching a HEMS if it can arrive at least 15 minutes faster than the ambulance would lower this value, thereby making it less realistic, so we do not evaluate this second scenario.

Additionally, we find that the fraction of HEMS dispatches that resulted in transportation by helicopter varies between 9.3% and 11.8%, which is higher than the target value of 3.5%. So, the next thing we do is reduce that value.

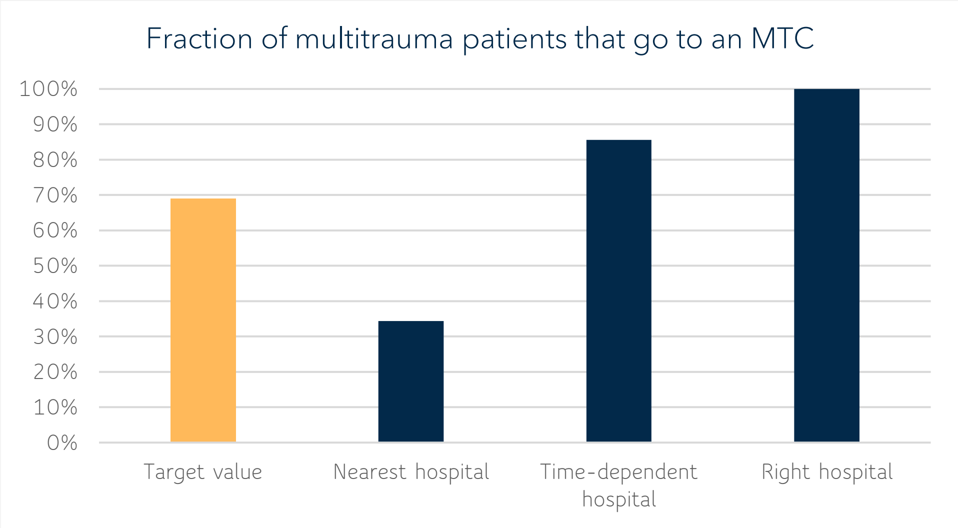


Figure 7 Fraction of multitrauma patients that go to an MTC

7.2.3. Varying the method to choose the transportation mode

To do this, and to let the fraction of multitrauma patients that are transported directly to an MTC get closer to the target value of 69%, we change the scenario of when to transport a patient by helicopter. Instead of transporting by helicopter if it saves at least 15 minutes, we evaluate the scenario in which it should save at least 30 minutes. Running one replication of this scenario shows that it reduces the fraction of multitrauma patients that go to an MTC from 86% to 83% and it reduces the fraction of HEMS dispatches that result in transportation by helicopter from 11.8% to 0.9%. Because the fraction of multitrauma patients that go to an MTC hardly decreased, we change the T^{max} to 45 minutes to further reduce it. Running one replication under this scenario, we find that it reduces the number of multitrauma patients that are transported directly to an MTC to 53%.

To let the scores on the KPIs get even closer to their target values, we use interpolation to create new scenarios of which we expect that the values are closer to the target values. Based on the interpolation, we derive a T^{max} of 49.4 minutes and minimum time savings of 26.4 minutes. To evaluate these new scenarios (i.e., scenarios Max49.4 and HT26.4), and also compare them to the previously run experiments, we run three replications of each of the four combinations of a T^{max} of 60 and 49.4 minutes and minimum time savings of 30 and 26.4 minutes.

In **Table 3**, we see the results of these four experiments on the two KPIs that differ most. We observe that when we look at which results are the closest to the target values, we see that experiment 4 dominates experiments 1 and 3. Additionally, we see that experiments 2 and 4 each perform best at one of the KPIs. However, the difference regarding transportation to an MTC is bigger than the difference in transportation by helicopter. Therefore, we choose to use the scenarios of experiment 4, which is HDFaster+TimeDependent+HT26.4+Max49.4, thus:

- *Only dispatch a HEMS to save time if it is faster than the ambulance.*
- *The destination depends on the prehospital time.*
- *Only transport the patient by helicopter if it saves at least 26.4 minutes.*
- T^{max} *= 49.4 minutes.*

7.2.4. Results of the most realistic scenario combination

The results of this scenario combination in the current situation of open MTCs and HEMS stations are shown in **Table 4**. In this table, the averages and standard deviations (SDs) are shown, as well as the target for the average values. We calculate the SDs of the prescene and prehospital times over the patients, and the other SDs over the days. Next to the results we already saw in **Table 3**, we see that the prehospital time is underestimated and the prescene time is overestimated. We should consider these differing observations when drawing conclusions from the main experiments. Therefore, when drawing conclusions we will do this by comparing results from our model with each other instead of with reality.

Table 3 Results (and differences with the target value) of the scenario combinations that we expect to be the most realistic

	T^{max}	Minimum time transportation by helicopter should save	Fraction of multitrauma patients that are transported directly to an MTC		Fraction of HEMS dispatches that results in transport by helicopter	
1	60 minutes	30 minutes	83%	(+14%)	0.8%	(-2.7%)
2	60 minutes	26.4 minutes	84%	(+15%)	1.2%	(-2.3%)
3	49.4 minutes	30 minutes	60%	(-9%)	0.2%	(-3.3%)
4	49.4 minutes	26.4 minutes	62%	(-7%)	1.0%	(-2.5%)
Target value			69%		3.5%	

Table 4 Results of the most realistic scenario combination in the validation phase

KPI name	Simulation result		Target value for validation
	Average	SD	
Average prescene time (mm:ss)	13:27	06:22	12:27
Average prehospital time (mm:ss)	45:37	12:16	Unknown, but 56:00 for trauma patients
Average prehospital time for multitrauma patients (mm:ss)	42:58	07:46	
Fraction of multitrauma patients with prehospital time ≤ 45 minutes	60%	15%	Unknown
Fraction of multitrauma patients with prehospital time ≤ 60 minutes	97%	4%	
Fraction of multitrauma patients that are transported directly to an MTC	62%	13%	69%
Fraction of patients for which a HEMS is dispatched	0.5%	0.1%	0.7%
Fraction of HEMS dispatches that resulted in transportation by helicopter	1.0%	2.1%	3.5%
Fraction of MMT requests for specialist care that are not satisfied	11.0%	6.7%	Unknown
Fraction of patients that are not treated	0.0%	0.0%	0%
Busy fraction of ambulances	29%	0.2%	Max. 60%
Busy fraction of HEMSs	14%	1.0%	Unknown

Additionally, we find that for most MTCs, the number of multitrauma patients is underestimated. When we correct for the fact that the total number of multitrauma patients that are brought to an MTC is underestimated, we find that the number of multitrauma patients per MTC is still underestimated for part of the MTCs and that it is overestimated for the other MTCs. Therefore, although the number of multitrauma patients that go to an MTC is close to reality, the numbers per

MTC are less valid. Therefore, in the remaining of this report, we present our results and conclusions on a national level. We therefore cannot conclude what the scores of the individual MTCs are regarding the minimum volume norm. However, we expect that these scores increase when reducing the number of MTCs.

7.3. Experimentation

Using the scenario combination described in the previous section (HDFaster+TimeDependent+HT26.4+Max49.4), we use the simulation model to further investigate the scenarios for opening MTCs and HEMS stations. We want to find the best combination of open MTCs and check if this combination also performs well if a HEMS station at Teuge Airport is used and/or if the German HEMSs cannot be used. Additionally, we evaluate the effect meeting the 90% norm has on the busyness of the EMSs.

The mathematical model suggested that opening nine MTCs would perform similar to the current situation with thirteen MTCs. To evaluate to which extent this holds when considering stochasticity and capacity, and to evaluate the performance of other combinations of opened MTCs, we run the following scenarios which we explained in Section 6.6: 8MTCsLowW, 8MTCsHighW, 8MTCsTeuge, 9MTCs, 13MTCs, LastYearMTCs, Last3YearsMTCs, NextYearMTCs. In the latter three scenarios seven, six and eight MTCs are opened, respectively. A table with all run experiments is shown in Appendix I.

We compare the results of the scenarios using a two-tailed paired t-test with a significance level α of 5% to find if the results of the scenarios differ from each other.

7.3.1. Current HEMS stations

First, we evaluate just changing the opened MTCs, while using the currently operational HEMS stations. In **Figure 8** and **Figure 9**, we see the main results of these experiments. In the figures, the average values and the 95% confidence intervals are shown. The values of the other KPIs do not vary much and in all scenarios, all patients are treated.

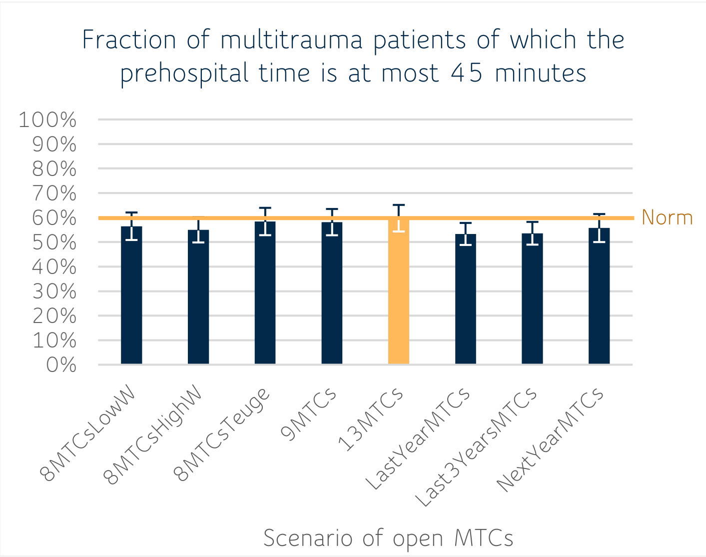


Figure 8 Fraction of multitrauma patients of which the prehospital time is at most 45 minutes

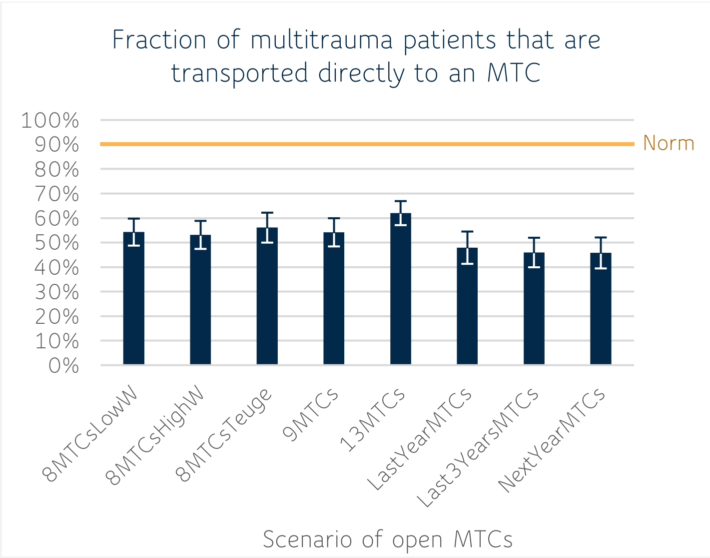


Figure 9 Fraction of multitrauma patients that are transported directly to an MTC

The prehospital time of multitrauma patients
Figure 8 shows the fraction of multitrauma patients of which the prehospital time is at most 45 minutes. We see that this fraction is the highest when opening all 13 MTCs. The difference with the other scenarios is 1 to 6 percent points. Next to scenario 13MTCs, the best-performing options are scenarios 8MTCsTeuge and 9MTCs. The standard deviation is 14 to 15 percent points for all of these three scenarios. The differences between the three scenarios are not statistically different with α = 5%.

In **Figure 8**, we also plotted the norm for this KPI. The norm is that emergency departments are not allowed to close if that reduces the performance on this KPI (Gezondheidsraad, 2020). So, the norm is to meet the current performance, which is the performance under the scenario with 13 MTCs.

The 90% norm
When looking at the performance on the 90% norm, which is the fraction of multitrauma patients that are transported directly to an MTC (**Figure 9**), we find that the situation with 13 MTCs again performs statistically best. Additionally, we find that the scenarios that came out of the mathematical model (scenarios 8MTCsLowW, 8MTCsHighW, 8MTCsTeuge, and 9MTCs), perform statistically better than the scenarios that are based on how the choice of MTCs to open would be made when no mathematical approach would be used (scenarios LastYearMTCs, Last3YearsMTCs, and NextYearMTCs). This is partly because of the smaller number of MTCs in the latter category.

Furthermore, it is remarkable that scenario 8MTCsTeuge seems to perform slightly better than scenario 9MTCs, although, in scenario 9MTCs, one additional MTC is opened. This unexpected difference might be related to scenario 8MTCsTeuge having more HEMS dispatches. This might be because, in scenario 8MTCsTeuge, one additional MTC is closed. So, patients from that region may more often be transported by helicopter and thus go to an MTC more often, because, in our model, we assume helicopters always go to an MTC. However, neither the difference between the performances on the 90% norm nor the difference between the number of patients that are transported by helicopter are statistically significant.

Another remarkable thing is that scenario 8MTCsTeuge seems to perform better than scenarios 8MTCsLowW and 8MTCsHighW, although this difference is not statistically significant with α = 5%. This is remarkable because the latter scenarios outperformed 8MTCsTeuge in our mathematical model when we used the current HEMS stations. This different outcome can be because in the mathematical model the differences between the results were small and including stochasticity and limited capacity, which we do in the simulation model, changes the performances.

Busyness of the EMSs
The busyness of the ambulances hardly differs across the scenarios and the standard deviations of the busyness of the ambulances hardly differ over the days. Namely, the 95% confidence intervals of all scenarios are from 28.7 or 28.8 minutes to 29.1 or 29.2 minutes. This might feel unexpected, but when considering that only 0.3% of the patients are multitrauma patients and should be directly transported to an MTC, the minimal impact on the busyness is logical. The confidence intervals for the busyness of the HEMSs are a bit bigger because the standard deviations within the scenarios are between 2.5 and 4.0 percent points. Additionally, for all scenarios, the busyness of the HEMSs is statistically higher than in the scenario with 13 MTCs. The increase is at most 1.4 percent points.

Scenarios with eight MTCs

There are four scenarios for opening eight MTCs. When looking at **Figure 8** and **Figure 9**, we see that, when looking at the average values of the two presented KPIs, scenarios 8MTCsLowW and 8MTCsTeuge dominate scenarios 8MTCsHighW and NextYearMTCs. Of the scenarios with eight MTCs scenario 8MTCsTeuge performs best when just looking at the average values. When taking a closer look, we find that with α = 5% we can only prove that scenarios 8MTCsLowW, 8MTCsHighW, and 8MTCsTeuge dominate scenario NextYearMTCs on the 90% norm. When we compare the score on this norm between the best scenario with eight MTCs (8MTCsTeuge) and scenario NextYearMTCs, we find that the score on the 90% norm for scenario NextYearMTCs is 7 to 10 percent points lower. There are no further statistical differences between the four scenarios.

7.3.2. The situations with different HEMS stations

In the future, the HEMS stations that can be used could change. For instance, the possibility to use the German HEMSs could be lost and/or a HEMS station at Teuge Airport could be added. We now analyse the effects of these possible changes.

The prehospital time of multitrauma patients

Analysing the fractions of multitrauma patients of which the prehospital time is at most 45 minutes, we observe that the standard deviations are 12 to 18 percent points. Furthermore, we find that in all situations of open HEMS stations, opening all 13 MTCs performs best, although this is only statistically significant for scenario NextYearMTCs in the situation AddTeuge and for all combinations of open MTCs in the situation AddTeuge+NoGerman. Additionally, we see that after scenario 13MTCs, the scenarios 8MTCsLowW, 8MTCsTeuge, and 9MTCs, are among the best-performing scenarios independent of which HEMS stations can be used. When comparing the fraction of multitrauma patients of which the prehospital time is at most 45 minutes in these three scenarios to scenario 13MTCs, we find that in these three scenarios, the fraction is 1 to 3 percent points lower in the situations NoGerman and AddTeuge and 5 to 7 percent points lower in the combined situation AddTeuge+NoGerman.

Several reasons explain why the other scenarios (i.e., 8MTCsHighW, LastYearMTCs, Last3YearsMTCs, and NextYearMTCs) seem to perform worse. For instance, scenarios LastYearMTCs and Last3YearsMTCs open fewer MTCs than the other scenarios, which reduces their coverage.

The 90% norm

When looking at the performance on the 90% norm, we again find that the situation with 13 MTCs statistically performs best and that the combinations of MTCs to open that came out of the mathematical model perform statistically better than the other combinations of open MTCs. Additionally, we find that it seems that under all situations of open HEMS stations, after scenario 13MTCs, scenarios 8MTCsLowW, 8MTCsTeuge, and 9MTCs perform best. However, we cannot find statistical differences between these scenarios, except that under the scenario AddTeuge+NoGerman, scenario 8MTCsLowW is the only one that does not perform statistically worse than scenario 13MTCs. Additionally, we cannot find a statistical difference between these three scenarios and scenario 8MTCsHighW.

Busyness of the EMSs
Which and how many MTCs are open hardly affects the busyness of the ambulances as the 95% confidence intervals within all experiments are still between 28.7 or 28.8 minutes to 29.1 or 29.2 minutes. The busyness of the HEMSs is affected more. Especially the scenarios 8MTCsHighW, LastYearMTCs, Last3YearsMTCs, and NextYearMTCs have statistically busier HEMSs than scenario 13MTCs. For the other scenarios, the difference with scenario 13MTCs is not statistically significant. So, the HEMSs are the least busy in scenarios 8MTCsLowW, 8MTCsTeuge, 9MTCs, and 13MTCs. However, the absolute differences are small. In general, compared to the scenarios with 13 MTCs, the average busyness of the HEMSs for the other combinations of open MTCs increases at most 0.8 to 1.4 percent points, depending on which HEMSs can be used. The standard deviations of the busyness of the HEMSs are between 2.6 and 3.5 percent points.

Scenarios with eight MTCs
When looking at which of the four scenarios of opening eight MTCs performs best with regards to the 90% norm and the fraction of multitrauma patients that reach a hospital within 45 minutes, we see that scenario NextYearMTCs performs the worst on both KPIs, independent of which HEMS stations are opened. Under most combinations of open HEMS stations, this is only statistically significant for the score on the 90% norm. When both the German HEMSs and a HEMS station at Teuge Airport are used, additionally the fraction of multitrauma patients that reach a hospital within 45 minutes is statistically the worst under scenario NextYearMTCs. All in all, we conclude that scenario NextYearMTCs is the worst-performing combination of eight MTCs. When comparing the other three combinations, scenarios 8MTCsLowW and 8MTCsTeuge seem to dominate scenario 8MTCsHighW on the 90% norm. However, this difference is not statistically significant. Also regarding the fraction of multitrauma patients that reach a hospital within 45 minutes, there are no statistical differences between the three scenarios.

Comparison with the current HEMS stations
When we compare the results of the situation in which we use the currently available HEMS stations (e.i., CurrentHEMSs) to the situation in which we cannot use the German HEMSs and/or we add a HEMS station at Teuge Airport (e.i., NoGerman, AddTeuge, and AddTeuge+NoGerman), we find that the average prehospital time for multitrauma patients changes at most half a minute, and the score on the 90% norm as well as the fraction of multitrauma patients that reach the hospital within 45 minutes change at most 4 percent points, although these differences are not statistically significant.

Reasons for these changes are that adding a HEMS station increases the number of HEMS dispatches, which means that more often a HEMS is at the scene. So, patients are more often transported to an MTC because if a HEMS is at the scene, we assume that the patient will be transported to an MTC. Additionally, having an additional HEMS station results in having shorter flight times to accident scenes near the new HEMS station. These factors increase the score on the 90% norm. On the other hand, not being able to use the German HEMSs reduces the performance regarding this norm.

Next to this, when comparing the current HEMS stations to the other combinations of HEMS stations, we find that in the situations AddTeuge and AddTeuge+NoGerman, the busyness of the HEMS statistically reduces. It becomes 2 percent points lower. This is logical because in these scenarios we add Dutch HEMS capacity. Furthermore, the unsatisfied MMT requests for specialist care decrease by 5.2 percent points when a HEMS station at Teuge Airport is added and increase by 3.7 percent points when the German HEMSs cannot be used.

7.3.3. Performance on the 90% norm

To evaluate the effect that actually meeting the 90% norm has on the busyness of the EMSs, we run two scenarios in which the 90% norm is more likely to be met and compare them to the current practice. We only run these scenarios for the current situation with thirteen MTCs and the currently operational HEMSs. The main results are shown in **Figure 10** and **Figure 11**. In the figures, the average values and the 95% confidence intervals are shown.

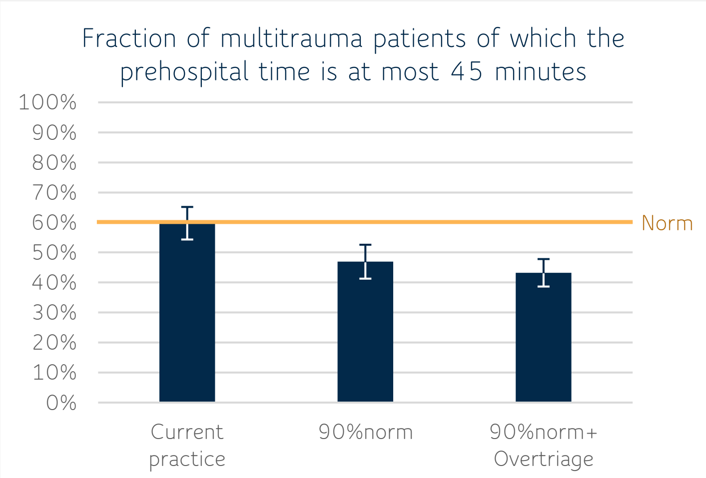


Figure 10 Fraction of multitrauma patients of which the prehospital time is at most 45 minutes

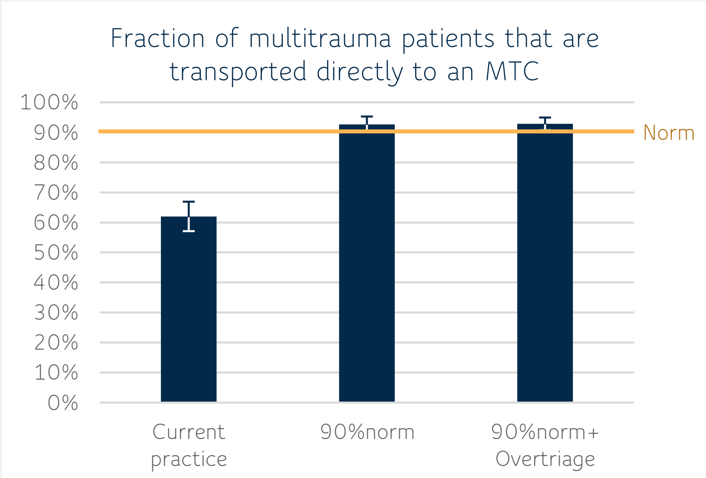


Figure 11 Fraction of multitrauma patients that are transported directly to an MTC

The 90% norm

When forcing the model to transport 90% of the patients to an MTC, we find that 93% of the multitrauma patients go to an MTC and that the 95% confidence interval around this value is small, as can be seen in **Figure 11**.

The prehospital time of multitrauma patients

As can be seen in **Figure 10**, meeting the 90% norm results in a strong decrease in the fraction of multitrauma patients that reach the hospital within 45 minutes. This difference is statistically significant. Additionally, the scenario 90%norm results in a significantly higher fraction than scenario 90%norm+Overtriage, although this difference is smaller (47% versus 43%). The prehospital time for multitrauma patients increases from 43 to 48 or 48.5 minutes for the scenarios 90%norm and 90%norm+Overtriage, respectively. Additionally, the fraction of multitrauma patients that reach the hospital within 60 minutes decreases from 97% to 85% or 84% for the scenarios 90%norm and 90%norm+Overtriage, respectively.

Busyness of the EMSs

The busy fraction of the ambulances hardly increases. This can be explained by the low number of multitrauma patients relative to the total patient population. When the 90% norm is met, our model shows that yearly approximately 1200 additional multitrauma patients are brought to an MTC. This corresponds to 4 patients per day, which hardly affects the busyness of the ambulances.

The busy fraction of the HEMSs increases more. Under the scenario 90%norm, the difference is not statistically significant compared to the current practice, although the average increases from 13.7% to 14.0%. However, the scenario 90%norm+Overtriage has a statistically significant higher busy fraction for the HEMSs, with the average values being 14.9% versus 13.7%. For the scenario

90%norm, the increase is caused by the slightly bigger fraction of the HEMS dispatches that results in transporting the patient by helicopter (1.4% instead of 1.0%). For the scenario 90%norm+Overtriage, the higher busyness is mainly caused by the higher number of patients that are classified as multitrauma patients. Another result of this fictitiously higher number of multitrauma patients is that the fraction of MMT requests for specialist care that are not satisfied seems to increase from 11.0% to 13.7%, although this difference is not statistically significant. In reality, this increase might not happen, because primary MMT dispatches are made based on the severity estimation of the dispatching centre operator, whereas overtriaging is done later by the staff at the scene. In our model, the patient is classified as multitrauma patient from the start, so the number of HEMS dispatches will be overestimated for this scenario.

7.4. Sensitivity analysis

In the previous section, we saw that in most situations, scenarios 8MTCsLowW, 8MTCsTeuge, 9MTCs and 13MTCs perform best. Therefore, we choose these three scenarios as the best scenarios and perform a sensitivity analysis to check if these scenarios also perform well if the number of patients increases by 2%, 5% or 10%. For this sensitivity analysis, we use the current situation regarding the available HEMS stations. A table with all experiments we run to perform the sensitivity analysis can be found in Appendix I.

7.4.1. Comparing the combinations of open MTCs

We find that with all three increases, the option with 13 MTCs still performs best and scenario 8MTCsLowW performs the worst. Of the other two scenarios, which one performs best depends on how much the number of patients increases. With the current number of patients, scenario 8MTCsTeuge performs slightly better than scenario 9MTCs, because on average 2 percent points more multitrauma patients go directly to an MTC, although this difference is not statistically significant. With a 2% increase in the number of patients, scenario 9MTCs performs best on all KPIs except for having more unsatisfied MMT requests for specialist care than scenario 8MTCsTeuge (13.3% versus 11.5%). For instance, the fraction of multitrauma patients that reach the hospital within 45 minutes is 59.4% instead of 55.7% and the score on the 90% norm is 55.2% instead of 53.6%. None of these differences is statistically significant. With a 5% increase, scenario 9MTCs causes statistically more multitrauma patients to go to an MTC than scenario 13MTCs (58% instead of 53%), which comes at a cost of statistically longer prehospital times for multitrauma patients (44.2 instead of 43.3 minutes). With a 10% increase in the number of patients, scenario 9MTCs performs better than scenario 8MTCsTeuge, because 1.2 percent points fewer MMT requests for specialist care are unsatisfied and the busy fraction of the HEMSs is 0.5 percent points lower. However, both of these differences are not statistically significant.

In general, scenario 9MTCs will perform slightly better than scenario 8MTCsTeuge, because the only difference is that in scenario 9MTCs an additional MTC is opened. However, the difference with scenario 8MTCsTeuge is small.

7.4.2. The impact on the KPIs

When analysing the results, for most KPIs we do not find a significant trend in their values if the number of patients increases. However, we do find that the busyness of the ambulances significantly increases with each of the increases in the number of patients. The average busynesses of the ambulances, as well as the 95% confidence intervals of this KPI, which have a width of at most 0.5%, are shown in **Figure 12**. We find that, up to an increase in the number of patients of 10%, for each percent that the number of patients increases, the busyness of the ambulances increases by 0.3 percent points.

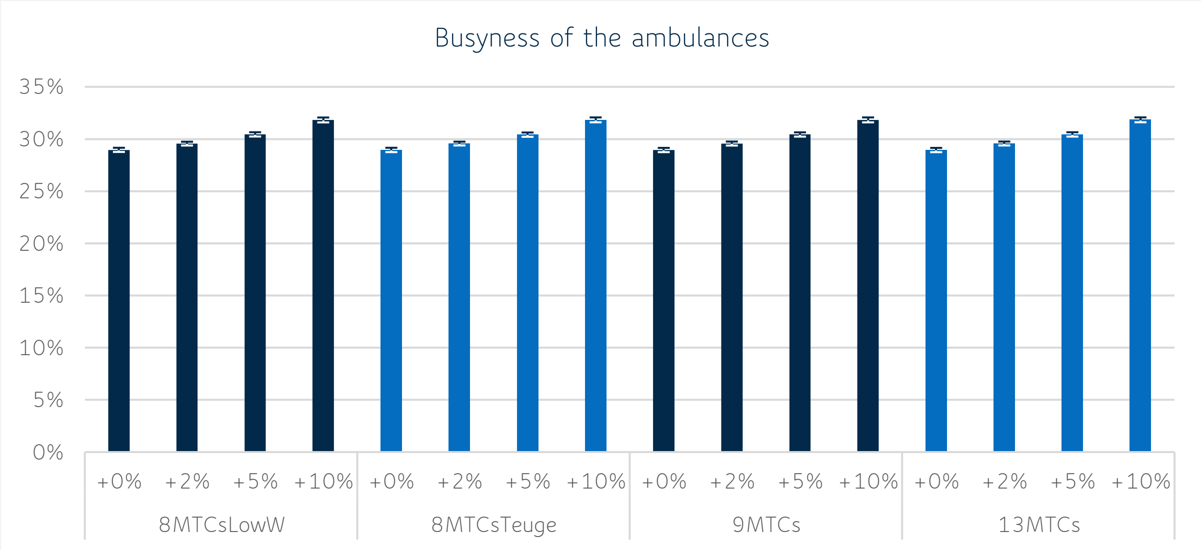


Figure 12 Busyness of the ambulances under four combinations of open MTCs and four increases in the number of patients (+0%, +2%, +5%, +10%)

7.5. Conclusion

In this chapter, we performed three phases of simulations: the validation phase, experimentation phase and sensitivity analysis phase.

7.5.1. Validation phase

In the validation phase, we calibrated the approximations of the real-time decision processes in the model. We found that the following combination of scenarios approximated the results of the real-time decision processes best:

- *Only dispatch a HEMS to save time if it is faster than the ambulance.*
- *The destination of the patient depends on the prehospital time.*
- *Only transport the patient by helicopter if it saves at least 26.4 minutes.*
- T^{max} = *49.4 minutes.*

Comparing the results of this approximation of the decision processes to the reality, we found that the model slightly underestimates the fraction of multitrauma patients that have a prehospital time of at most 45 minutes as well as the fraction of HEMS dispatches that results in transport by helicopter. Additionally, it slightly overestimates the prescene time. Furthermore, at a hospital level, we find that the model overestimates the number of multitrauma patients for some MTCs, whereas for the other MTCs it underestimates this number. So, in presenting the results we focus on a national level.

7.5.2. Experimentation phase

In the experimentation phase, we found that independent of the HEMS stations that can be used, opening all 13 MTCs results in the shortest prehospital times for multitrauma patients and the highest fraction of multitrauma patients going to an MTC. The other three best-performing scenarios are scenarios 8MTCsLowW, 8MTCsTeuge, and 9MTCs. In these scenarios, four or five MTCs are closed, which reduces the performance on the 90% norm by 4 to 9 percent points.

Additionally, we found that the scenarios that are based on how the choice of MTCs to open would be made when no mathematical approach would be used, result in fewer multitrauma patients going to an MTC (90% norm) than when using the scenarios that followed from our mathematical model. This is partly because the latter scenarios open a few more MTCs. When comparing the best combination of eight MTCs according to our mathematical model to the combination of eight MTCs that did not follow from this method, we found that using the mathematical model increases the score on the 90% norm by 7 to 10 percent points.

Furthermore, we found that the main effect of concentrating the trauma care is a significantly lower score on the 90% norm (α = 5%). When comparing the score under the current situation with 13 MTCs to the score of the best combination of 8 MTCs (i.e., 8MTCsLowW or 8MTCsTeuge), we find that the score on the 90% norm reduces by 3 to 8 percent points depending on which HEMS stations are open. Next to the effect on the 90% norm, we find that the fraction of multitrauma patients that reach the hospital within 45 minutes increases. However, only under some combinations of open HEMSs stations, this difference is statistically significant. Additionally, we find that the concentration of trauma care does not strongly increase the busyness of the EMSs. The busyness of the ambulances hardly changes at all and the busyness of the HEMSs increases by at most 2 percent points.

Next to this, forcing the system to meet the 90% norm hardly affects the busyness of the ambulances, but it increases the prehospital time for multitrauma patients by 5 to 5.5 minutes. Therefore, the fraction of multitrauma patients that reach the hospital within 45 or 60 minutes decreases by 12 to 17 percent points. Furthermore, the busyness of the HEMSs increases by 0.3 to 1.2 percent points.

7.5.3. Sensitivity analysis phase

In the sensitivity analysis phase, we found that when the number of patients increases, the scenario with 13 MTCs still performs best. Of the other three scenarios, scenario 9MTCs performs best, because it has one additional open MTC, but the difference with 8MTCsTeuge is small. The main effect of an increasing number of patients is a statistically significant increase in the busyness of the ambulances. Up to an increase in the number of patients of 10%, for each percent that the number of patients increases, the busyness of the ambulances increases by 0.3 percent points.

8. CONCLUSION

In this conclusion, we first show the conclusions of our study. Thereafter we discuss the limitations and make recommendations for further research.

8.1. Conclusion

The core problem which we address in this study is: *'The multitrauma healthcare organisations in the Netherlands cannot yet decide on logistical improvements to the multitrauma care chain, because they have little insight into the relationship between further concentration of MTCs and the use of EMSs for patient transportation.'*

8.1.1. Methodology

After exploring the existing body of knowledge on the topic of the positioning of healthcare facilities and/or EMS stations, we chose to first develop a mathematical model to determine which combinations of open MTCs result in the best coverage. We based this model on the MCLP of Church and ReVelle (1974) but added to this that we considered that the use of ambulances for patient transport is preferred over the use of HEMSs. After creating this model, we evaluated the output using a simulation model in which we could simulate the busyness of the EMSs and the stochasticity of the prehospital times. Additionally, in developing our simulation model we considered that multitrauma patients should be treated differently than other patients and we used several scenarios to approximate the real-time decision processes regarding the transportation mode to use and the hospital to go to. Our model simulates the prehospital process of Dutch (multitrauma) patients and allows for evaluating several changes to the prehospital trauma care system.

8.1.2. Mathematical model

The binary linear programming model we developed suggested that for several combinations of nine to twelve open MTCs, the coverage is approximately equal to when we open all thirteen MTCs. The fraction of patients that are transported by helicopter is approximately equal as well. Additionally, we found that when opening eight MTCs, the results are only slightly worse. Therefore, we chose to further evaluate the options of opening eight and nine MTCs and compare them to opening all thirteen MTCs. Concerning the MTCs to open if we want to open eight MTCs, we evaluate three combinations of open MTCs, because which one is the best depends on the relative weight that we put on maximising the coverage on the one hand and on minimising the transportation by helicopter on the other hand. We refer to the four options of opening eight and nine MTCs as scenarios 8MTCsLowW, 8MTCSHighW, 8MTCsTeuge, and 9MTCs.

8.1.3. Simulation model

Before we evaluated these scenarios in the simulation model, we compared several methods of approximating the real-time decision processes in the model to find the method which results were the closest to reality. We found that the following combination of scenarios approximates the reality best:

- *Only dispatch a HEMS to save time if it is faster than the ambulance.*
- *The destination of the patient depends on the prehospital time.*
- *Only transport the patient by helicopter if it saves at least 26.4 minutes.*
- T^{max} = *49.4 minutes.*

Using these methods to decide where to transport patients and which transportation mode to use, we evaluated the performance of the scenarios that came out of the mathematical model. Additionally, we evaluated three scenarios that were based on a more pragmatic approach that was close to how the choice of which MTCs to open would be made when no mathematical approach was used. We refer to these three additional scenarios as scenarios LastYearMTCs, Last3YearsMTCs, and NextYearMTCs. The main difference between the scenarios that follow from the pragmatic approach and the scenarios that follow from the mathematical model is that using the pragmatic approach results in opening fewer MTCs.

Using the approximations of the real-time decision processes as described above, we found that opening all thirteen MTCs results in the shortest prehospital times for multitrauma patients and the highest fraction of multitrauma patients going to an MTC. In the other three best-performing scenarios (i.e., 8MTCsLowW, 8MTCsTeuge, and 9MTCs), four or five MTCs are closed. This reduces the score on the 90% norm from 60-63% to 54-58% depending on which HEMS stations can be used. The differences in performance between scenarios 8MTCsLowW, 8MTCsTeuge, and 9MTCs are small, although when the number of patients increases, scenario 9MTCs seems to perform slightly better in terms of the 90% norm and the fraction of multitrauma patients that arrive at a hospital within 45 minutes. In general, scenario 9MTCs will perform better than scenarios 8MTCsLowW and 8MTCsTeuge, because it has one additional open MTC.

In conclusion, when the number of MTCs should be reduced to concentrate the trauma care, we expect that logistically it is best to close four specific MTCs. However, this would reduce the score on the 90% norm by 4 to 8 percent points and it would decrease the fraction of multitrauma patients that reach a hospital within 45 minutes by 1 to 5 percent points, depending on which HEMS stations could be used. If we force the trauma system to meet the 90% norm, this will mainly affect the prehospital times and the busyness of the HEMSs, which increase by 5 to 5.5 minutes and by 0.3 to 1.2 percent points, respectively. The busyness of the ambulances will hardly change.

8.1.4. Added value of combining the mathematical model with a simulation model

Our results show that using a simulation model in addition to the mathematical model is of added value. Firstly because the values of the KPIs that follow from the simulation model are more realistic than the values that follow from the mathematical model. This is because, in the mathematical model, all multitrauma patients go to an MTC, whereas in reality and in the simulation model part of the multitrauma patients go to another hospital, which reduces the prehospital time such that in the simulation model the fraction of multitrauma patients that arrive at the hospital within 60 minutes is 7 to 19 percent points bigger than in the results of the mathematical model, which is a difference of 8% to 24%. Additionally, in the mathematical model, there is infinite HEMS capacity and patients are always transported by helicopter if that is the only way to reach the MTC within the T^{max}. In reality and in the simulation model, HEMS capacity is limited and if transporting a patient by helicopter only saves a few minutes compared to transporting the patient by ambulance, the patient is transported by ambulance, even though the T^{max} might be exceeded. Therefore, in the mathematical model, the fraction of multitrauma patients that are transported by HEMS is 4 to 7 percent points higher than in the results of the simulation model. This is a big increase of 83% to 100%.

A second reason why the simulation model is of added value is that it enables us to evaluate more KPIs, which supports the decision-making process regarding which combination of MTCs to open. For instance, when only considering the two KPIs of the mathematical model, scenario 8MTCsHighW performs slightly better than scenario 8MTCsLowW on both of the KPIs (0.2 to 0.3 percent points). However, as we saw from Section 7.3, when considering more KPIs and calculating the confidence intervals, we find that scenario 8MTCsLowW actually performs better than scenario 8MTCsHighW, although this difference is not statistically significant.

8.2. Discussion

To the best of our knowledge, this study is one of the first to create an MCLP-based mathematical model in which multiple transportation modes are included and the first study in which one transportation mode is prefered over the other while making a trade-off between maximising the coverage and minimising the use of the least prefered transportation mode. Therefore, we contributed to theory by developing an adapted multi-objective objective function and extending the model with a constraint set to prevent it from making the operational decision not to use the least prefered transportation mode even though it is the only transportation mode that covers the patient. Furthermore, we combined the mathematical model with a simulation model to include real-time decision processes, manage different injury severities (e.g., multitrauma patients) differently, and include the capacity and busyness of the EMSs. The literature on (models including) real-time decision processes regarding dispatching EMSs and choosing a destination and transportation mode for patients in the emergency and trauma care sectors, is limited. Therefore, we made a start to fill this gap by deciding to calibrate our simulation model of the trauma care sector by simulating several approximations of decision processes and comparing the results on several KPIs to the real historic values of these KPIs.

In our study, we made several assumptions and used some simplifications that might affect our results. First, because of the lack of more granular data on the elements of the prehospital time, such as the dispatch, driving and on-scene times, we used a pragmatic approach to make those times stochastic in our simulation model. We approximated them with a normal distribution around the known means. Therefore, these times might slightly differ from reality. However, the main results about the closure of which MTCs would the least reduce the performance on the logistical KPIs are clear and can also be logically explained. So, we believe that these conclusions can be drawn. Furthermore, our models are suitable for inserting real probability distributions if more information is available. Additionally, our simulation model can easily be adapted to provide insights into future research questions regarding the trauma system, just as we did to evaluate the impact of meeting the 90% norm, for instance by overtriaging trauma patients. To improve the analysis of the latter, we suggest adapting the simulation model to address that the medical staff at the scene, instead of the call operator, performs the overtriage.

A limitation of our study is that, in our mathematical model, we included a constraint set to determine whether or not an MTC covered a postcode. An alternative approach would be to use subsets that only contain the MTCs that can cover a postcode and apply the other constraints only to these subsets, as Church and ReVelle (1974) did. This would reduce the computation time, which now was on average two hours for ten values of w (e.i., ten experiments). The total computation time for running the full-factorial design of ten values of w, thirteen numbers of MTCs to open and four combinations of HEMS stations (520 experiments) took hundred hours. However, in our study, this was sufficiently short, because we only performed these experiments once. In cases with more possible MTC locations or HEMS stations, applying the method of Church and ReVelle (1974) would be beneficial.

Another limitation is that we use the data of only one year (2019) to calibrate the approximations of the real-time decision processes in our simulation model and we also use the results of these approximations to compare our alternative combinations of open MTCs to. This might cause some overfitting, meaning that the way we simulate the real-time decision processes may be less generalisable to other years or situations. In further studies, it would therefore be useful to also use data from other years to calibrate the approximations of the real-time decision processes.

Additionally, it would be useful to use a longer run length, to validate if the results about the multitrauma patients are representative for all postcodes, because the results of our simulation model only include multitrauma patients in 9% of the postcodes. Nonetheless, these postcodes are spread across the whole country.

Further, we used some simplifications in our simulation model. First, we assumed that helicopters that transport a patient always go to the nearest MTC, whereas in reality, they also often bring the patient to the MTC that manages their HEMS station. Additionally, whereas the Dutch HEMSs only transport patients in 7% of the cases that they are at the scene, the German HEMSs transport patients more often. We did not address this in our model, but in further studies, this could be done to make the predictions of the prehospital times in the regions near the German border more accurate. Furthermore, we did not include the Belgian HEMSs, because they are used less, but including these would slightly increase the validity of the model.

Next to this, we want to remark that, whereas we included the German HEMSs in our model, we did not include the German accidents. For, we assumed that all accidents happened within the Netherlands, whereas in reality Dutch MTCs near the German border also treat patients from Germany. Therefore, in our results, the importance of opening the MTCs near the German border may be underestimated, because in reality these MTCs also treat foreign patients. Including foreign accidents is a useful addition to the model. This could also affect the busyness of the Dutch EMSs, although the difference for the ambulances will be minimal.

Another simplification is that in the scenarios in which we evaluate the effect of overtriage, we assume that the patients that are classified as multitrauma patients stay in the hospital to which they are brought, even though they might turn out not to be multitrauma patients. In reality, if they turn out to be less severely injured, they might be brought to another hospital because the capacity in the MTC is limited. This causes ambulances to be busier. Another, possibly more important, reason that our model might underestimate the busyness of the ambulances is that, because of the lack of data, we assumed that only one ambulance is dispatched, except for when resuscitation is needed. However, in reality, multiple ambulances might be dispatched, which increases the busyness of the ambulances.

Finally, in our simulation model, we only evaluated the options of opening eight, nine or thirteen MTCs, because our mathematical model suggested that opening nine MTCs would perform as good as opening twelve MTCs. However, in reality, the performance of opening nine MTCs is likely to differ from opening ten, eleven, or twelve MTCs, although our mathematical model did not show this because it does not consider stochasticity, real-time decision processes, and the capacity of EMSs. This limitation of our mathematical model should be considered. So, also evaluating the options of opening ten to twelve MTCs would be a useful addition.

8.3. Further research

To improve the validity of the results, further research can be done. First, it would be valuable to further study the real-time decision processes on the transportation mode to use and the hospital to go to. Having insights into the way medical staff makes these decisions helps to improve the simulation model and therefore contributes to getting insights into the effects of changes to the trauma system. We believe that for the Dutch context, this research topic would be the most relevant because it most strongly affects the results of the simulation model, and thus contributes most to providing insights into the relationship between further concentration of MTCs and the use of EMSs for patient transportation. Additionally, we expect that this might also enable drawing valid conclusions at a hospital level. This is important because when for instance one MTC is closed, the average prehospital time of multitrauma patients might increase by only 0.5 minutes. However, for the individual patients in the region of that MTC, the prehospital time will increase more.

Second, next to studying the real-time decision processes, it is important to check if the capacity of the MTCs is sufficient to treat more patients if other MTCs close. We did not include this in our study, but this would be a useful next step. Also when concentrating multitrauma care is not done by reducing the number of MTCs but by increasing the fraction of multitrauma patients that is brought to an MTC, this is relevant because more capacity will be needed in the MTCs, especially in case you want to achieve 50% overtriage.

Third, it would be valuable to further develop the mathematical model, especially for cases in which the number of possible facilities is big. This can be done by including the busyness of EMSs. In the literature, busyness of EMSs is usually addressed by incorporating busy probabilities as parameters in a mathematical model. However, this is not possible if the busy probabilities depend on other variables in the model. We found only one study (Cho et al., 2014) that addressed this issue by including the busy probabilities as variables. However, they did not include the busyness of ambulances and including busy probabilities as variables made the problem non-linear and complicated solving the model. Therefore, we developed a more straightforward binary linear model which could be solved to optimality and thereafter evaluated the busynesses in a simulation model. This method is easier to understand. However, this mathematical model also less accurately calculates the values of the KPIs for the several solutions. For instance, in the results of our mathematical model, the scenarios 9MTCs and 13MTCs seemed to have the same performance, whereas our simulation model showed that there are differences. So, it would be useful to adapt the mathematical model to include the busyness of the EMSs, for instance as variables, to already get better suggestions from that model regarding which MTCs should be opened. For, if the mathematical model already indicates this, a decisionmaker can decide to, for instance, not only further evaluate scenarios with eight, nine or thirteen MTCs, but also the option in between (e.g., eleven MTCs). An alternative approach to improve the suggestions regarding which facilities to open is to use the simulation model to determine the busyness of the EMSs and use that information to train the mathematical model or an artificial neural network.

Another topic of future research could be to locate the HEMS stations from scratch, preferably simultaneously with choosing the MTCs. In our study, we only investigated the effect of a possible additional HEMS station at Teuge Airport and of not using the German HEMSs, but choosing the positions from scratch could result in a better coverage.

Finally, this study focussed on the logistical aspects of concentrating trauma care. Next to this, studying the impact of concentration on the costs and medical aspects are relevant directions for future research.

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Appendix A
Derivation of the flight time formula

In Chapter 4, we state that we rewrite formula [3a] to formula [3b]. In this appendix, we show this derivation.

We start with formula [3a] of Zwakhals et al. (2008).

$$d_{i,j} = e^{\frac{Speed + F_t^2}{F_t^1}} \qquad \text{with } 30 \leq Speed \leq 220 \qquad [3a]$$

This corresponds to:

$$Speed = F_t^1 \cdot \ln(d_{i,j}) - F_t^2 \qquad \text{with } 30 \leq Speed \leq 220$$

From physics, we know that travel time can be calculated by dividing a travelled distance by the travel speed. So, the following holds:

$$T_{i,j,t}^{FH} = \frac{d_{i,j}}{Speed} \qquad \text{with } 30 \leq Speed \leq 220$$

To ensure that $Speed$ is within its boundaries, we first take the maximum of $Speed$ and its lower bound and then take the minimum of this value and the upper bound. We then arrive at the following formula:

$$T_{i,j,t}^{FH} = \frac{d_{i,j}}{\min(220, \max(30, Speed))}$$

Combining this with the formula we derived for calculating $Speed$, we find formula [3b].

$$T_{i,j,t}^{FH} = \frac{d_{i,j}}{\min(220, \max(30, F_t^1 \cdot \ln(d_{i,j}) - F_t^2))} \qquad [3b]$$

Appendix B
Driving time calculation method

In our model, we need to approximate the driving times of ambulances between postcodes. In this appendix, we show the output of the model for four methods of driving time calculations and compare these to the real situation shown in **Figure 13**. Using this comparison, we choose the most realistic driving time calculation method.

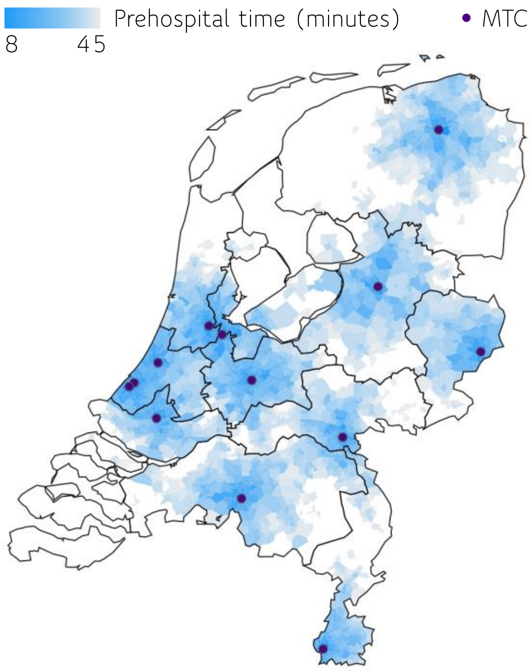


Figure 13 Current real coverage by ambulance within 45 minutes
(Adapted from: Landelijk Netwerk Acute Zorg (n.d.-d))

The four methods that we compare are based on the estimated real driving times of cars between postcode i and j (Object Vision, 2019). The first method uses these driving times. However, these driving times are an overestimation, because on average ambulances drive faster than normal cars. Ambulances can reduce the driving time by approximately 30% to 40% (Schuil, 2019). Therefore, in the second, third, and fourth methods, we reduce the driving times by 30%, 35%, and 40%, respectively.

In **Figure 14**, the coverage by ambulance for the four methods is shown. We see that the time reduction of 35% resembles the real coverage (**Figure 13**) best. Additionally, this reduction is in the middle of the estimation of Schuil (2019). Furthermore, this time reduction equals the time difference between the average prescene driving times of A1 and A2 ambulance dispatches (Ambulancezorg Nederland, 2021c). Therefore, we assume that driving times of ambulances are 35% shorter than normal driving times.

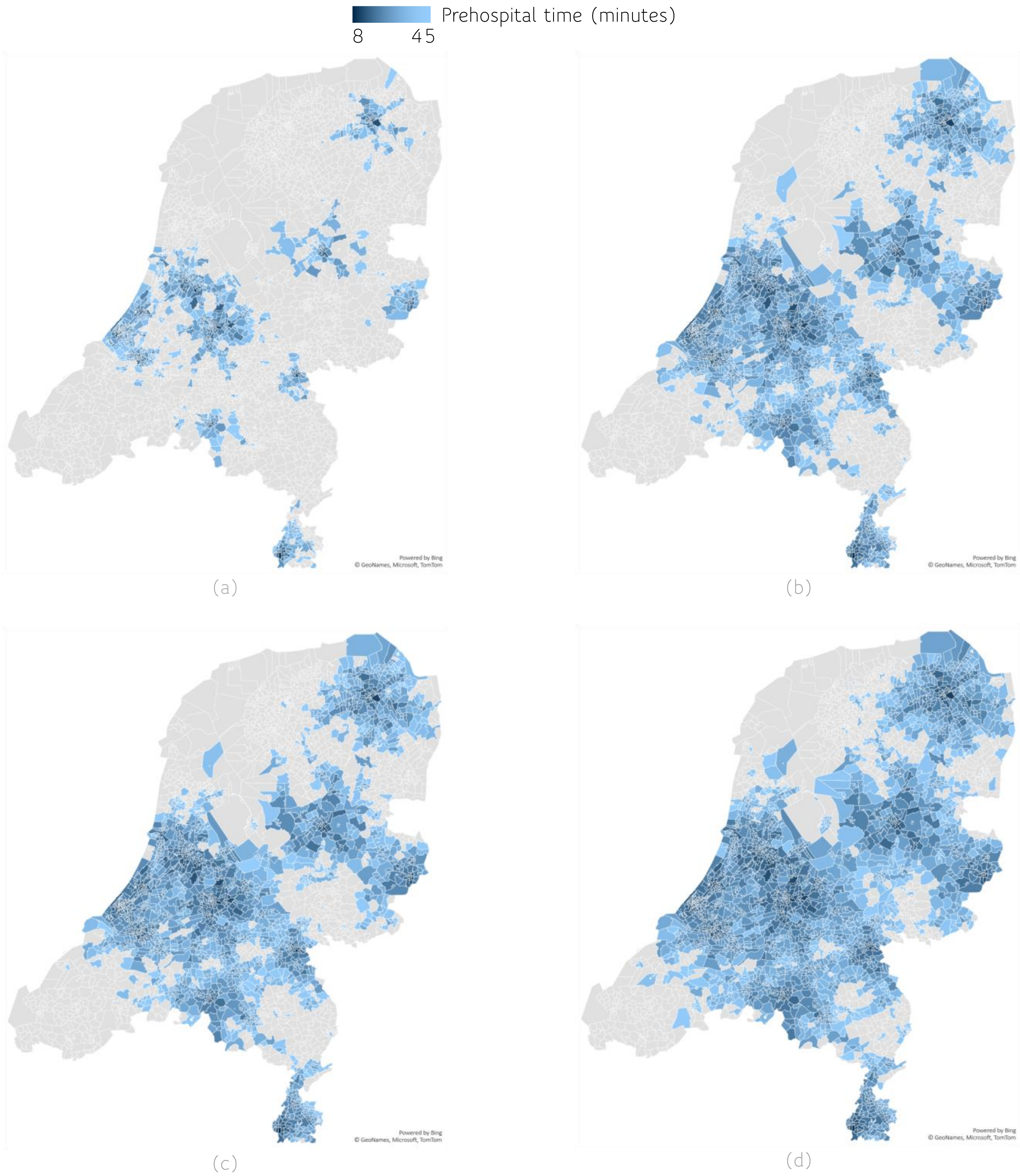


Figure 14 Coverage by ambulance when reducing the normal driving times by 0% (a), 30% (b), 35% (c) and 40% (d)

Appendix C
More results of the mathematical model

[Restricted]

Appendix D
Approximating the probability distributions

In this appendix, we show how we approximated the probability distributions of the prehospital activities, e.g., on-scene treatment and driving times.

D.1. The chosen probability distributions

The durations of the prehospital activities are stochastic, but we only know their average values. To approximate the stochasticity, we use normal distributions around the average values of the data of 2019 with standard deviations of 5%. We do this for dispatch, landing and post-landing times of HEMSs during time period t as well as for the dispatch times of ambulances with dispatch level l and for the duration of the on-scene treatment. For the driving and flight times, we also use normal distributions with standard deviations of 5%, but for these variables, we use the origin-destination pair dependent averages.

D.2. Finding the chosen probability distributions

In this section, we explain why we use normal distributions in our simulation model.

D.2.1. Fitting the probability distribution of the prescene time

We did not find literature or data on the real probability distributions, but we found that it seems that the average prescene time, so the sum of the durations of the prescene activities, of 2019 can be approximated by a gamma distribution with a shape of 6.4 and a scale of 1.51 (**Figure 15**). We found this distribution in two steps. First, we determined which type of distribution would theoretically fit the data. Law (2015) states that a gamma distribution can be used to approximate the 'time to complete some task, e.g. customer service'. Therefore, we chose that distribution. Second, we fitted a gamma distribution to the historic average and median values of the prescene times of 2019, which are 9.68 and 9.18 minutes, respectively (Ambulancezorg Nederland, 2020). This gave the distribution shown in **Figure 15**.

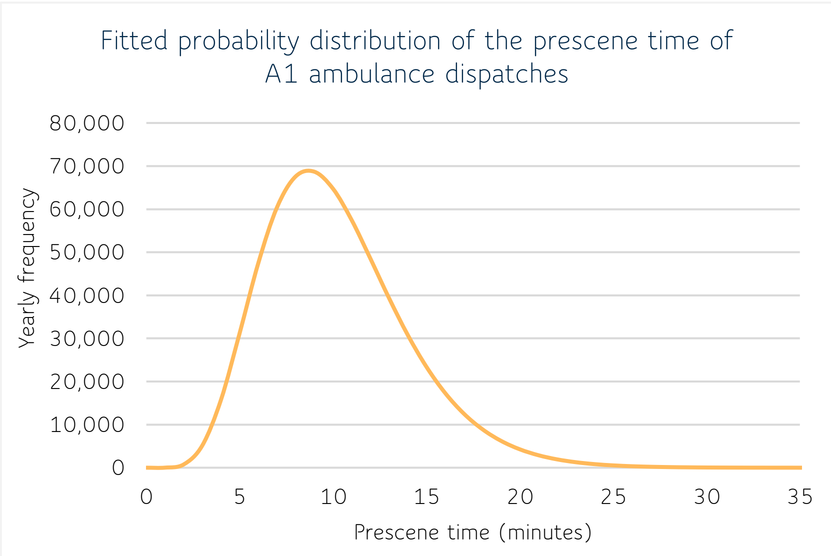


Figure 15 Fitted probability distribution of the prescene time of A1 ambulance dispatches

D.2.2. Comparing the probability distributions of the duration of the prescene activities

However, in our model, we do not need the distribution of the prescene time, but the distributions of the durations of the prehospital activities, among which there are several prescene activities. We did not know the real distributions of these durations, so we should approximate them. We chose two probability distributions for which we only needed to know an average value of the data and a deviation: the normal distribution and the uniform distribution. For the normal distribution, we used a standard deviation of 5% of the historic average value and for the uniform distribution, we used a range of 5% below and above the means, because we did not know the standard deviation of the historic data. We ran the simulation model with the current HEMS stations and MTCs under the scenario HDFaster+TimeDependent+HT15+Max60[2] using these distributions. Within the simulation model, we multiplied the generated durations by -1 if they were negative because negative durations are not possible. The resulting prescene times are shown in **Figure 16**.

In the graphs of the probability distributions that follow from our simulation model, we see two peaks. The left peak in both graphs is caused by patients of which the ambulance to dispatch is already located at the postcode at which the accident occurred. In those cases, the prescene time only consists of the dispatch time, which is approximately 2.6 minutes. When comparing the graphs of the prescene times that are based on normal distributions to those that are based on uniform distributions, we see that they are quite similar, although the right peak of the prescene time of the uniform distribution is a bit flatter. Therefore, we choose to use normal distributions for the durations of the prescene activities, which are the dispatch time and travel time to the scene, as well as for the other activities, which are the duration of the on-scene treatment, the travel time to the hospital and the travel time to the EMS station.

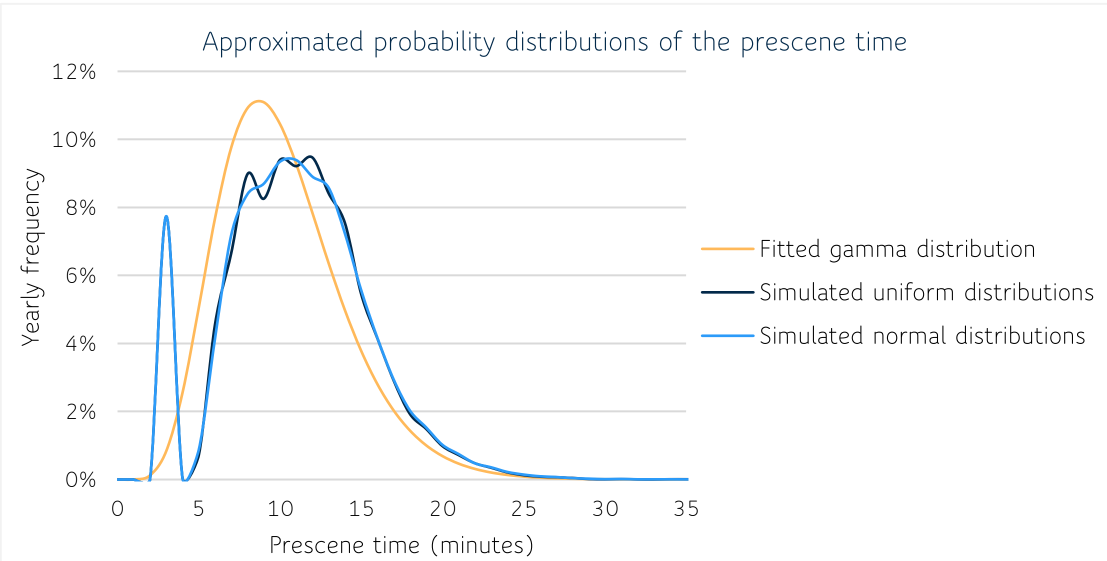


Figure 16 Approximated probability distribution of the prescene time

[2] Explanations of the scenarios can be found in Section 6.5.

Appendix E
Coverage per combination of open MTCs

[Restricted]

Appendix F
Flowcharts of the simulation model logic

In this appendix, we explain the logic we built into our simulation model. We show several flow charts to explain what the process that our model simulates looks like. We start by explaining the process from a high level and then zoom in on each of the subprocesses.

F.1. High-level process

In **Figure 17**, the high-level process of a patient as simulated by the simulation model is shown.

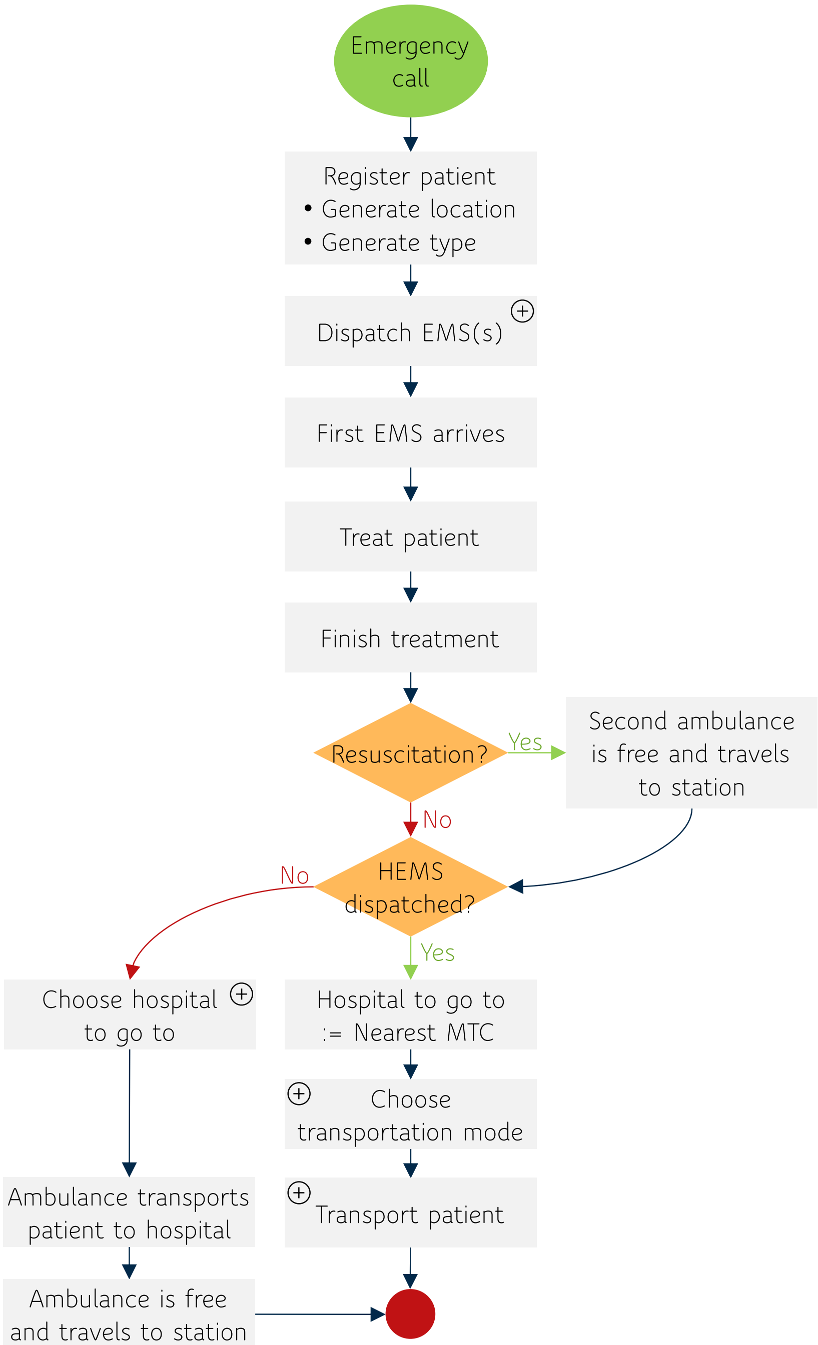


Figure 17 Flow chart of the high-level process of a patient in the simulation model.

The process starts by receiving an emergency call. The model then generates a patient and determines the accident location and the patient type (A1/A2 urgency and multitrauma/other patient). Then, one or more EMSs are dispatched. How this is done, is explained in Section F.2. The next event is that the first EMS arrives at the scene and starts the treatment. Once the treatment is finished, it should be decided to which hospital the patient should be brought and which transportation mode should be used. If there was a resuscitation, so two ambulances were dispatched, the second ambulance is marked free and is sent back to its station. Then, the model checks if a HEMS was dispatched.

If that is not the case, the only decision to make is to which hospital the patient should be brought, because the transportation mode can only be an ambulance. The process of choosing a hospital is explained in Section F.3. Once the hospital is chosen, the patient is transported to that hospital and thereafter the ambulance is free again and travels back to its station and the process of the patient is finished.

In case a HEMS was dispatched, the hospital to go to is always the nearest MTC. So, the only choice to make is which transportation mode to use. Thereafter the patient is transported to the hospital and then, the process of the patient is finished. The subprocess of choosing the transportation mode and the subprocess of transporting the patient including sending the EMSs back to their stations are explained in Sections F.4 and F.5.

F.2. Subprocess: Dispatch EMS(s)

In **Figure 18**, the process of dispatching one or more EMS(s) as simulated by the simulation model is shown. This process starts after an emergency call comes in and the model has generated a patient.

F.2.1. Ambulance

First, always an ambulance is dispatched. This is done by finding the nearest available ambulance, which can either be an ambulance that is waiting at its station or an ambulance that is on its way back to its station. If an available ambulance is found, it is dispatched. Otherwise, the patient is dropped from the system and this is registered.

F.2.2. HEMS

After an ambulance is dispatched, the model checks if it should dispatch a HEMS. It does this by first checking if the patient has A1 urgency. If this is not the case, no HEMS is dispatched. However, if the patient has A1 urgency, the model checks if the dispatched ambulance can reach the scene within the norm of 15 minutes.

If this is not the case, we try to dispatch a HEMS to ensure the patient gets help as quick as possible. Therefore, the model looks for the nearest available HEMS and checks if it can reach the scene within a scenario-dependent time limit. This limit depends on the scenarios as described in Section 6.5.1. If the HEMS can reach the scene in time, it is dispatched. If no HEMS is found or if it cannot reach the scene in time, no HEMS is dispatched.

If the dispatched ambulance can reach the scene within 15 minutes, dispatching a HEMS to reduce the time before the treatment starts is not needed. However, it can still be possible that specialist care is needed. If this is not the case, no HEMS is dispatched, but if a HEMS is needed for medical care, the model tries to dispatch a HEMS. If no HEMS is available, the request for specialist care cannot be satisfied, because no HEMS can be dispatched. However, if a HEMS is available, and the nearest one can reach the scene within the limit of 30 minutes that was set in assumption 27 of the simulation model, that HEMS is dispatched.

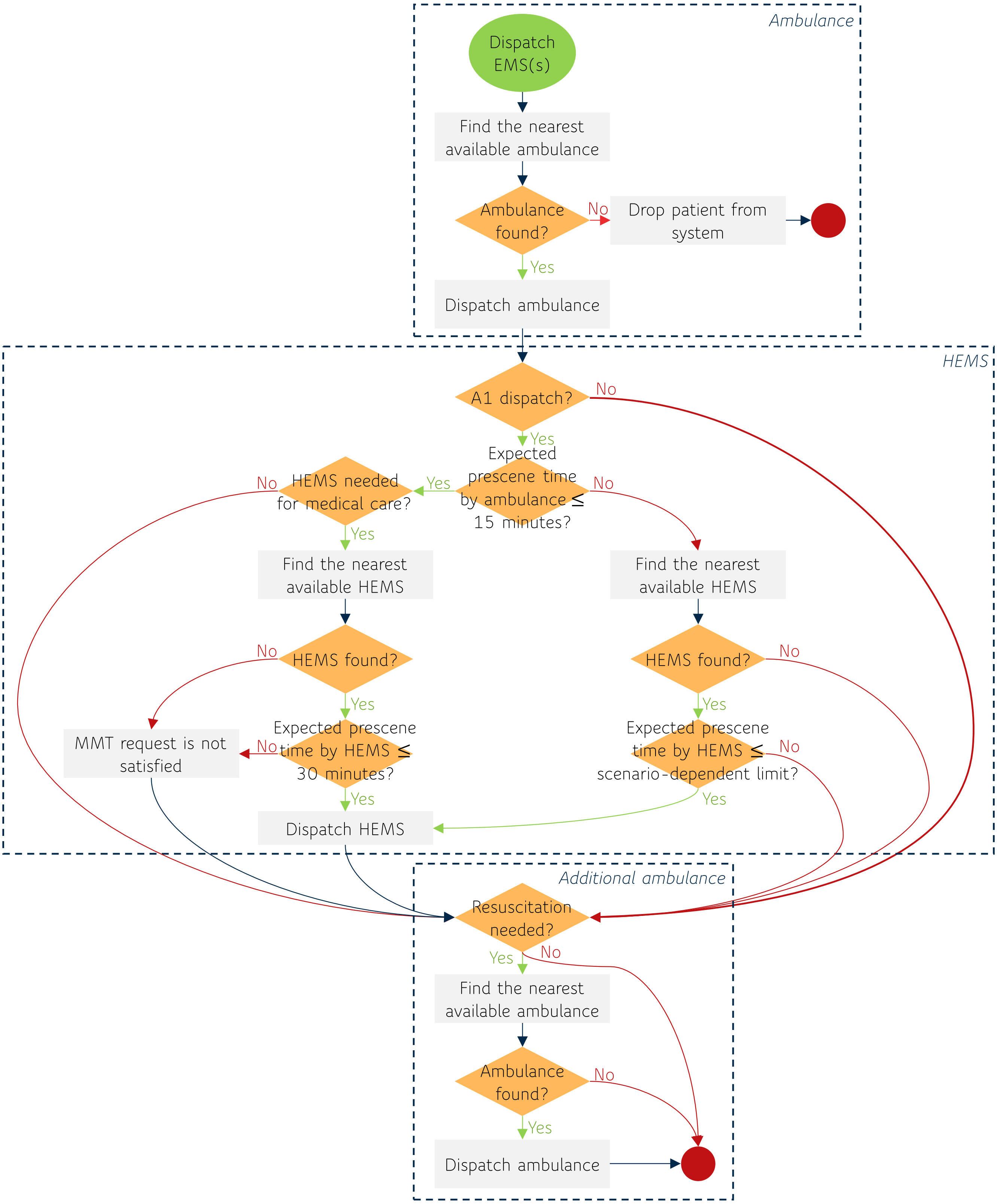


Figure 18 Flowchart of the process of dispatching EMS(s)

F.2.3. Additional ambulance

The final thing the model needs to do when dispatching the EMSs is checking if resuscitation is needed, because in that case, an additional ambulance needs to be dispatched. If no resuscitation is needed or no ambulance is available, the process of dispatching EMSs is finished. However, if resuscitation is needed, the model dispatches the nearest available ambulance and then the process of dispatching EMSs is finished.

F.3. Subprocess: Choose the hospital to go to

In **Figure 19**, the process of choosing a hospital to go to as simulated by the simulation model is shown. This process starts after the treatment has finished and it only takes place if no HEMS is dispatched.

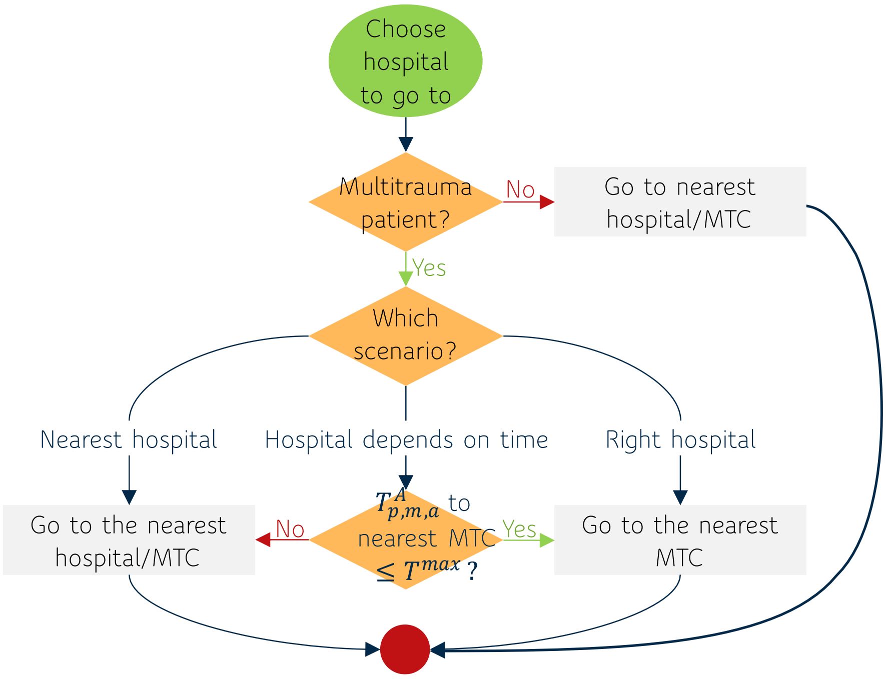


Figure 19 Flowchart of the process of choosing the hospital to go to

When the hospital to go to should be chosen, the model first checks if the patient is a multitrauma patient, because if that is not the case, the patient always goes to the nearest hospital independent of whether it is an MTC or not. If the patient is a multitrauma patient, the hospital to go to depends on the scenario. First, in the scenario that the patient always goes to the nearest hospital, it goes to the nearest hospital independent of whether this is an MTC or not. Second, in the scenario that the patient always goes to the right hospital, the multitrauma patient always goes to the nearest MTC. Third, in the scenario in which the choice of the hospital is time-dependent, the model checks if the expected prehospital time in case of transport by ambulance to the nearest MTC is within the maximum allowable prehospital time. In that case, the patient goes to the nearest MTC, because that hospital type is preferred. If the expected prehospital time is too long, the patient goes to the nearest hospital independent of whether this is an MTC or not.

F.4. Subprocess: Choose transportation mode

In **Figure 20**, the process of choosing the mode of transportation as simulated by the simulation model is shown. This process starts after the treatment has finished and it only takes place if a HEMS is dispatched. The transporting EMS will always transport the patient to the nearest MTC.

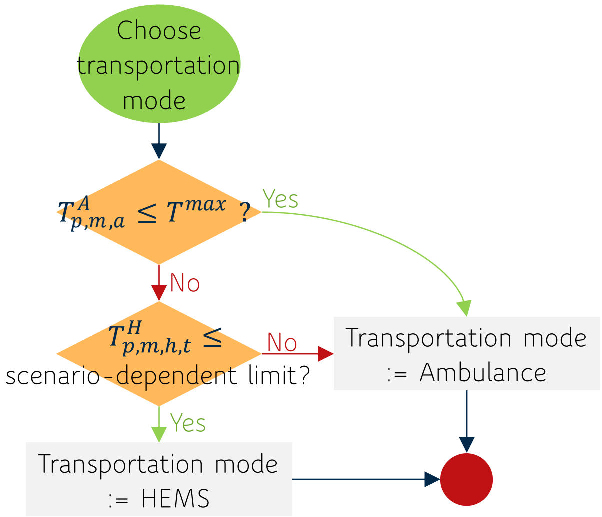


Figure 20 Flowchart of the process of choosing the transportation mode

If the expected prehospital time when transporting the patient by ambulance to the nearest MTC is within the maximum allowable prehospital time, the patient is transported by ambulance. Otherwise, the model checks if the HEMS could transport the patient within the scenario-dependent maximum allowable time. If this is the case, the patient is transported by helicopter and otherwise, it is transported by ambulance, because if the HEMS has no time-advantage, transportation by ambulance is preferred.

F.5. Subprocess: Transport patient

In **Figure 21**, the process of transporting a patient as simulated by the simulation model is shown. This process starts after the model has chosen to which hospital the patient will be transported and which transportation mode will be used. This process only holds for situations in which a HEMS is dispatched. Otherwise, the patient is transported following the process that is shown in the main process, because in that case no decision needs to be made on whether or not the MMT physician should accompany the patient and no waiting for EMSs to arrive is needed, because the transporting EMS always is already at the scene. So, in the subprocess explained below, we only look at situations in which a HEMS was dispatched.

If the patient will be transported by helicopter, possibly you need to wait for the HEMS to arrive, and then the HEMS transports the patient to the hospital and the ambulance is free and returns to its station again. If the patient is transported by ambulance, possibly you need to wait for the ambulance to arrive and then the model checks if the HEMS was dispatched to provide specialist care or if it was dispatched to shorten the time until the treatment could start. In the first case, the MMT physician accompanies the patient in the ambulance and both the ambulance and the helicopter go to the hospital. In the second case, the ambulance transports the patient to the hospital and the HEMS, including the MMT physician, is free and goes back to its station.

In all cases, after the patient is handed over to the hospital, the transporting EMSs are free again.

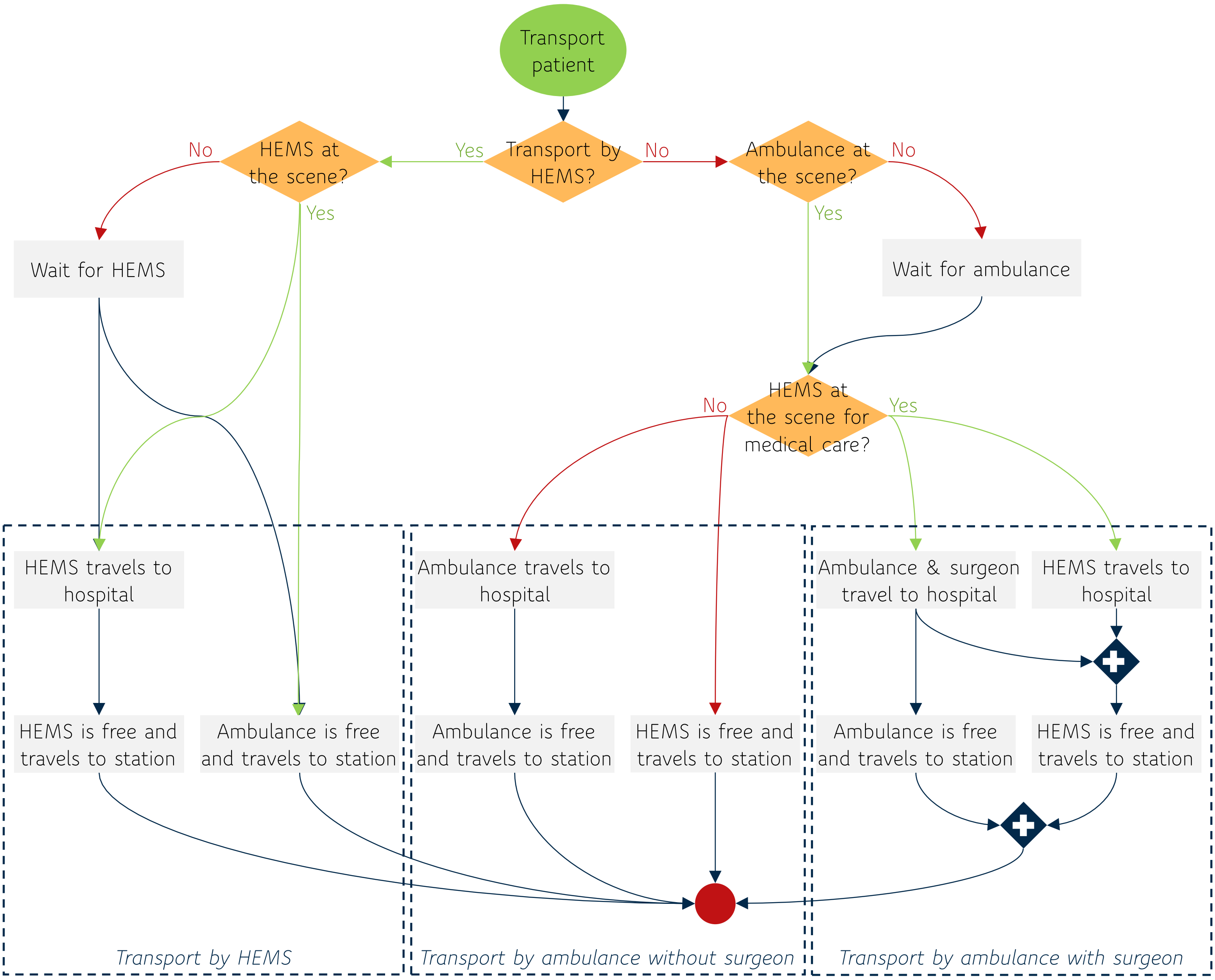


Figure 21 Flowchart of the process of transporting a patient

Appendix G
Hierarchy of patient types

In this appendix, we explain which patient types we distinguish in our simulation model and how we approximate the probability that the patients need specialist care from a HEMS.

In **Figure 22**, the hierarchy of the patient types is shown. In 2019, there were 1346055 ambulance dispatches and 10000 HEMS dispatches (Ambulancezorg Nederland, 2020; Landelijk Netwerk Acute Zorg, 2015). These dispatches can be split into A1 and A2 dispatches (and B dispatches, but we treat them as A2 dispatches).

G.1. Patients with A2 urgency

Following our assumptions that multitrauma patients always get assigned an A1 urgency level and that HEMS are only dispatched for patients with an A1 urgency level, in our model all A2 dispatches are part of the category of 'A2 Other patients' and for this patient type, no HEMSs are dispatched.

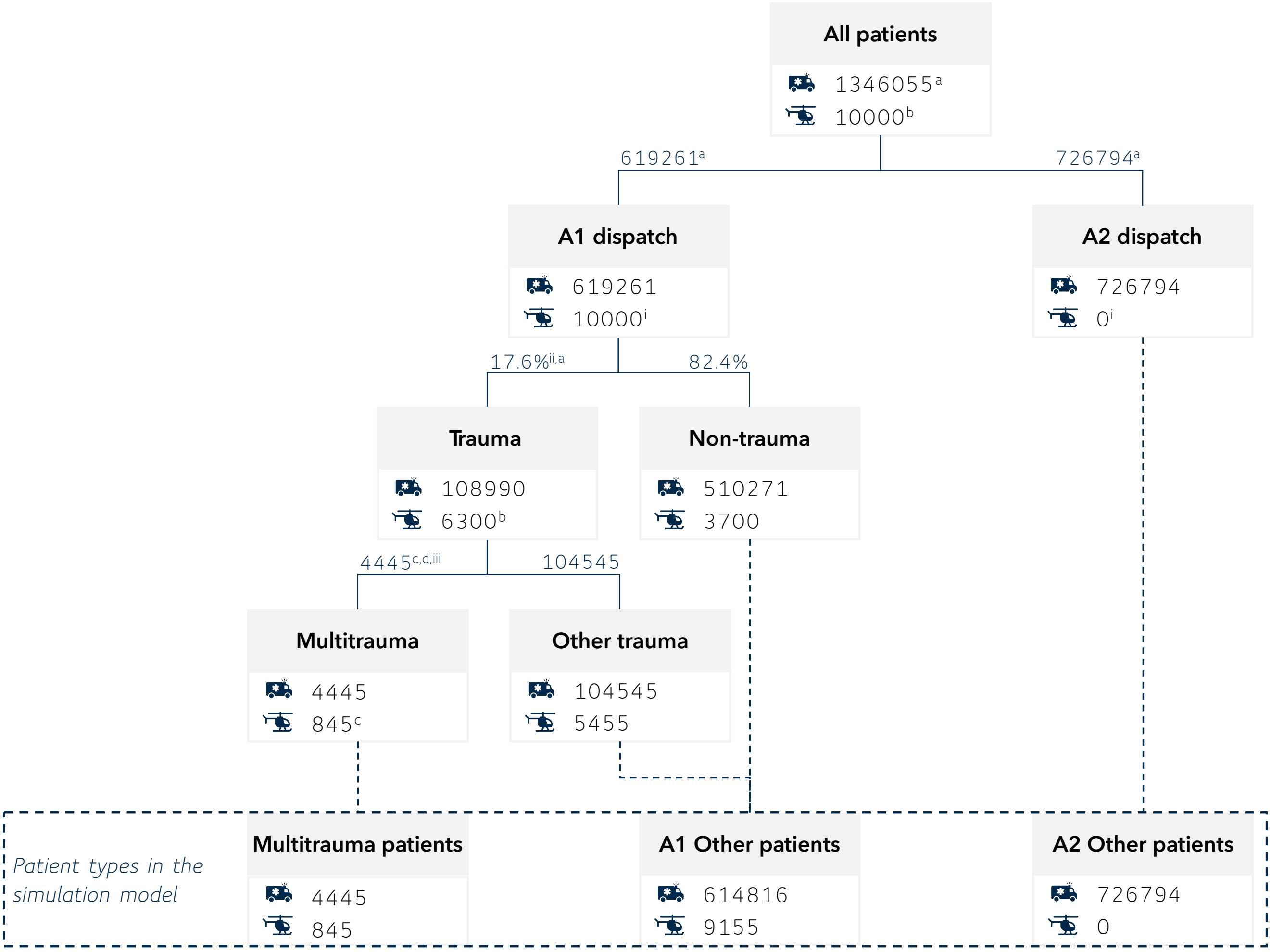
G.2. Patients with A1 urgency

The A1 dispatches can be split into two patient types. 17.6% are trauma patients and the remaining 82.4% are non-trauma patients (Ambulancezorg Nederland, 2020). For the group of trauma patients, the probability of the need for a HEMS dispatch is higher than for the group of non-trauma patients, because 63% of the HEMS dispatches are related to a trauma patient (Landelijk Netwerk Acute Zorg, 2015). Additionally, we know that 4445 multitrauma patients were hospitalised (Landelijk Netwerk Acute Zorg, 2020; Zorginstituut Nederland, 2020), and because we assume that all multitrauma patients are hospitalised, we assume that there were 4445 multitrauma patients in total. Further, for 19% of the multitrauma patients an MMT is dispatched (Landelijk Netwerk Acute Zorg, 2020). This corresponds to 845 dispatches.

In the simulation model, we use two patient types within the category of patients with A1 urgency. The first patient type are the multitrauma patients because they are the subject of our study. The other patient type are the other patients with A1 urgency. This type includes both the non-trauma patients and the trauma patients that are not multitrauma patients. We merge these two non-multitrauma subgroups into one patient type, because we do not have KPIs that differ per subgroup, so we can treat them the same.

G.3. HEMS dispatches

Regarding the HEMS dispatches, we know that in 7% of the cases in which the HEMS was at the scene, the patient is transported by helicopter (Landelijk Netwerk Acute Zorg, 2015). Therefore, we assume that in 7% of the cases, the main purpose of the HEMS was to transport the patient to save time and that in the remaining, and major, part of the HEMS dispatches (93%), the main purpose of the dispatch was to provide specialist care. Thus, in our model, the probability that a HEMS is dispatched to a multitrauma patient with the main purpose to provide medical care is $19\% \cdot 0.93 = 17.67\%$.



Legend

Number of ambulance dispatchess

Number of HEMS dispatches

Sources

[a] (Ambulancezorg Nederland, 2020)

[b] (Landelijk Netwerk Acute Zorg, 2015)

[c] (Landelijk Netwerk Acute Zorg, 2020)

[d] (Zorginstituut Nederland, 2020)

Assumptions

[i] HEMSs are only dispatched in case of an A1 dispatch, because A2 dispatches are used for less injured patients with a lower need for speed.

[ii] The number of trauma patients equals the number of patients that are classified to belong to the traumatology specialism, which are 17.6% of the patients.

[iii] All multitrauma patients are hospitalised, because they are severely injured.

Figure 22 Hierarchy of patient types

Appendix H
Results of the warm-up period and run characteristics calculations

In this appendix, we show the results of our calculations for determining the warm-up period, run length and number of runs to execute for our experiments in our simulation model.

H.1. Warm-up period and run length

To calculate the warm-up period, we use Welch's graphical procedure (Law, 2015), which we apply to the following KPIs:

- Prehospital time
- Prehospital time for multitrauma patients
- Probability that a multitrauma patient is transported directly to an MTC
- Probability that a patient is transported by helicopter
- Probability that an MMT request for specialist care is not satisfied
- Probability that a patient is not treated
- Busyness of the ambulances
- Busyness of the HEMSs

To determine the warm-up period, we run five replications of the simulation under the scenario HDFaster+TimeDependent+HT15+Max60 with the current HEMS stations and MTCs. We use a run length of fifteen days. The moving averages of the results of these experiments are shown in **Figure 23** to **Figure 28**. The probability that a patient is not treated is always zero. So, we do not show that in a figure. The used window of the moving averages depends on the KPI and is shown in the caption of the figures. If the window of a KPI is 2, this means that the average value of that KPI around, for instance, patient 4, is the average value over the values of patients 2 to 6.

We observe that for the prehospital time, both for all patients and for the multitrauma patients, the warm-up period is less than a day, because one day corresponds to approximately 3688 patients, among which there are 12 multitrauma patients. Also for the probabilities that a patient is transported by helicopter, or an MMT request for specialist care is not satisfied, a warm-up period of a day is suitable. For the probability that a multitrauma patient is transported directly to an MTC, it is slightly more difficult to determine the warm-up period, because this KPI keeps fluctuating, but one day seems to be suitable. The KPIs about the busyness of the EMSs are measured per day. We find that for the busyness of the ambulances, a warm-up period of a day is suitable. The busyness of the HEMSs has a slightly bigger warm-up period, so a warm-up period of 2 days might perform a bit better. However, assume that the usable run length is for instance 10 days. Then, the difference between the average busyness of the HEMSs from days 2 to 11 only differs 0.2 percent points from the average busyness from days 3 to 12. This is a small difference but would double the computation time.

So, we decide to use a warm-up period of 1 day. Additionally, we use a usable run length of ten times the warm-up period. This means that the total run length is 11 days.

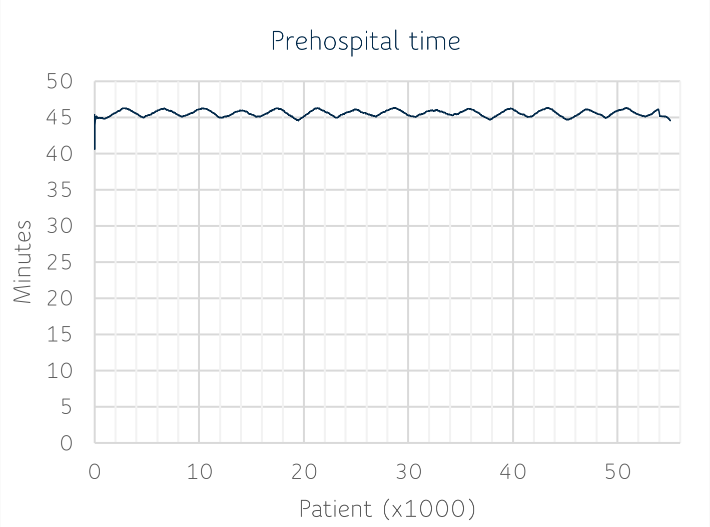


Figure 23 Moving average of the prehospital time (Window = 1000 patients)

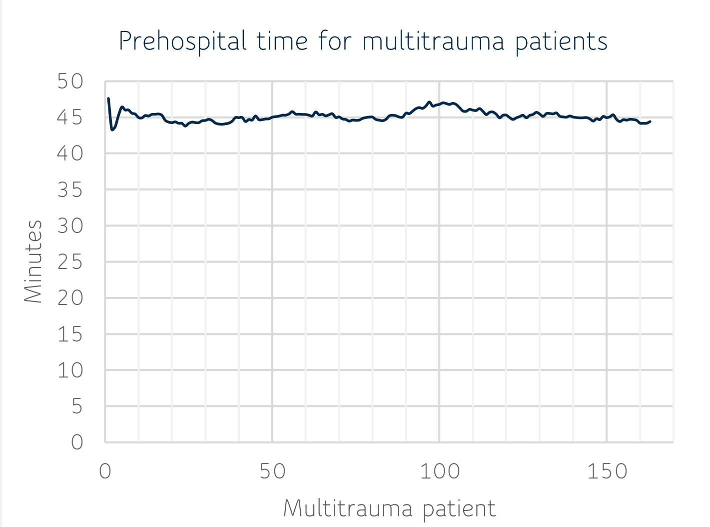


Figure 24 Moving average of the prehospital time for multitrauma patients (Window = 10 patients)

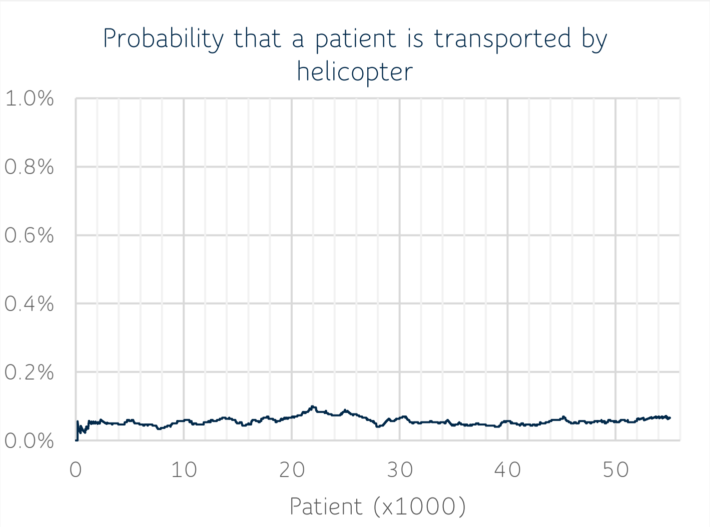


Figure 25 Moving average of the probability that a patient is transported by helicopter (Window = 3000 patients)

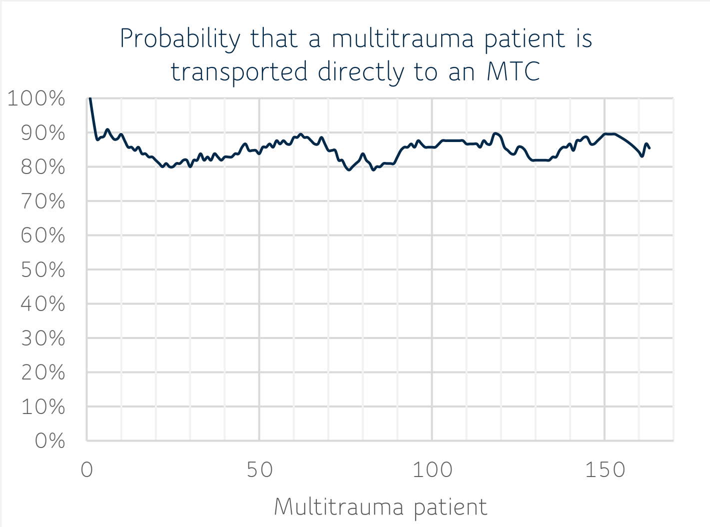


Figure 26 Moving average of the probability that a multitrauma patient is transported to an MTC (Window = 10 patients)

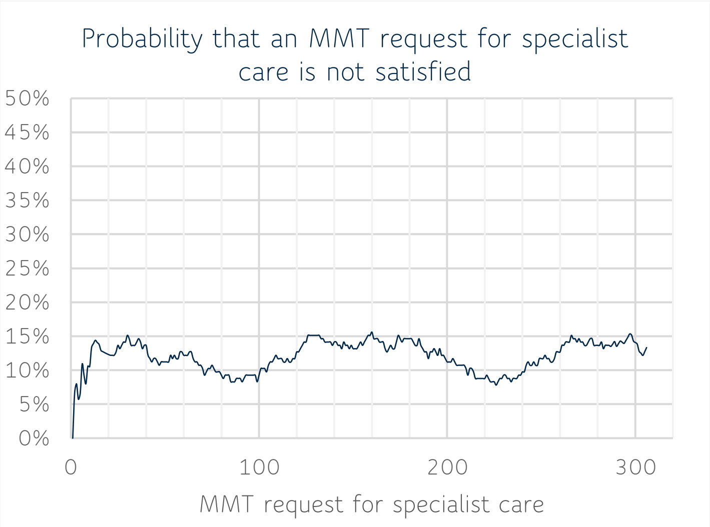


Figure 27 Moving average of the probability that an MMT request for specialist care is not satisfied (Window = 20 MMT requests)

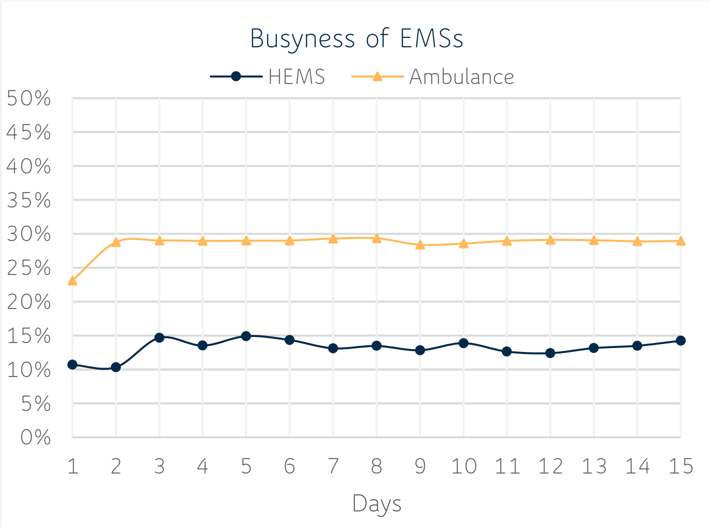


Figure 28 Busyness of the EMSs (Window = 0 days)

H.2. Number of replications

To determine the number of replications that we should perform, we use the replication/deletion approach with a 95% confidence interval (Law, 2015). We apply this approach to the prehospital time for all patients and the prehospital time for multitrauma patients and find that for the first KPI two replications are sufficient and for the second KPI three replications suffice. Therefore, we choose to use replications.

H.3. Evaluated postcodes

The run length and the number of replications determine the number of patients for which we simulate the prehospital process. Thus, they affect the number of postcodes in which an accident occurs in the simulation model. To provide insight into which postcodes are included in the results, we create two maps. **Figure 29** shows the number of patients that we simulated per postcode and **Figure 30** shows this information for the multitrauma patients. From **Figure 29**, we conclude that most postcodes are included in the results. It is not a problem that some postcodes are not included or are only included a few times, as long as other postcodes that are near are included.

In **Figure 30**, we see that the number of postcodes in which a multitrauma patient is simulated and the frequency within these postcodes is more limited because only a small fraction of the patients is a multitrauma patient. Including more multitrauma patients would be useful, however, this would increase the computation time proportionally. So, in this study, we do not do that.

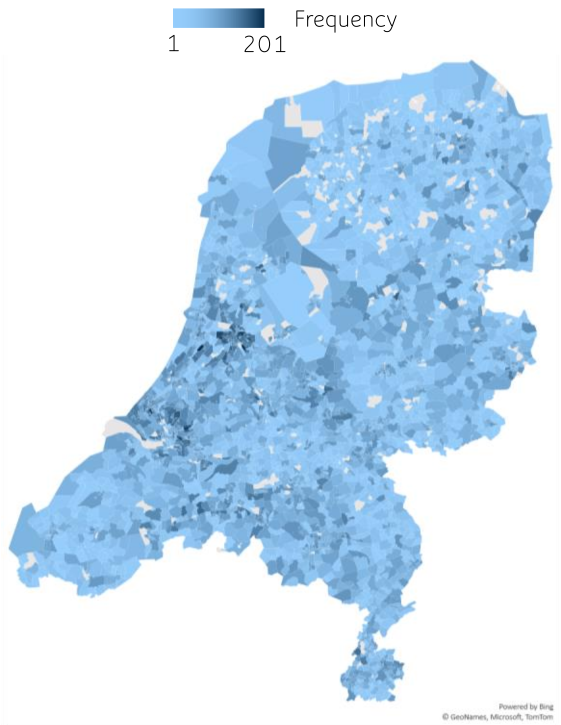


Figure 29 Number of simulated patients per postcode

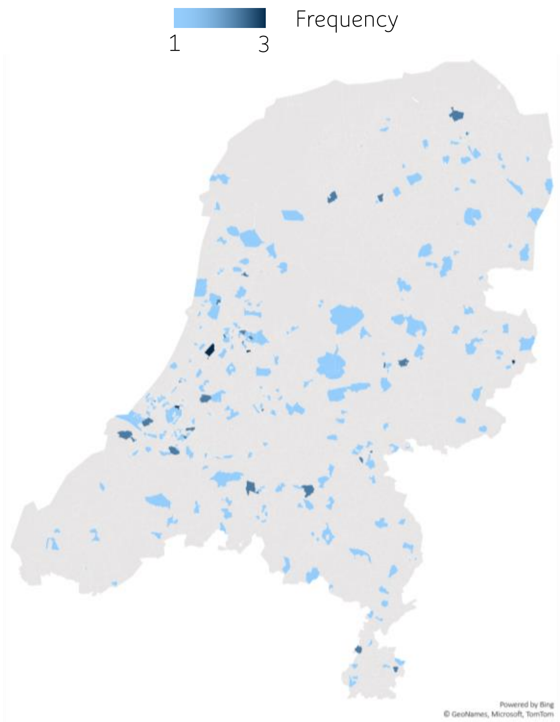


Figure 30 Number of simulated multitrauma patients per postcode

Appendix I
Experimental design

In this appendix, we show the experiments that we performed during our validation, experimentation, and sensitivity analysis phases. Additionally, in each table, the section in which the results of the experiments are discussed is shown.

I.1. Validation phase

The experiments in **Table 5** are run with the current HEMS stations and the current 13 MTCs.

Table 5 Experiments of the validation phase

ID	Dispatch a HEMS?	Hospital to go to	Transportation mode	T^{max}	Section
V1	HDFaster	Nearest	HT15	Max60	7.2.2 *1 replication per experiment*
V2	HDFaster	TimeDependent	HT15	Max60	
V3	HDFaster	Right	HT15	Max60	
V4	HDFaster	TimeDependent	HT30	Max60	7.2.3 *3 replications per experiment*
V5	HDFaster	TimeDependent	HT30	Max45	
V6	HDFaster	TimeDependent	HT26.4	Max60	
V7	HDFaster	TimeDependent	HT30	Max49.4	
V8	HDFaster	TimeDependent	HT26.4	Max49.4	

I.2. Experimentation phase

The experiments in **Table 6** are run under the scenario HDFaster+TimeDependent+HT26.4+Max49.4.

Table 6 Experiments of the experimentation phase

ID	HEMS stations	Open MTCs	90% norm	Section
E1	CurrentHEMSs	8MTCsLowW	-	7.3.1
E2	CurrentHEMSs	8MTCsHighW	-	
E3	CurrentHEMSs	8MTCsTeuge	-	
E4	CurrentHEMSs	9MTCs	-	
E5	CurrentHEMSs	13MTCs	-	
E6	CurrentHEMSs	LastYearMTCs	-	
E7	CurrentHEMSs	Last3YearsMTCs	-	
E8	CurrentHEMSs	NextYearMTCs	-	

ID	HEMS stations	Open MTCs	90% norm	Section
E9	NoGerman	8MTCsLowW	-	7.3.2
E10	NoGerman	8MTCsHighW	-	
E11	NoGerman	8MTCsTeuge	-	
E12	NoGerman	9MTCs	-	
E13	NoGerman	13MTCs	-	
E14	NoGerman	LastYearMTCs	-	
E15	NoGerman	Last3YearsMTCs	-	
E16	NoGerman	NextYearMTCs	-	
E17	AddTeuge	8MTCsLowW	-	
E18	AddTeuge	8MTCsHighW	-	
E19	AddTeuge	8MTCsTeuge	-	
E20	AddTeuge	9MTCs	-	
E21	AddTeuge	13MTCs	-	
E22	AddTeuge	LastYearMTCs	-	
E23	AddTeuge	Last3YearsMTCs	-	
E24	AddTeuge	NextYearMTCs	-	
E25	AddTeuge+NoGerman	8MTCsLowW	-	
E26	AddTeuge+NoGerman	8MTCsHighW	-	
E27	AddTeuge+NoGerman	8MTCsTeuge	-	
E28	AddTeuge+NoGerman	9MTCs	-	
E29	AddTeuge+NoGerman	13MTCs	-	
E30	AddTeuge+NoGerman	LastYearMTCs	-	
E31	AddTeuge+NoGerman	Last3YearsMTCs	-	
E32	AddTeuge+NoGerman	NextYearMTCs	-	
E33	CurrentHEMSs	13MTCs	90%norm	7.3.3
E34	CurrentHEMSs	13MTCs	90%norm+Overtriage	

I.3. Sensitivity analysis

The experiments in **Table 7** are run under the scenario HDFaster+TimeDependent+HT26.4+Max49.4+ CurrentHEMSs.

Table 7 Experiments of the sensitivity analysis

ID	Open MTCs	Increase in number of patients	Section
S1	8MTCsLowW	+0%	7.4
S2		+2%	
S3		+5%	
S4		+10%	
S5	8MTCsTeuge	+0%	
S6		+2%	
S7		+5%	
S8		+10%	
S9	9MTCs	+0%	
S10		+2%	
S11		+5%	
S12		+10%	
S13	13MTCs	+0%	
S14		+2%	
S15		+5%	
S16		+10%	

Appendix J
Results of the simulation model

[Restricted]