Ministerie van Defensie

Protective Resource Allocation on Critical Road Segments

THE CASE OF MALI AND THE FIGHT AGAINST TERRORISM

Msc. Engineering and Policy Analysis

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ABSTRACT

The Sahel region has become a focal point of concern due to the alarming escalation of terrorism, culminating in devastating attacks that have claimed numerous lives and disrupted regional stability. Mali, in particular, has experienced a **significant surge in terrorist activity** due to amplifying factors of insecurity like an intricate ethnic landscape (Ping, 2014; Mosely, 2017) and impact of climate change (Armstrong, 2022). One of the keys to the reconstruction of a country is a well-established road network (Rebosio & Wam, 2011; Kaplan & Teufel, 2016), which is already fragile in (Mali Kaplan & Teufel, 2016) but under even more pressure because of the very terrorism threat itself (Department of State, 2023).

The multilayered problem addressed in this thesis includes the understanding of terrorism activity, the dynamics thereof on road networks and the necessity of ensuring safety of individuals on the road network in Mali. The identified research gap encompasses inadequacies in **understanding road network dynamics** in terrorist contexts, a lack of literature on **connectivity within conflict areas**, limited research on **protective resource allocation** for road networks, and the in**novative application of criticality measures within a game theoretical mode**l. This study contributes to academic fields encompassing counter-terrorism, network science, and game theory within conflict settings.

To address the existing knowledge gap, an in-depth exploration is conducted into road network dynamics and protective resource allocation, with the situation in Mali serving as a case study. Consequently, the central research question is as follows:

How can road network protection be enhanced such that terrorist attack impact is minimized by allocating protective resources in conflict areas?

This core query will be tackled through the following sub-questions.

- SQ1: What is the state of the art of Malian road network protection against terrorist attacks?
- SQ2: How can protective resources be allocated over critical road segments?
- SQ3: How can the allocation of protective resources over critical parts of the road network be modelled taking into account adversary actions in the case of Mali?
- RQ4: How can protective resources be optimally distributed over the road network in Mali according to the developed model?
- RQ5: How can the approach and results be generalized for allocating resources to protect road networks against terrorist attacks in conflict areas?

This thesis presents a **novel approach** of using criticality measures based on network science as pay-offs for a game theoretical model in order to protect connectivity of road networks in conflict areas. Through two comprehensive literature reviews the **network scan approach**, based on shortest paths, population sizes, travel distances, and travel times and the **two-player zero-sum game** structure were selected as the basis for the methodology. In order to enhance understanding of dynamics on the road network, semi-structured expert interviews were conducted. The model is applied to the region of Segou in Mali and optimal strategies were compared to empirical terrorist attack data of the ACLED database.

It is concluded that road network protection can be strengthened to minimize the impact of terrorist attacks through the allocation of protective resources. Firstly, experts highlight the positive impact of **combining military patrols and convoys with explosive ordnance disposal** on road safety. Conversely, insufficient resource allocation for road network protection was found to compromise safety, potentially yielding outcomes worse than having no resources dedicated. Secondly, the results revealed the **network scan approach's potential** as a valuable tool for criticality assessment, offering precise identification of essential roads. This approach proves particularly valuable in resource-constrained conflict areas, where the scarcity of resources necessitates strategic prioritization. Thirdly, contexts lacking empirical traffic data, directing network protection efforts towards roads identified as **optimal strategies** by the model becomes prudent, as these represent the most effective choices attainable. Lastly, the comparison of optimal strategies derived from regional and national criticality values against real-world data provides the means to decipher whether insurgent groups strategize with a nationwide scope or focus on regional connectivity. When employed by state actors possessing empirical defender distribution information, the model can assist in enhancing the understanding of **insurgent behaviour**, facilitating more informed decision-making. While the existing model can be considered rudimentary, it is believed to have laid down essential foundational principles.

Specifically in the region of Segou, it was found that the governmental actors should **focus on the roads just North of Segou** as indicated by the optimal strategy. It was found that optimal **attacker's strategies are not very similar to empirical data of attacks** in Mali. Multiple reasons could contribute to that finding. Firstly, the model's simplicity may not account for all the complex factors at play. Secondly, the behaviour of one or both players might not be rational leading to entirely different outcomes as the model assumes rational players. Finally, it is possible that the real-life situation has not yet reached its equilibrium, implying that the players are still in the process of finding the equilibrium. It was however found that the optimal strategies based on national criticality values was more similar to empirical data than optimal strategies based on regional criticality values. This could be an indication that insurgent groups plan their attacks with a nationwide view to connectivity rather than solely focussed on the region.

For generalisation of the model it is important to note that the **model's chosen boundaries** impact the results of the criticality values and the optimal strategies significantly. On top of that, it is important to note that the model does not fit all **geopolitical situations**.

The main limitation of this research is the restriction to a **relative distribution of resources** instead of specific resource distribution figures and related costs. The step of comparison with actual defender strategies and analysis of related expenses, is envisioned as an independent undertaking by policy makers or military analysts. Furthermore, entail limitations of this research inaccu**racies and biases in the data** sources used (OpenStreetMap, ACLED), the **simplifications and assumptions** in the network scan approach and game theory model, **potential biases** in the semi-structured interviews, and the **challenges in handling unpaved roads, road length, and simultaneous attacks** in the model. These limitations affect the accuracy and comprehensiveness of the findings and recommendations.

Further research is recommended the extend the model further, including validate the model's effectiveness and determine its applicability to different types of attacks and different insurgency groups.

Survival of the model and derived policy advice in the **political arena** will present challenges. Implementing the model within the Malian armed forces faces resistance against data-driven approaches and cultural disparities. Similarly, international missions in Mali encounter challenges due to outdated mandates, multicultural operational complexities, and misaligned priorities. The Western perspective inherent in international missions further hampers effective policy execution

The **scientific relevance** of this research is portrayed by a methodological contribution of an innovative integration of network science and game theory to address challenges in conflict-area road network protection. On top of that, enriches the synergy of quantitative methodologies, interviews, and qualitative insights understanding of road network dynamics. This approach informs more nuanced security policies, fostering safer road networks in conflict areas. Moreover, the study highlights the significance of scientific research in conflict-affected developing countries, emphasizing the reciprocal benefits of mutual learning and growth between diverse environments and the Western world. The **societal relevance** of this research entails enhancing the understanding of terrorism dynamics on road networks in conflict areas, contributing to global peace and infrastructure resilience. Culturally, the research introduces a first step towards a more data-oriented military approach. On an economic note, the developed model can optimize resource allocation, indirectly contributing to economic prosperity. Concluding, findings contribute to the EPA program's mission of fostering interdisciplinary policy analysis, showcasing the importance of tackling multifaceted challenges with integrity and efficacy in both policy and engineering realms.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

LIST OF ABREVIATIONS

EPA	Engineering and Policy Analysis
FAMa	Forces Armees Maliennes
IED	Improvised Explosive Device
IS	Islamic State
JNIM	Jama'at Nusrat al-Islam wal-Muslimin, organisation affiliated to Al-Qaeda
NSA	Network Scan Approach
OED	Explosive Ordnance Disposal

1 INTRODUCTION

This chapter serves as the introduction to this thesis, offering a fundamental framework for the upcoming research. It commences by providing context on the topic. The context is followed by articulating the central problem statement. Subsequently, it identifies gaps in existing research, emphasizing the need for further investigation. Thereafter, the presentation of research questions is given. Furthermore, the chosen research approach is outlined. Next, a brief explanation of how this research relates to the Engineering and Policy Analysis program is provided, showing its possible contributions. Lastly, it provides an outline of the ensuing chapters, providing a roadmap for the reader.

1.1. CONTEXT

On June 26th, 2022, a deeply distressing incident occurred in Bankass, Central Mali, claiming the lives of 132 individuals, making it the deadliest attack in the region in the past two years (VOA, 2022). This violent act was attributed to JNIM, the African branch of the infamous militant organization Al-Qaeda (VOA, 2022). Tragically, this event represents only one of many attacks perpetrated by Islamic militias over the years, reflecting an alarming escalation of violence within the region.

The year 2022 marked a new peak in the increasing trend of terrorism attacks in Mali and the Sahel region overall. In the preceding three months leading up to the Bankass attack, the toll of terrorism claimed the lives of more than 300 civilians and soldiers in the Sahel region (AfricaNews, 2022). These abhorrent acts have been largely claimed by two jihadist groups, Al-Qaeda and the Islamic State (IEP, 2023). Figure 1 underscores the startling rise in terrorism-related deaths, surpassing an increase of 2000% over the past 15 years.

For the purpose of this research, terrorism will be defined following the parameters set by the global terrorism index (IEP, 2023). According to their definition, terrorism involves acts and continuous threats of violence that are politically, religiously, or ideologically motivated and carried out by non-governmental actors (IEP, 2023). It is crucial to note the specific term used for terrorism in this study, as the definition remains a subject of ongoing debate in the literature (Ruby, 2002; Schmid, 2011; Kovacevic, 2019; IEP, 2023). The contentious nature of this discussion arises from the complex nature of the phenomenon.

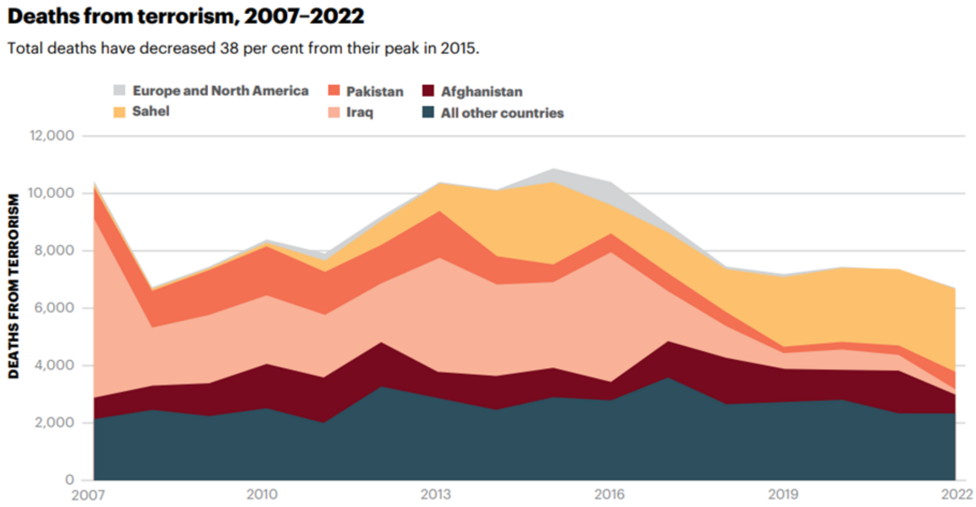

Figure 1. Total deaths from terrorism globally per region from 2007 until 2021 (IEP, 2023).

Of most concern is the fact that the Sahel region has now overtaken the Middle East, North Africa, and South Asia combined, in terms of terrorism-related fatalities, as shown in Figure 2 (IEP, 2023). Moreover, three of the top 5 countries with the highest incidence of terrorism-related deaths are located within the Sahel region. In recognition of this alarming reality, the global terrorism index designates the Sahel as the new epicentre of terrorism (IEP, 2022). These unsettling developments have not gone unnoticed, with the vice-president of the European Commission expressing deep apprehensions regarding the potential consequences on the global community (Borrell, 2022).

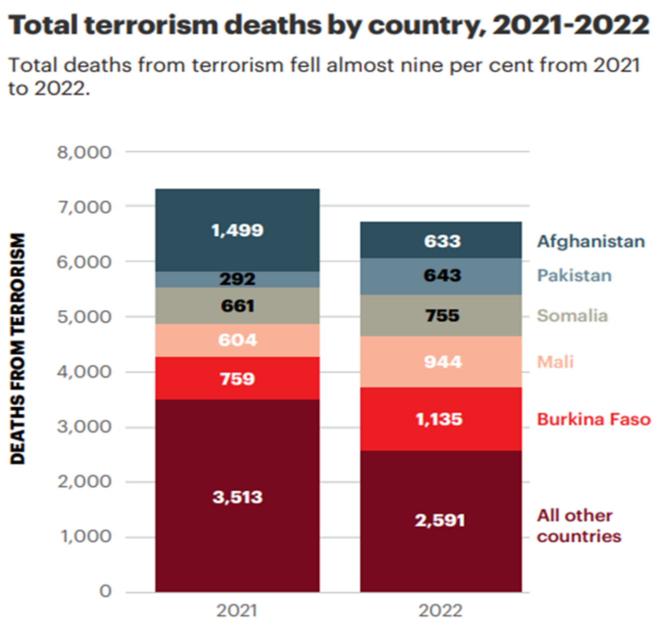

Figure 2. Countries with the highest number of deaths by terrorism in 2021 and 2022 (IEP, 2023).

Among these nations in the Sahel region, Mali has garnered heightened attention due to an alarming surge in terrorism attacks, experiencing a 56% increase in attacks in 2022 compared to the previous year (IEP, 2023). Moreover, not only has the frequency of attacks risen, but they have also grown increasingly lethal (IEP, 2023). Mali, especially when compared to its neighbouring countries, stands out with the highest rise in both the number and severity of these attacks (IEP, 2023).

Researchers argue that the worsening situation especially in Mali can be attributed to its intricate ethnic landscape (Ping, 2014; Mosely, 2017) and impact of climate change (Armstrong, 2022) that form a fruitful fundament for extremist activity (Asaka, 2021; Mavrakou, 2022). The diverse ethnic landscape in Mali characterized by various groups such as the Tuaregs, Peuls, and Bambara, among others has a bloody history mainly because of historical ethnic tensions and desired independence of the national government (Smith & Vivekananda, 2007). This complex ethnic landscape may offer extremist groups a platform to exploit grievances and manipulate local ethnic dynamics for recruitment and support (Ping, 2014; Mosely, 2017). Besides that, Mali is one of the African countries mostly impacted by climate change because of the heavy dependence on relatively simple agriculture (Armstrong, 2022). Drought, heavy rain and overall extreme weather conditions give rise to extreme scarcity of resources. Asaka (2021) and Mavrakou (2022) name the consequences of climate change as an amplifier of terrorist activity via increasing social vulnerability. Climate change-induced resource scarcity, displacement, and livelihood insecurity can intensify competition for already limited resources, potentially exacerbating historical ethnic tensions (Smith & Vivekananda, 2007; Werrell & Femia, 2013). A simplified overview of these dynamics can be found in Figure 3. A more detailed explanation of the conflict in Mali is provided in Appendix A. Hence, while not a direct cause-and-effect relationship, the interplay between these factors has the potential to exacerbate existing vulnerabilities and contribute to an environment conducive to extremist activities.

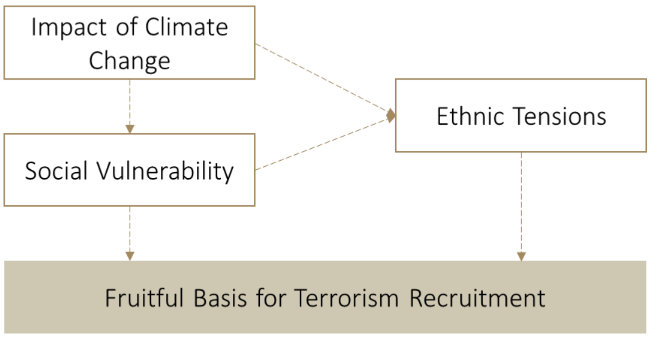

Figure 3. Visualisation of indirect relations between climate change, ethnic tensions and terrorism in Mali. The heavy impact of climate change is amplifying already existing social vulnerability and ethnic tensions in Mali which both add to a fruitful basis for terrorism recruitment.

The prevailing situation prompts policymakers, military leaders, and scholars to grapple with the question of how to achieve stability in countries like Mali (Rebosio & Wam, 2011). In regions affected by terrorism, establishing functional transport networks are proven vital for the stabilization and reconstruction of nations or regions (Rebosio & Wam, 2011; Kaplan & Teufel, 2016). In the case of Mali, the road network emerges as the sole somewhat established transportation infrastructure (Kaplan & Teufel, 2016). Kaplan and Teufel (2016) use Mali as a prominent example to illustrate how the absence of a well-developed road network contributes to a country's fragility. Roads have significant impact over economic well-being, the flow of goods, as well as the maintenance of order and security within a nation (Apostolakis & Lemon, 2005). A vulnerable road network has been found to accentuate inequality, marginalize communities, and foster instability (Kaplan and Teufel, 2016). Consequently, a robust road network aligns with three of the United Nations' sustainable development goals: SDG9, SDG10, and SDG16 (Kaplan and Teufel, 2016).

However, while the road network holds immense significance for the rehabilitation of a country beset by terrorism, the very threat of terrorism exerts pressure on the nation's connectivity. Terrorist attacks, utilizing tactics such as improvised explosive devices (IEDs), limit freedom of movement in Mali (US Department of State, 2021). IEDs target critical infrastructure, governmental figures, and international military personnel, often with unintended civilian casualties. Furthermore, rampant banditry exacerbates the challenges on many roadways (US Department of State, 2021). Terrorist activity like this renders transportation unsafe and posing grave risks to both human lives and cargo (US Department of State, 2021). Given the dual nature of the road network's importance for stabilization and the substantial threat it faces, this research focuses on this critical topic.

In conclusion, the Sahel region has become a focal point of concern due to the alarming escalation of terrorism, culminating in devastating attacks that have claimed numerous lives and disrupted regional stability. Mali, in particular, has experienced a significant surge in terrorist activities, due to amplifying factors of insecurity like an intricate ethnic landscape (Ping, 2014; Mosely, 2017) and impact of climate change (Armstrong, 2022). One of the keys to the reconstruction of a country beset by terrorism is a well-established road network (Rebosio & Wam, 2011; Kaplan & Teufel, 2016), which is under high pressure in Mali because of the very terrorism threat itself (US Department of State, 2021). Therefore this research focusses on the terrorist threats on the road network in Mali.

1.2. PROBLEM STATEMENT

As introduced above, there has been a growing concern for the current situation in Mali (UN, 2023). Finding a solution to the problem is highly complicated as the problem is multilayered.

The first layer of the problem is the increasing terrorism activity by frequency and lethality in Mali. Terrorism is a complicated integration of social, technological and institutional systems (Hayden, 2006). The interrelatedness of many actors like states, civilians, armed forces and radicalised groups add to the complexity. On top of that, is the role of victims and perpetrators highly unclear which makes identification of the problem owner nearly impossible (Argomaniz & Lynch, 2018). The phenomenon of terrorism is so complex that pinpointing direct causes is highly problematic (Pilat, 2009). The increasing impact of terrorism in combination with a bare understanding of the phenomenon asks for further research in the field (Mertens, 2015; Schmid, 2020). In order to assist policymakers and military leaders, it is essential to enhance understanding of the behaviour of terrorist groups to maintain as much safety and security as possible.

The second layer of the problem entails the protection of Malians against terrorist attacks on the road network. As described above, the road network plays a central role in the stabilisation and reconstruction of a country beset by terrorism. The road network provides connectivity which facilitates the exchange of goods and in turn increases prosperity and economic welfare. However, the Malian road network is fragile and on top of that under pressure of terrorist attacks which limit the freedom of movement of Malians. A survey conducted in 2023 sought the opinions of 2295 Malian citizens regarding their top priority for immediate government focus. The survey revealed that an overwhelming 73% of participants prioritized "immediate physical security" as the foremost concern (Klatt, 2023). In comparison, "agricultural development" secured the second position with 49% support, while "peace restoration" ranked only sixth. Remarkably, "construction of roads and infrastructure" garnered a mere 5% and held the ninth position in citizens' preferences. This data underscores the pressing urgency of addressing physical security on the road network instead of expanding the network by constructing new roads. Hence, the second layer of the problem is the necessity of ensuring the safety of individuals on the road network to uphold connectivity.

The next layer of the problem faces the dynamics of road network protection. Protection of a road network is highly complicated. Little research is found on existing policies on road network protection in conflict areas. Especially in a country like Mali with a surface of 1,24 million square kilometres (RVO, 2022). It is however known that military and police checkpoints are used in Mali to prevent attacks or violence (Department of State, 2023), but no further literature can be found on this topic. Regarding IEDs, the literature is elaborate on the prevention of fabrication (Wilson, 2007) but is not very extensive on the prevention of IED placement. Hence, the third facet of the problem involves comprehending the types of attacks that road networks face in conflict zones and devising strategies to safeguard the network, thereby preserving connectivity.

The multilayered challenge of terrorism affecting Mali's road network (IEP, 2023), coupled with the urgent requirement for enhanced physical security for Malians (Klatt, 2023), beckons the scientific community to focus on this geographic region. As a result, this thesis confronts the issue of the enigmatic nature of terrorism and the imperative to comprehend strategies for safeguarding road networks to ensure sustained connectivity.

1.3. RESEARCH GAPS

The identified research gap that emerges comprises four main dimensions.

Firstly, the understanding of road network dynamics within a terrorist context remains inadequate. Scarce literature exists on safeguarding road networks, particularly in a geographical area similar to Mali. While literature addresses the types of attacks impacting movement in conflict zones, this lacks specificity to Mali. There is a notable absence of literature on road networks protection policies from attacks, despite the existence of measures like military convoys and checkpoints.

Secondly, there is a dearth of literature concerning connectivity on road networks within conflict areas. Connectivity is often examined through the lens of network science, a widely used tool for a understanding of complex systems such as road networks (Latora & Marchiori, 2005). Network science is a data-driven approach of mathematical nature that is able to describe and make computations on networks (Barabási, 2013). Network science has the capability to assess the criticality of specific road segments (Latora & Marchiori, 2005), thereby indicating the necessity for protective measures. However, network science research on road networks in a terrorism context mainly pertains to Western and Asian geographies, largely neglecting conflict areas that crucially require enhanced connectivity for rehabilitation of a country or region.

Thirdly, is research on allocation of protective resources over a road network is highly limited. A method that is widely used for studying resource allocation and studying terrorist behaviour is game theory

(Sandler, 2003; Fang et al., 2016). Game theory is based on a game with players, payoffs, strategies and a particular information structure (Lindelauf, 2021). In game theory, optimal strategies are derived through Nash equilibrium, a decisive end point. Yet, game theory's application to protecting transportation network connectivity is an uncharted realm.

Lastly, the application of criticality measures as pay-offs within a game theoretical model introduces a novel approach. This fusion of methodologies holds promise, as game theory's optimal strategies can align with criticality measures. This combined approach holds potential to enrich policy formulation for security stakeholders.

To conclude, the identified research gap encompasses inadequacies in understanding road network dynamics in terrorist contexts, a lack of literature on connectivity within conflict areas, limited research on protective resource allocation for road networks, and the innovative application of criticality measures within a game theoretical model. Beyond practical implications, this study contributes to academic fields encompassing counter-terrorism, network science, and game theory within conflict settings. Consequently, the study aspires to deepen the comprehension of safeguarding pivotal segments of road networks against terrorist threats.

1.4. RESEARCH QUESTIONS

To address the existing knowledge gap, an in-depth exploration will be conducted into road network dynamics and protective resource allocation, with the situation in Mali serving as a case study. This choice is motivated by Mali's profound exposure to terrorism, offering potential contributions to the UN mission MINUSMA and Malian anti-terrorism initiatives. Consequently, the central research question is as follows:

How can road network protection be enhanced such that terrorist attack impact is minimized by allocating protective resources in conflict areas?

This core query will be tackled through the following sub-questions, briefly summarised in Figure 4. A detailed overview of the research design can be found in Appendix A.2.

SQ1: What is the state of the art of Malian road network protection against terrorist attacks?
This sub-question aims to comprehend the prevailing road network protection measures in Mali. The answer to this question explains the basis of the model, including the players and the strategies. It forms the playing field of the game. Stakeholder interviews will be utilized as research approach as literature on road network protection is highly scarce and specific to the context of Mali non-existent.

SQ2: How can protective resources be allocated over critical road segments?
This sub-question initially seeks to determine a suitable approach for identifying and ranking the criticality of road segments in relation to terrorist attacks. Through an extensive literature review, the most relevant criticality measure for this specific context will be assessed. Secondly, this sub-question addresses the allocation of protective resources. Game theory has been identified as a valuable tool for modelling interactions between terrorists and governmental entities, and a separate literature review

will be conducted to determine the most appropriate game theoretical approach. This research question shapes the structure of the model, it provides a guide on how to calculate the criticality measures which will be the pay-off values and it provides the rules to which the model will adhere.

SQ3: How can the allocation of protective resources over critical parts of the road network be modelled taking into account adversary actions in the case of Mali?
This sub-question integrates the two previous sub questions into a game theoretical model with criticality values as pay offs. It further deals with any difficulties creating a formal model from a conceptual one. This will entail dealing with all the problems that may arise when implementing the game to the specifics of Mali. The outcome of this model will suggest an optimal resource allocation distribution for the players.

RQ4: How can protective resources be optimally distributed over the road network in Mali according to the developed model?
This sub-question delves into the outcomes of the model, directing its inquiry towards the optimal allocation of protective resources across the road network as guided by the model. It initiates by analysing the critical road segments and its ranking pertinent to Mali's connectivity, a process aligned with the approach selected in SQ2. Subsequent investigation entails an in-depth analysis of both the optimal strategies for defenders and attackers. An examination of the comparison between the model-derived optimal attacker strategy and the empirically observed attacker behaviour aids in enhanced understanding the dynamics of adversary actions. It is worth noting that the optimal defender's strategy, owing to considerations of classified military intelligence, remains exempt from direct comparison to real-world implementation. Ultimately, this section offers protection policy recommendations grounded in the obtained criticality values, optimal strategies, and the comparison between the attacker's optimal strategy and empirical terrorist data.

RQ5: How can the approach and results be generalized for allocating resources to protect road networks against terrorist attacks in conflict areas?
The final sub-question delves into the prospect of extending the methodological framework and findings beyond the specific context of Mali, thereby encompassing diverse geographical settings. It entails a comprehensive evaluation of how the method and insights obtained can be adapted for safeguarding road networks in various locations facing similar security concerns. By analysing the inherent principles and insights derived from the model, this sub-question aims to identify generalizable lessons that can be adapted to other regions facing similar threats. The aim is to identify the requirements for the model's applicability and explore assumptions that need consideration during its implementation within other geographical contexts.

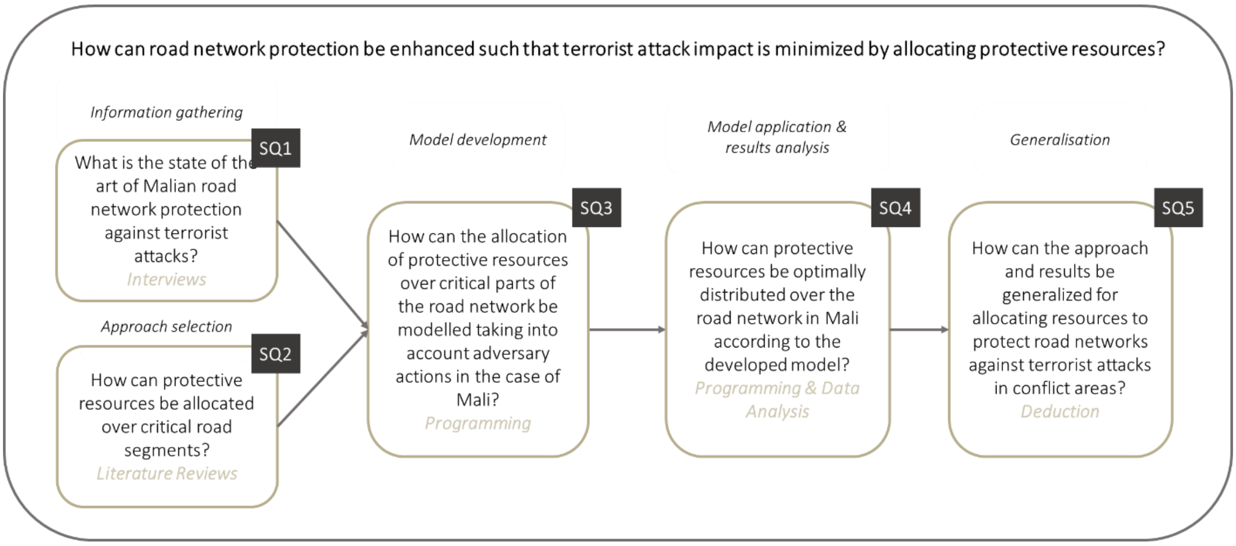

Figure 4. Research design overview

1.5. RESEARCH APPROACH

1.5.1. RESEARCH DESIGN OVERVIEW

In order to answer the research question, this study is divided into three phases which include the different sub questions. A brief overview is displayed in Figure 4 while a detailed version can be found in Appendix A.2. A combination of approaches will be used to find answers to all research questions. This chapter gives an overview of all phases, how they correlate to the research questions and what methods will be used.

This research employs a combination of modelling and case study approach. A game theoretical model is developed by using input from a network science approach and interviews with experts. In order to use the right modelling method and network science approach literature review is conducted. The model will use the Malian road network which is plagued by terrorism as a case study.

1.5.2. PHASE I – DATA COLLECTION AND METHOD SELECTION

To establish a comprehensive model, a broader information foundation is essential to enhance our understanding of the issue. This data collection process comprises three primary components.

Firstly, it is imperative to gain insight into contemporary strategies for safeguarding road networks against terrorist threats. This entails comprehending the spectrum of attack types targeting road networks and discerning the mitigation policies employed. To achieve this, interviews with domain experts in Mali will be undertaken. The outcome of these interviews will be the basis of the model, it determines the players, strategies and information structure.

Secondly, the investigation focusses on the optimal distribution of protective resources across critical road segments. This entails methodological considerations on two fronts: identifying a robust approach for resource allocation and determining methodologies for identifying critical road segments. To address these aspects, a comprehensive review of pertinent academic literature will be conducted.

Lastly, the acquisition of geospatial data pertaining to the road network is a requisite. OpenStreetMap will serve as the primary source for this dataset, which will subsequently undergo data cleaning and preparation utilizing the Python programming language. The analysis of geospatial attributes will be facilitated by leveraging the capabilities of the GeoPandas Python package, renowned for its efficacy in geospatial data manipulation (GeoPandas, 2021).

1.5.3. PHASE II - MODELLING

The modelling phase involves the construction of a game theory model, comprising key components such as players, strategies, payoffs, and information structure. The precise configuration of these components will be dictated by the outcomes of Phase I. Preliminarily, the game is envisaged to involve two primary players: protective forces and terrorists. The formulation of the defenders' and attackers' strategies is contingent upon insights derived from Phase I. Determining the payoffs demands meticulous scrutiny, contingent upon Phase I findings as well. Given the intricate nature of this interplay, a conceptual model will be initially formulated, followed by the development of a formal model integrating Mali's critical road segments as the game's environment.

For the development of the game, Python will be harnessed, with a specific emphasis on the Nashpy library in the case of a two-player game. Nashpy, an open-source project, offers robust functionalities for game creation and equilibrium identification (Nashpy, 2017).

1.5.4. PHASE III - RESULTS

The concluding phase involves an examination of the game's results. These outcomes, in a game theoretical model, encompass a set of optimal strategies that attain equilibrium. An equilibrium is reached when players cannot achieve better outcomes individually (Lindelauf, 2021). The anticipation is that optimal strategies will be ascertained for both parties, allowing the resolution SQ4. The analysis of results will encompass a comparative study involving reported incidents within the region. Subsequently, the final step encompasses a process of generalization, aiming to extend the insights garnered from the optimal resource allocation in Mali to a broader context.

1.5.5. SCOPE OF THE MODEL

The research scope is deliberately delimited and necessitates elucidation. The model's application is confined solely to the Segou region. This choice arises from the alignment between the geopolitical landscape of Segou and the assumptions of the selected game theoretical model derived from the literature review. The model will integrate two variants of criticality measures: firstly, based on the national road network, and secondly, grounded in the regional road network. This duality aims to explore whether the spatial boundaries of criticality measures influence the outcomes of optimal strategies.

An crucial note is the fact that the research focuses and is limited to the distribution of resources. The model thus assigns percentages of the total available resources to different road segments. The percentages thus represent the optimal resource distribution strategy. The costs of these allocations lie outside the scope of this investigation. This deliberate choice originates from the classified nature of detailed information on the resources available to armed forces' within the region, making exact numerical estimations unattainable for public disclosure For the same reason can a comparative analysis only be conducted between the derived optimal attacker's strategy and attacker's empirical data as this data is open source. Conversely, empirical data for the optimal defender's strategy is both unavailable and ethically unsuitable for inclusion.

While in the first phase of the research, experts in the field are interviewed on existing measures of road network protection, the sole purpose of those interviews is to understand the dynamics on the road network. For instance to understand what types of measures provide road network safety and what types of measures have different goals like intercepting smugglers. These interviews are thus not conducted to make numerical estimations of the sizes of armed forces.

The underlying aim of this research is to construct a model that offers guidance in the allocation of resources. The ultimate step, involving the application of the model-derived percentages to real-world resource distribution of military resources and subsequent comparison with actual strategies, is envisioned as an independent undertaking by policy makers or military analysts.

1.6. EPA RELEVANCE

This study functions as a master thesis for the master program Engineering and Policy Analysis (EPA) at TU Delft. So called grand challenges, lie at the centre of the EPA programme. Grand challenges are large-scale problems characterised by high complexity, high uncertainty and evaluative (Ferraro et al., 2015). This thesis assesses a multi facet problem that relates to various grand challenges. On one hand, the grand challenge of protection against terrorism is addressed which relates to global peace UN sustainability goal (SDG16) (Jarzabkowski et al., 2019). On the other hand the study focusses on the protection of transport which relates to grand challenges as infrastructure resilience (SDG9) and indirectly reducing inequalities (SDG10) (Kaplan and Teufel, 2016).

The highly complicated problem at hand is viewed systematically by breaking the problem down step by step. The problem is seen as a complication with interplay between terrorism, critical infrastructure and protection policy. The study will on one hand contribute to improved policy decisions on protection against terrorism and on the other hand provide new scientific insight in the cutting edge technique of combining network science and game theory. The EPA relevance found in the outcome of the research is described in Chapter 5.6.

1.7. STRUCTURE

The thesis is structured into several chapters, each subsequently addressing specific research objectives. Chapter 1 introduces the study's context, presents the research problem, and formulates research questions. It also identifies research gaps and discusses the research approach, subsequently highlighting EPA relevance and outlining the report's structure. Chapter 2 follows with a comprehensive literature review, delving into network science, game theory, and synthesizing relevant findings. In Chapter 3, the research methods are detailed, including expert interviews, data collection and processing, criticality analysis, and game theory methods. Subsequently, Chapter 4 is the results and discussion section and discusses key insights from expert interviews, criticality results, and game theory outcomes. Chapter 5 concludes the thesis by offering a summary and recommendations, addressing research questions, policy implications, limitations, and suggestions for future work. After which, Chapter 5 explores the scientific, societal and EPA relevance of the study. Lastly, the thesis includes a References section and Appendices containing supplementary information.

2 | LITERATURE REVIEWS

This chapter embarks on an in-depth analysis of relevant literature, playing a fundamental role in shaping the trajectory of this research. Through the PRISMA method, this chapter navigates through various aspects of existing scholarship, aiming to illuminate methodologies on criticality measures for road networks and game theoretical models for resource allocation. This chapter aims to present a comprehensive overview of the existing research landscape in order to select fitting methodologies for this research. The chapter is organized in a systematic fashion, encompassing a methodological overview, a detailed presentation of literature review, and a synthesis that integrates key findings to guide the subsequent stages of the research.

2.1. METHODS OF LITERATURE REVIEW

To conduct this literature review, chapter four of the book Writing for Science and Engineering (Silyn-Roberts, 2013) has been used as a guideline. The PRISMA method (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) is used as systematic core to this literature review, as the method has the advantage of circumventing the author's bias (Selçuk, 2019). In brief, the PRISMA method consists of four steps. Firstly, screening all articles in a certain area and in- or excludes them based on a set of requirements. In this literature review, a more flexible approach has been applied by allowing snowballing from relevant articles as well. Snowballing was done using the AI webtool 'Litmaps' (Litmaps Ltd., 2023).

Relevant articles were selected from the search engine Scopus. The research gap is addressed by synthesise information in two main areas: road criticality and road protection modelling. Within the field of network science the overlap between three key words has been examined:

1. Road network
2. Criticality
3. Terrorism

In the field of road protection modelling two key words has been studied:

1. Game theory
2. Network
3. Resource allocation

In the database these key words were supplemented with synonyms or words close to synonyms. An overview of the final query is provided in Table 1.

TOPIC	QUERY
NETWORK SCIENCE	("road network" OR "transport network") AND ("criticality" OR "centrality" OR "network science" OR "vulnerability") AND ("military" OR "terrorism" OR "violence")
ROAD PROTECTION MODELLING	("game theory") AND (“network”) AND (“resource allocation” OR “checkpoint” OR "control post")

Table 1. Literature Review Search Terms

Limitations of queries were set to English, no limitation was handled for timing or geographics of the publication. The first query led to a collection of 11 articles of which one was found to be overarching. The second query led to the collection of 8 articles. Articles related to the protection of autonomous vehicles and internet of vehicles were excluded as these studies focus a digital network between vehicles and therefore were found to be irrelevant for the proposed study. An overview of the results of each stage of the PRISMA method can be found in Appendix A.3.

2.2. RESULTS OF LITERATURE REVIEW

2.2.1. CRITICALTIY MEASURES ON ROAD NETWORKS

Background of Network Science

The assessment of network criticality, which involves evaluating the significance and vulnerability of nodes and edges within a network, has garnered considerable attention in recent years (Holme & Saramäki, 2012; Watts, 2004). To comprehend and analyse network criticality, researchers have increasingly turned to network science, an interdisciplinary field that integrates concepts from mathematics, computer science, and physics to study complex systems (Barabási, 2016; Newman, 2010). Through the application of network science methodologies, researchers can identify key components and structural properties of networks, such as node centrality, community structure, and robustness, which are pivotal for network functioning (Albert & Barabási, 2002; Freeman, 1978). This enables a comprehensive understanding of how specific nodes and edges impact information flow, network resilience, and the overall reliability of complex systems (Boccaletti et al., 2014; Newman, 2003). This literature review aims to explore the utilization of network science in assessing network criticality within the context of terrorist attacks.

Road Criticality with Regards to Natural Disasters

An elaborate field has examined the criticality of transportation network components with regard to natural hazards (Kruse et al., 2021). Academics have looked at the criticality of the road network for tropical cyclones (Yang et al., 2018), earthquakes (Aydin et al., 2018), floods (Colon et al., 2021)) and volcanic eruptions (Hayes et al., 2022).

In the various applications, diverse approaches are employed to evaluate the criticality of road networks. However, Yang et al. (2018) shed light on the dissimilarities between assessing criticality for natural hazards and terrorist attacks, emphasizing three key distinctions. Firstly, terrorist attacks typically consist of a single or a few concentrated strikes, whereas natural hazards tend to affect entire regions. Secondly, the likelihood of recurrence for natural hazards differs significantly from that of terrorist attacks. Yang et al. (2018) explains further that the probability of a natural hazard happening again is higher than that of an attack. Lastly, while the duration of natural hazards is often taken into consideration, it holds less significance when analysing terrorist attacks. Given these disparities in criticality rankings between natural hazards and terrorist attacks, it is prudent to focus on the specific field of criticality ranking concerning critical infrastructure vulnerability to terrorist attacks.

Road Criticality with Regards to Terrorist Attacks

The criticality of infrastructure specifically in the context of terrorist attacks was mainly based on the connectedness of the nodes before 2005 (Latora & Marchiori, 2005). Latora and Marchiori (2005) were one of the first to introduce a graph-based method that assessed the performance of a network by eliminating segments one by one and set by set. The performance of a network was associated with a single value, also called the efficiency of the network. The network efficiency can be defined in multiple ways. Firstly with the inverse of the average shortest path length and secondly with the average flow rate. The further this value decreases by the elimination of certain elements, the more critical the elements were found to be. Based on the assessment, the criticality of a network segment was determined and thus should be prioritised in protection against terrorism. The methodology was tested on multiple applications including the Boston subway network. The study laid the foundation for using network science for criticality measures with respect to terrorist attacks (Scott et al., 2006).

In that same year, Apostolakis and Lemon (2005) described another new method to identify and rank critical infrastructural segments by their criticality for the purpose of understanding vulnerability towards terrorist attacks. Similarly, Apostolakis and Lemon (2005) proposed a method based on network science as well. However, their approach to criticality is very different compared to the approach described before. Where Latora and Marchiori (2005) calculate the criticality, Apostolakis and Lemon (2005) make the decisionmaker decide what elements of the graph are of most importance to them. The first step is to identify possible vulnerabilities, the identification is not further than the fact that the user has no service anymore. In the second step, the decision maker appoints a value to these vulnerabilities in a systematic way using the multiattribute utility theory (MAUT). MAUT means that the decision-maker assigns a disutility of achievement to each vulnerability. The method is tested on a gas distribution network of 6 buildings. The method results in more than 1000 vulnerabilities. The method of Apostolakis and Lemon have had a serious impact on evaluating criticality of complex systems. Extensive further development of their method happened in the field of electrical transmission system networks (Bier et al., 2006). Bier et al. (2006) explains however that the methods developed in this field differentiate from other networks as electrical networks adapt dynamically to disruptions. Consequently, these models are unsuitable for identifying geographical locations in infrastructure.

Apostolakis built further on that methodology in cooperation with Patterson in 2006 by adding a Monte Carlo network analysis and spatial analysis to identify locations where multiple infrastructural critical elements overlap. The method however does not disaggregate further than the regional level.

In that same year, Scott et al. (2006) introduced a novel and inclusive methodology for identifying critical links and assessing network performance. The approach, named the Network Robustness Index, takes into account various factors, including network flows, link capacity, and network topology, in a system-wide manner. Additionally, it relies on easily accessible sources of data, which enhances its practicality and applicability. Through the utilization of three hypothetical networks, the authors illustrated the effectiveness of the approach, referred to as the Network Robustness Index. The Network Robustness Index incorporates traffic volume and travel time to evaluate the effect on the average travel time when a link is removed. Scott et al. (2006) also explain the gamma index, which serves as a valuable metric for assessing the overall connectivity of the network in relation to other factors. The Network Robustness Index has been acknowledged in subsequent literature (Dowds et al., 2017) as a firmly established method.

In 2007, Taylor and D'este developed a method to identify critical locations in transport infrastructure systems. The driving idea of the study was a growing concern for natural disasters and human sabotage in cases of war or terrorism. They see the most critical locations as the locations with the most socio-economic impact when disrupted. Taylor and D'este analysed the Australian National Highway System. Their methodology entailed a weighted travel cost approach that takes distance as well as population size into account. The study pointed out four highway parts as the most critical. An advantage of this method is that the approach accounts for demographic influence as well besides a solely numerical perspective like betweenness centrality. One aspect that is not taken into account is that multiple road segments might be targeted simultaneously. It is an important aspect to note as two roads might be able to substitute each other, but when attacked simultaneously disconnection of the network may occur.

On the contrary, Segovia et al. (2012) use two link-based approaches. The heuristic methods focused on transport network resilience and specifically on large-scale failures (multiple links destroyed simultaneously). The authors refer to intentional attacks as potential causes of such large-scale disruptions. The assumption is made that there is the possibility to protect a limited number of links from attack. Firstly, the betweenness centrality method is proposed. The limitation of this approach is stated to be the fact that the betweenness centrality depends on the original topology of the graph. When the network is disrupted, the betweenness centrality of the links might change. Therefore, the betweenness centrality can merely be seen as an approximation. The second approach is the observed link criticality method. In this approach, every link has an accompanied 'counter value' that represents how many paths use the link. The relative importance is then measured by dividing it by the total number of active connections at a specific moment. Using a moving average, the criticality of a link is determined subsequently. As general features of a network, the authors look at network diameter, average shortest path, and average nodal degree.

Another method developed by Rodríguez-Núñez and García-Palomares (2014) uses a real trip distribution in combination with increase of travel time in order to assess the criticality of not only the nodes but the links as well in case of disruption including disruptions by terrorists. The increase of average travel time over the whole network is calculated for the disruption of each link and is multiplied by the total number of trips generated from a particular node. This method was applied to the metro network of Madrid.

In their study, Cats and Jenelius (2015) focused on examining the robustness of public transport networks against unforeseen disruptions, such as terrorist attacks. They developed an agent-based model that incorporated stochastic supply and demand models, dynamic route choice, and limited operational capacity. The model was applied to the rapid Public Transport Network (PTN) in Stockholm. Various scenarios were tested, and the model successfully identified priority segments within the network to enhance its overall robustness against disruptions.

Another recent robustness method for targeted attacks, developed by Kim and Yoon (2019), was applied to the air route transport network in Northeast Asia. Weighted, unweighted, and demand-weighted air route segment networks were considered. The study compares a few topological features of the regional network and national networks like average degree, characteristic path length, and clustering coefficient. Node importance was determined by strength, weighted closeness, and weighted betweenness. However, link importance was not considered as this is typically irrelevant in the case of air routes.

In 2021, Zhang and Thomas looked specifically at public transport networks. They identified and quantified the criticality of intersections for disruptions including terrorism. They state that degree centrality does not explain the whole story as it does not respect the criticality of the adjacent nodes. Moreover, do betweenness centrality and closeness centrality neither meet the desired characteristics as both have a high computational complexity and are relatively limited. For these reasons, They introduced a new method, the EWM-TOPSIS (entropy weight method - technology for order preference by similarity to an ideal solution). The EWM is a common method used for weighing factors in decision-making to measure structural complexity and information size. On the other hand, TOPSIS is a multicriteria decision-making approach that addresses the problem of inaccurate assessments and avoids relying solely on a single criterion. The method proposes calculating the centrality degree, betweenness centrality, and closeness centrality, which are standardized in a matrix. The objective weight is then calculated and subsequently standardized. The distances to the ideal solutions are subsequently calculated. Then, the relative closeness degree is computed, and the rank node importance. The reasoning of the high calculation complexity however, and the used method seem contradicting. The method was applied to Hong Kong's metro system.

2.2.2. GAME THEORY FOR RESOURCE ALLOCATION ON NETWORKS

Background of Game Theory

Game theory is a mathematical framework used to analyse and understand strategic decision-making in situations where multiple participants, referred to as players, interact with each other. Originating in the field of economics, game theory has found applications in various disciplines such as political science, biology, and computer science. Neumann and Morgenstern (1944) explained that game theory can provide a formal structure for modelling and predicting the behaviour of rational individuals or organizations in strategic interactions. It focuses on the study of games, which are abstract representations of real-world situations involving conflicting interests and choices. Using mathematical models and concepts like players, strategies, payoffs, and equilibrium, game theory enables researchers to analyse different strategies and outcomes, helping to determine the optimal choices for individuals and predict the behaviour of others in interactive decision-making scenarios (Binmore, 2007). By studying the strategic interactions among players, game theory provides valuable insights into human behaviour, cooperative and competitive strategies, and the dynamics of negotiations and conflicts.

Game theory has emerged as a valuable tool for policymakers and researchers in studying terrorism specifically, as evidenced by the works of Sandler (2003) and Lindelauf (2021). Its applicability stems from several key factors. Firstly, game theory enables the incorporation of strategic behaviour exhibited by both terrorist and governmental actors involved in the conflict. By considering the actions and reactions of each party, decision-makers can anticipate and plan accordingly. Secondly, the approach consists of the possibility to foresee actions and reactions thereof. That means that there exists and interplay between strategies. Thirdly, the framework accommodates the analysis of threats and promises exchanged between the parties, providing insights into the dynamics of negotiation and coercion. Additionally, game theory facilitates the optimization of goals within specific constraints, as both sides strive to maximize their desired outcomes. Notably, the information structure in terrorism often involves limited knowledge and uncertainty, making it a fitting context for game-theoretic analysis. Consequently, the widespread use of game theory in military and terrorist contexts is unsurprising, given its ability to capture the complexities of these scenarios (Lindelauf, 2021). The following section therefore aims to provide a comprehensive overview of the existing literature on game theory models that allocate protective resources over road networks.

Lindelauf (2021) provides an overview of the different types of games that exist in the field of game theory. These types will be kept in mind when discussing the literature to be able to find the best fitting type of game for this study.

1. Cooperative versus Non-cooperative Games: In cooperative games, players have the option to negotiate and form alliances with each other. Conversely, non-cooperative games do not allow such alliances, and players act independently.
2. Games of (In)complete Information: In some games, players possess complete knowledge of the game's payoffs and the strategies chosen by other players. In contrast, games of incomplete information involve uncertainties and partial knowledge about the payoffs or strategies of other players.
3. Simultaneous versus Sequential Games: In simultaneous games, players act simultaneously without awareness of other players' actions. In sequential games, each player is aware of the actions taken by others, and the moves occur one after another.
4. Symmetric versus Asymmetric Games: In symmetric games, all players share identical goals, and the outcome solely depends on their chosen strategies. On the other hand, asymmetric games entail differing goals or roles for each player, influencing the game's dynamics.
5. Perfect versus Imperfect Information Games: Perfect information games entail players having complete knowledge of all moves made by other players throughout the game. In contrast, imperfect information games involve uncertainties or partial knowledge about the moves made by other players.
6. Zero-Sum versus Non-Zero-Sum Games: In zero-sum games, one player's loss directly translates to another player's gain, resulting in a constant total payoff. Non-zero-sum games, however, do not adhere to this strict relationship, allowing for varying total payoffs among players.

Game theoretical Models for Resource Allocation

As a reaction to the Mumbai attacks in 2008, several game theoretical models focussed on terrorism specifically. Jain et al. (2011) analysed police resource allocation strategies in a zero-sum game. In game theory, a zero sum game is a type of game where the gains of one player come at the direct expense of the other player(s), resulting in a zero-sum outcome. The game models attackers moving from one node to another while the defender selects nodes to place checkpoints in order to intercept the attacker. While the model thus shows some similarities with the case of Mali, the overarching goal is different. It is not to protect the network, it is to intercept the attacker. Therefore, the payoffs are solely binary. The model has been applied to the city of Mumbai, which is a significantly smaller scale compared to the country of Mali. The main difference therefore is that only nodes are considered as a possibility to place protection and not the edges.

A well-cited study by Jain et al. (2013) developed a novel method SNARES (Securing Networks by Applying a Randomized Emplacement Strategy) to protect a road network against an opponent. This model included edges as possible places for checkpoints. The attacker still moves from any node to any other node. The rest of the model is similar to the model of 2011. The SNARED method does provide a more efficient way that makes computation less heavy. therefore it was possible to apply to the whole road network of Mumbai.

A recent study by Li et al. (2022) analysed the transportation protection of hazardous materials against terrorist attacks. The methodology included the identification of key urban roads that are most likely subject to terrorist attacks and applying a game theoretical systematic risk management approach. The risk management approach consisted of four risk scenarios. The game theory model was constructed as a non-zero, two-person game. The case of the Beijing was subsequently used to test the effectiveness of the study.

Baïou and Barahona (2022) studied a security network and define a cooperative game between a player that is moving over arcs and other players that control checkpoints on the arcs. A polynomial combinatorial algorithm calculates the nucleolus of the game. The nucleolus results display an allocation of resources, where larger values point at more significant locations to place resources.

Game Theoretical Models for Network Protection

In the perspective of urban security, Tsai et al. (2010) applied an attacker-defender Stackelberg game model as a strategic framework for resource allocation. The defender's primary objective is to devise an optimal mixed strategy to distribute resources efficiently. However, the computational complexity of the problem escalates exponentially with the number of resources for the defender and with the network size for the attacker. As a result, Tsai et al. found existing algorithms falling short in addressing this challenge, especially in larger networks. To overcome these limitations, this review introduces a solution approach based on two key ideas. Firstly, a polynomial-sized game model derived from approximating the strategy space, efficiently solved through linear programming techniques. Secondly, two efficient techniques for mapping solutions from the approximate game model to the original, supported by proofs of correctness under specific assumptions. Notably, the approach's effectiveness is supported by in-depth experimental results, including a comprehensive evaluation on a segment of the Mumbai road network.

Brown et al. (2014) built further on the defender-attacker Stackelberg game framework and developed randomized traffic patrol strategies in Singapore. Addressing scalability and unpredictability challenges, the application employs a Markov Decision Process for dynamic patrol planning and introduces a compact game representation with adversary and state sampling. This study is thus less focussed on counterterrorism, it does include patrolling. The approach optimizes patrol strategies through a objective optimization problem, striking a balance between violation reduction and increased presence. Real-world traffic data evaluation demonstrates the promising potential of STREETS for enhancing urban security and law enforcement efforts.

In 2020, Yingmo et al. used again the Stackelberg game framework to allocate public safety resources more effectively over a road network to inspect drunk driving. Firstly, the issue of drunk driving was simulated as a defender-attacker Stackelberg game. In the game, the law enforcement agency (the defender) allocates public safety resources in a traffic network to arrest drunk drivers (the attackers), and the attacker seeks to choose a feasible route given the defender's strategy to maximize the escape probability. Second, we develop an effective approach to compute the optimal defender strategy based on a double oracle framework. Third, we analyse the complexity of the defender oracle problem. Then, we conduct simulations on directed graphs, which are abstracted from the city traffic network in Dalian, China, to demonstrate that our scheme achieves a robust solution and higher utility, and is capable of scaling up to handle realistic-sized drunk-driving problems.

In 2022, Chen et al. built a simple yet effective attacker-defender game theoretical model on the protection of water treatment plants. It finds optimal strategies by finding the Nash equilibrium. The optimal Nash equilibrium was compared to alternative distribution strategies based on risk assessment. The results presented the Nash equilibrium as optimal strategies. The game is based on a zero-sum game as the two players have opposing interests. A case study was conducted on 5 water treatment plants on networks in the middle of China.

2.3. SYNTHESES OF LITERATURE REVIEWS

This section provides an overview of the existing literature in the field of criticality measures by network science in the context of terrorist attacks and in the field of resource allocation by game theory in the context of terrorist attacks.

2.3.1. CRITICALTIY MEASURES ON ROAD NETWORKS

A total of 10 methods were identified for assessing the criticality of road segments using network science. Table 4 provides an overview of these methods. Based on their applicability to the case of Mali, these methods were categorized into four groups.

Firstly, four methods were deemed unfeasible for execution in the context of Mali due to the lack of necessary data. One such method is the network robustness index (Scott et al., 2006), which requires traffic volume data that is unavailable in Mali. The MAUT methodology and the MAUT methodology with a Monte Carlo network analysis are also not viable options for the road network of Mali either due to two primary reasons. Firstly, decision-makers would need to assign a disutility value to all road segments, leading to an overwhelmingly high number of vulnerabilities for a large network like Mali's road network. Secondly, in the case of Mali, the need for an analysis of criticality arises precisely because decision-makers lack knowledge about which segments are more valuable compared to others, rendering the fundamental assumptions of this method incompatible with the case. Lastly, the method developed by Rodríguez-Núñez and García-Palomares (2014) was found to be impossible for Mali due to the unavailability of real trip distribution data in the country.

The second category comprises basic centrality methods, including centrality degree, network efficiency, and the two link-based approach. While the first two methods are considered viable options, they are regarded as relatively simplistic. The observed link criticality method is more advanced, utilizing a combination of betweenness centrality, the number of active connections, and a moving average. While it does consider attacks on multiple geographical locations simultaneously, its application to a large network like Mali's road network would result in high computational intensity. Additionally, a drawback of this method is that it is heuristic, implying that it may not necessarily yield an optimal solution.

The third category consists of more advanced methods. Firstly, the network scan approach, which is specifically developed for road networks, and highly promising for the case of Mali. This approach strikes a balance between simplicity and detail by utilizing shortest paths while also considering population sizes, travel distances, and travel times. The other two advanced methods are a combination of centrality measures and the EWM Topsis approach. However, these methods can only calculate criticality for nodes and not for edges, making them less relevant to the case of Mali.

Proceeding to the final category, it encompasses the Agent-Based Modelling (ABM) approach. Nonetheless, this method is deemed inapplicable for the current study due to its exigent development process. Moreover, the creation of a coherent model employing this approach necessitates a distinct and dedicated investigation, which does not match the research objectives of this study.

CATEGORIZATION	AUTHOR	METHODOLOGY	NECESSARY DATA	APPLICATION
IMPOSSIBLE	Scott et al. (2006)	Network Robustness Index	Traffic volume, traffic time	Multiple including Boston subway network
	Apostolakis and Lemon (2005)	MAUT	Decision-maker's perception of disutility of achievement to each vulnerability	Gas distribution network of 6 buildings
	Apostolakis and Patterson (2006)	MAUT with Monte Carlo network analysis and spatial analysis	Decision-maker's perception of disutility of achievement to each vulnerability	MIT infrastructur e
	Rodríguez-Núñez and García-Palomares (2014)		Real trip distribution in and travel time	Road network of Madrid
BASIC CENTRALITY METHODS	Multiple authors before 2005	Centrality Degree		
	Latora and Marchiori (2005)	Network Performance	Average shortest path length or average flow rate	Multiple examples
	Segovia et al. (2012)	Observed link criticality	Shortest paths, nr of active	Transport networks

			connections at a specific moment and moving average	
ADVANCED	Taylor and D'este (2007)	Network Scan Approach	Distance, population size and travel times	Australian national highway system
	Kim and Yoon (2019)	Combination of centrality measures	Degree centrality, characteristic path length, and clustering coefficient. Node importance was determined by strength, weighted closeness, and weighted betweenness.	Air route transport network in Northeast Asia
	Zhang and Thomas (2021)	EWM Topsis	Centrality degree, betweenness centrality, and closeness centrality	Hong Kong's metro system
EXTREMELY ADVANCED	Cats and Jenelius (2015)	ABM model		Stockholm's rapid PTN

Table 2. Overview of the approaches discussed in the literature review on criticality measures.

Lastly, what was found striking is that none of the found literature has a focus on networks in Africa, while this is the area that is plagued by terrorism the most (IEP, 2023).

All in all, the network scan approach is found to be most suitable for the case of Mali because of its relative simplicity while accounting for multiple factors to enrich the analysis.

2.3.2. GAME THEORY FOR RESOURCE ALLOCATION ON NETWORKS

The literature reviewed on resource allocation exhibited a notable divergence from the intended focus of this study. The primary objectives of these studies revolved around intercepting moving attackers traversing the network, diverging from the objective of safeguarding connectivity, as pertinent to the Malian context. The SNARES method and the framework proposed by Baïou and Barahona (2022) centred solely on the placement of checkpoints, which, as elucidated in Chapter 4.1.2, does not provide adequate protection measures for Mali's road network. Li et al.'s investigation delved into safeguarding individual vehicle transportation, employing a non-zero-sum two-person game, which is again a distinct scenario from the safeguarding of a network.

Several studies, however, distinctly addressed the protection of entire road networks. Among these, three utilized the Stackelberg game framework to optimize resource allocation, entailing a two-player game with an initial mover advantage. Yet, due to the inherent complexity of modelling the Stackelberg game, a time constraint renders it less feasible for this research. Consequently, the game proposed by Chen (2022) emerges as the most pragmatic choice. This attacker-defender model employs a two-player zero-sum game structure, where optimal strategies can be ascertained through Nash equilibrium calculations. Nash equilibrium signifies a state in which neither player can achieve a better payoff by deviating from their current strategy. Chen et al. (2022) corroborated these optimal strategies with risk assessment approaches, affirming that Nash equilibrium provided the most effective strategies. Given its simplicity, applicability, and seamless integration into the Malian case, the two-player zero-sum game stands out as a fitting method for this study.

3 | METHODS

This chapter presents a comprehensive outline of the research's systematic approach for data collection, analysis, and interpretation. This chapter is designed to provide a clear understanding of the methodologies employed to address the research questions and objectives. It begins with a description of the interview process, detailing participant selection, procedural considerations, and ethical safeguards. Subsequent sections delve into the meticulous collection and processing of data pertaining to the road network, population statistics, and violent incidents. Furthermore, the chapter elucidates the methodologies employed to assess criticality within the road network and the allocation of protective resources. Finally, a comparative analysis is detailed, allowing for the evaluation and interpretation of the subsequent findings.

3.1. INTERVIEWS

3.1.1. PARTICIPANTS

The participants in this study were selected using a purposive sampling technique. Purposive sampling is a non-probability sampling technique in which participants are selected based on specific characteristics or qualities that make them suitable for the research study (Patton, 2015). Instead of randomly selecting individuals from a larger population, purposive sampling involves intentionally handpicking participants who possess the desired attributes or experiences that align with the research objectives. In this research, participants were selected on their knowledge of actor's strategies, the road network and dynamics thereof.

Over a time period of two months, a total of 31 participants were interviewed, ensuring representation from each category. Due to possible sensitivity of the information, the interviewees were kept anonymous.

3.1.2. PROCEDURE

Interviews were conducted according to the following procedure.

1. Recruitment: Potential participants were identified through extensive networking, liaising with relevant organizations, and utilizing professional contacts within the target field. It was aimed

to include individuals with direct experience and expertise in the Malian road network and its related dynamics.

2. Informed Consent: Prior to the interviews, participants were provided with an informed consent form that outlined the purpose of the study, the voluntary nature of participation, and the assurance of anonymity and confidentiality.

3. Interview Guide Development: A semi-structured interview guide was developed specifically for each interview, tailored to the participant's knowledge as suggested by Creswell (2014). The guide included open-ended questions and prompts designed to elicit rich and detailed responses from the participants.

4. Data Collection: The interviews were conducted in Bamako, Mali, in a setting that ensured privacy and comfort for the participants. Each interview lasted approximately 60 minutes on average. Written notes were taken during the interviews to capture participants' responses, key points, and relevant contextual information.

5. Data Analysis: The written interview notes were carefully reviewed and analysed to identify key trends and patterns. All interview data were summarized and anonymized during the analysis process.

6. Trustworthiness: To ensure the trustworthiness and rigor of the findings, multiple strategies were employed. These included member checks at the end of interviews as suggested by Lincoln & Guba (1985). In member checks, summaries and understanding of the findings were shared with the participants. This allows participants to review the data and interpretations related to their own responses. The purpose of member checks is to ensure that participants agree with and confirm the researcher's understanding and provides room for correction, clarification or addition of information. Member checks are seen as a key strategy for enhancing the credibility and trustworthiness of qualitative research findings (Lincln & Guba, 1985). A second method employed to enhance trustworthiness was the conduction of a comparative analysis (Merriam, 2009).

3.1.3. ETHICAL CONSIDERATIONS

This study adheres to ethical guidelines and principles of TU Delft. Risks related to the interviews were analysed and mitigated as much as possible. Participants were fully informed about the study's objectives and procedures, and their voluntary participation was emphasized. Confidentiality and anonymity were strictly maintained throughout the research process. The study received approval from the TU Delft's Human Research Ethics Committee. During and after the research, the interview data has been handled according to the set up data management plan which has been approved by the Human Research Ethics Committee as well.

The interview period of two months consisted of two separate trips to Bamako. Both trips were approved by the TU Delft's executive board and the integral safety team.

3.2. DATA COLLECTION AND PROCESSING

This chapter entails the data collection and processing for this research. Multiple visualisations are provided. In order to make a clear distinction between maps, maps have been given different backgrounds. Directly downloaded graphs are portrayed white with a black background, as for example in Figure 5. Graphs that have solely undergone some sort of cleaning are portrayed with a broken white background, as for instance in Figure 7. Lastly, networks under analysis have an OpenStreetMap background as for example in Figure 9.

3.2.1. ROAD NETWORK DATA COLLECTION

In this study, the Malian road network serves as a necessary component for conducting comprehensive spatial analysis. However, encountering the unavailability of up-to-date road network data online and the limitations in accessing classified road network maps developed by various international military missions due to military intelligence concerns, an alternative solution was sought. To address this requirement, the study adopts the combined use of OpenStreetMap (OSM) and the OSMnx Python library.

OpenStreetMap (OSM) is a collaborative mapping project that offers a vast collection of geospatial data contributed by a global community of volunteers (Nordbeck & Zipf, 2017). Additionally, the OSMnx Python library, developed by Boeing (2017), provides the essential tools for retrieving, modelling, and analysing street networks based on OSM data. By utilizing OSMnx, this study ensured access to a comprehensive and most up-to-date representation of the road network in Mali available, facilitating accurate spatial analysis (Rahmani et al., 2019; Fawaz et al., 2019).

The road network data retrieval process entails specifying the geographical extent of Mali as the designated study area and utilizing the functionality provided by the OSMnx library to obtain the relevant road network data. It was found that the types ‘motorway‘, ‘motorway_link‘, ‘trunk‘, ‘trunk_link‘, ‘primary‘ and ‘secondary‘ were representing paved roads in Mali. The upload date per road segment varies from 2021 until 2023. The resulting graph, acquired through this query, is visually represented in Figure 5.

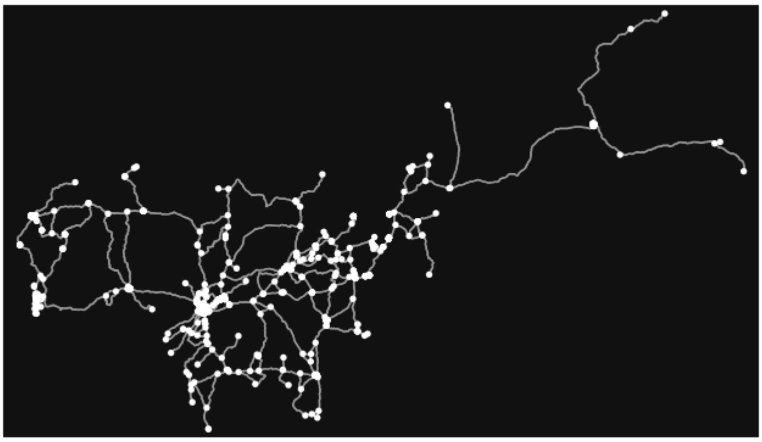

Figure 5. The retrieved graph of the national road network in Mali from OSMnx

The decision to exclusively concentrate on paved roads was undertaken for several reasons. Firstly, in the network scan approach, the road network is crucial in determining the shortest route between two cities. By excluding unpaved roads from consideration, shortest routes can not traverse these. This approach is imperative due to the considerable uncertainty surrounding the accessibility, capacity, and traffic speed of unpaved roads. By focusing solely on paved roads, the study avoids potential ambiguities and ensures a more reliable calculation of shortest routes between cities. Moreover, insights gleaned from interviews affirm that larger transportation between cities predominantly relies on paved roads, a point elaborated upon in detail in Chapter 4.1. Furthermore, the incorporation of unpaved roads in the network would introduce computational complexities, as the network's scale would substantially increase. Thus, due to the combination of uncertain knowledge, confirmed preference for paved roads in transportation, and computational limitations, the study has deliberately chosen to focus solely on the paved road network in Mali.

3.2.2. ROAD NETWORK DATA PROCESSING

The acquired graph underwent comprehensive analysis, which brought to light an absent portion within the northern region of Mali, specifically surrounding the area of Timbuktu. To establish the nature of the road infrastructure in the vicinity of Timbuktu, a manual verification process was conducted, utilizing both OpenStreetMap (OSM) data and Google Maps imagery, to determine if these roads were paved. The omission of this particular network segment from the dataset is likely attributed to its lack of integration and connectivity with the broader road network. The manual verification process revealed that Timbuktu maintains connectivity with the rest of the network through a ferry service. This finding explains the apparent disconnectedness of Timbuktu in the OSM dataset. Furthermore, the road networks around other cities in Mali were carefully examined to check for any missing segments. However, it was found that solely the network covering Timbuktu was not included in the Malian network dataset. In order to complete the network, a similar query was executed for Timbuktu which is displayed in Figure 6.

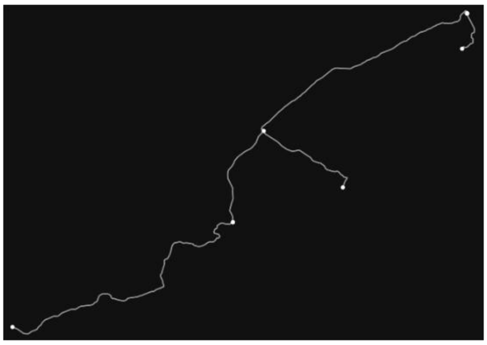

Figure 6. The graph obtained by query 2 for the region of Timbuktu.

The two networks were combined into a single comprehensive network. To that end, the Timbuktu network was manually integrated with the broader Malian network by manually establishing a connecting edge between the corresponding nodes, where normally the ferry passes. The rationale behind creating this edge, typically denoting a road, was that the alternative of leaving no connection between the subnetworks would yield a larger deviation from reality than the chosen approach. By not establishing an edge, the network would be rendered disconnected, inaccurately suggesting that there is no possible movement between the Timbuktu network and the rest of Mali. Therefore, the decision was made to create an edge, resulting in a unified and interconnected network encompassing both regions which is presented in Figure 7.

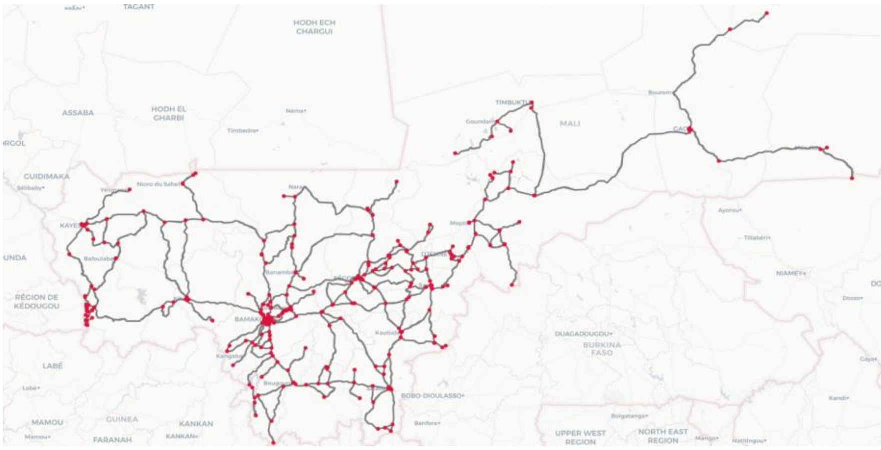

Figure 7. Combination of both the Malian network and the Timbuktu network. Edges are portrayed in grey and nodes are displayed as red dots.

The graph was converted into an undirected graph due to the discovery of some cities being only reachable in one direction. For instance, paths could be found towards the city of Segou but not originating from it, which does not accurately reflect reality. To rectify this, the decision was made to transform the entire graph into an undirected representation. Details of the general features of this undirected network are provided in Appendix A.2. Additionally, the Appendix contains comprehensive statistics on the network, including degree betweenness, centrality betweenness, closeness betweenness, intersection counts, total street length, and other relevant information related to the directed graph. Furthermore, the attributes of the nodes and edges are described in Appendix A.2 as well.

To construct the game theory model, it was necessary to exclude the region of Segou from the rest of the graph. The choice for the Segou region was made because of the findings about geopolitical differences between regions in the interviews (Chapter 4.1.3.). A subgraph of Segou was achieved by creating a subset of the graph through a slicing procedure using boundary coordinates. Specifically, the coordinates (12.88706, 6.93167) and (15.33617, -4.86764) were utilized to define the boundary. Although these coordinates extended slightly beyond the actual region of Segou, the nodes that fell outside the Segou area were removed manually. This process resulted in the creation of a subgraph, which is illustrated in Figure 8, and serves as the basis for the game theory analysis.

Figure 8. The subgraph of the Segou region.

3.2.3. POPULATION DATA COLLECTION

The data on Malian city populations was retrieved from simplemaps, a comprehensive online platform that provides access to geospatial information and demographic data (simplemaps, 2023). simplemaps offers a user-friendly interface for extracting relevant population statistics for specific geographic regions, including cities within Mali. The data on Malian city populations originates from the US National Geospatial-Intelligence Agency. As city definitions in Mali are not very strict, the definition of a city has been copied from simplemaps and which use the cities as determined by the US National Geospatial-Intelligence Agency. By utilizing Simple Map, this study ensured access to reliable and up-to-date population data.

Mali encompasses a total of 36 cities, exhibiting diverse population sizes ranging from 3,019 to 1,978,748 inhabitants. Despite some cities being relatively small in terms of population, the decision was made to incorporate all available data into the model, under the premise that a more comprehensive dataset enhances the model's robustness and accuracy. A geographical plot depicting the spatial distribution of these cities along with their corresponding population sizes is presented in Figure 9.

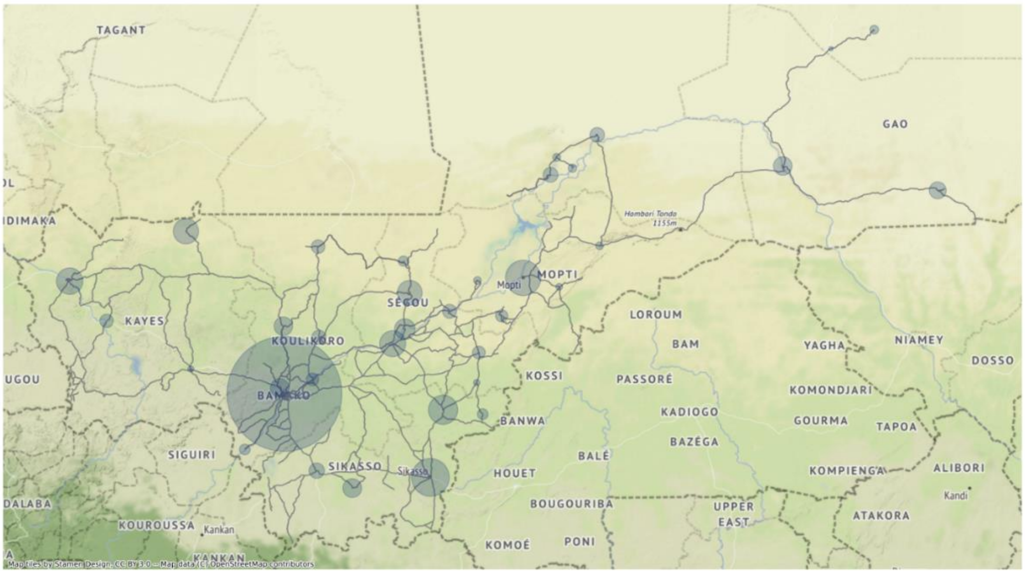

Figure 9. Overview of location of all cities in Mali. The size of the blue circle indicates relative population sizes.

For the Segou region, a specific determination of cities was required. Utilizing the region selection from the simplemaps data, a total of six distinct cities were identified within the Segou region, displaying population sizes ranging from 15,782 to 102,099 inhabitants. A comprehensive overview of the population distribution among these cities is visually represented in Figure 10.

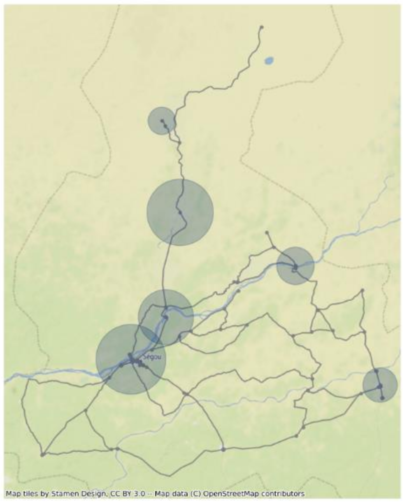

Figure 10. Population sizes in the Segou region.

3.2.4. POPULATION DATA PROCESSING

To facilitate the network scan approach, integration of population data with the road network graph was essential, specifically by associating it with the nodes. Accordingly, a new attribute named 'population' was assigned to the nodes. For each city, it was checked which network node was closest using the tree.query function. This function uses the R-tree algorithm to find the nearest node. Appendix A.6. elaborates further upon this algorithm. Figure 11 provides a comprehensive overview, illustrating all cities and their respective distances, measured in meters, to the closest node within the network.

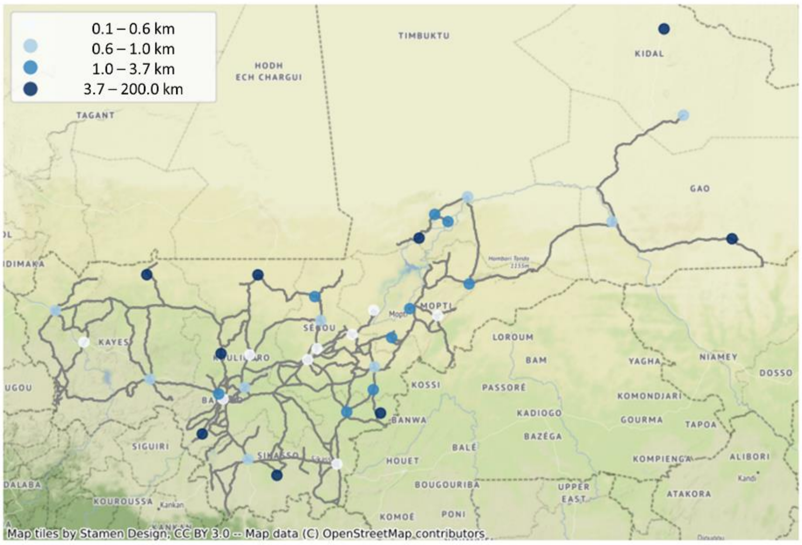

Figure 11. The road network and blue dots indicating cities.
The darker the blue, the further the distance to the closest node (in kilometres).

Cities in close proximity to a node were linked to the nodes by assigning the city's population size as an attribute. Specifically, cities located within a 10km radius from a node were considered for this association. It is noteworthy that cities were typically situated adjacent to nodes, rather than directly overlapping, as nodes represent road intersections and not the city locations themselves. Figure 12 provides an illustrative example, showcasing the distinction between their respective positions within the network.

Figure 12. Example of a the geographical location of a city (blue dot) and the closest nodes (red). It can be observed that the geographical locations of cities do not overlap with the geographical locations of nodes.

In certain instances, some cities are situated far from a node (>10 km) within the network, and this can be attributed to two primary reasons. Firstly, a city may lie close to an edge but be geographically distant from the nearest node. An illustrative example of such a scenario is provided in Figure 13. To address these cases, the edge was partitioned into two segments at the location of the city, and a new node was introduced to connect the two newly created edges. Subsequently, the new node was assigned the population size of the respective city. The Euclidean distances from each of the two nodes of the original edge to the newly introduced node were calculated, and these distances were designated as weights for the respective new edges. This process was applied to four distinct cities: Kolokani, Niafunke, Nara, and Kangaba. On another note, there were situations where a city was connected to the road network through an unpaved road. This circumstance was only observed for Tessalit, as depicted in Figure 14. To address this, the decision was made to manually relocate the city of Tessalit to the point where its unpaved road was connected to the paved road. This option was preferred over deleting the city altogether, as it ensures that the weight of this city to the corresponding section of the network is not lost. An alternative approach, treating the unpaved road as a paved road, was considered, but it would contradict the study's deliberate choice to solely focus on paved roads. Hence, the chosen method preserves the overall methodology's coherence and consistency.

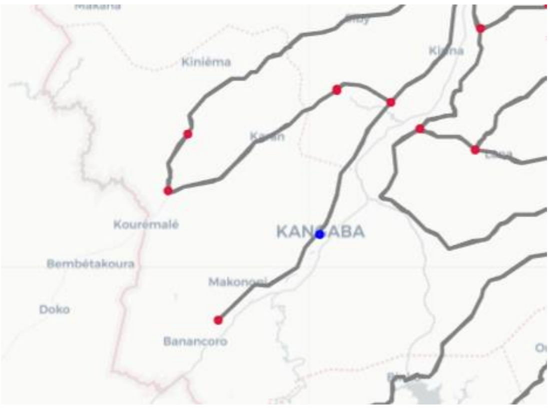

Figure 13. Example where a city (blue dot) lies on the road network but no node (red dot) is near.

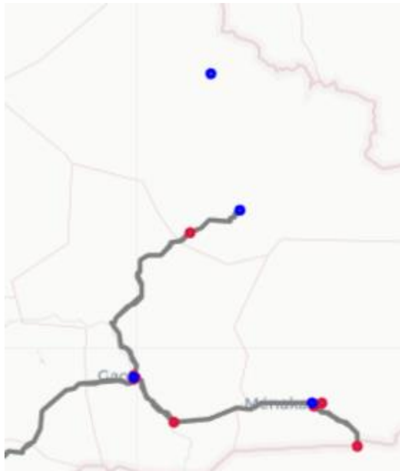

Figure 14. Example of a city that is solely connected to the road network by an unpaved road. The figure depicts the city of Tessalit (top blue dot) and shows no connecting edge.

During this process, a particular challenge emerged concerning how to handle the edges that lead towards the border. These roads, while crucial for facilitating transportation between countries, may appear less significant in the model due to uncertainties regarding the population to be attributed at the end of such road segments and the appropriate distance from the border. Considering the lack of a definitive and optimal approach for placing the population data in these scenarios, the decision was made to exclude these border edges from the model. This choice was driven by the desire to avoid introducing undue randomness and uncertainty in the model, thus ensuring the model's coherence and reliability in representing the road network within Mali.

3.2.5. VIOLENT INCIDENTS DATA COLLECTION

Data from the Armed Conflict Location and Event Data Project (ACLED) for the year 2022 was acquired to conduct a comparative analysis with the obtained optimal strategies. ACLED has emerged as a comprehensive and credible real-time data source, offering insights into conflict-related events on a global scale (ACLED, 2023). Its data is widely utilized for various purposes, including trend monitoring, early warning systems, operational safety, academic research, media reports, NGO initiatives, and security decision-making (ACLED, 2023).

The ACLED dataset boasts a remarkable level of detail, encompassing a diverse range of events and being consistently updated with minimal time lag (ACLED, 2023). It provides geographic information at the city/village level, although it does not extend to the street level (ACLED, 2023). An important aspect to consider is that ACLED data adheres to strict privacy measures, ensuring the exclusion of any personally identifiable information, such as individual names or mobile device IDs. Consequently, the dataset cannot be employed for individual tracking.

The retrieved dataset includes all reported conflict-related incidents in Africa from 1997 until 2023, as of the 21st of April 2023. Appendix A.4. provides a comprehensive list of the variables encompassed within the dataset.

3.2.6. VIOLENT INCIDENTS DATA PROCESSING

The ACLED data was filtered specifically for the country of Mali and the Segou region during the year 2022. The rationale for selecting the year 2022 stems from its status as a complete year, encompassing changes in seasonality and representing the most recent data available. Incidents within the dataset are categorized by ACLED as detailed in Appendix A.5.

To ensure a focused analysis, the incidents were further filtered, excluding demonstrations and strategic developments, while concentrating solely on political violence. This choice was motivated by the fact that demonstrations are not directly linked to terroristic incidents on the road network, and strategic developments include withdrawals of certain insurgent groups but not necessarily violent incidents.

Subsequently, a comparison analysis was conducted between the optimal strategies and incidents attributed to the insurgent group JNIM specifically. To perform this analysis, the ACLED data was filtered to identify incidents where JNIM was reported as 'ACTOR1: Group for Support of Islam and Muslims'. It was observed that some incidents in the database included JNIM as 'ACTOR2'. However, the focus of the comparative analysis on comparing the attacker's optimal strategy with actual attacks carried out by insurgent groups. This is the case when JNIM militants are the subject of the incident, rather than just the passive participant.

3.3. CRITICALITY IN THE ROAD NETWORK

The weighted travel cost approach, developed by Taylor and D'este in 2007, was selected for its relative simplicity while accounting for multiple factors to enrich the analysis (see Chapter 2.3.1. for further details). In the network scan approach, a weighting factor was devised for each pair of cities using a basic gravity model to depict city interactions. This weight was determined by considering the population of city i (Bi), the population of city j (Bj) and the network travel distance (xij) between cities i and j (Equation 1). As the graph was undirected, calculations for each city combination only needed to be performed one way, avoiding redundancy. The travel distance (xij) was computed using the shortest path length function of the Networkx library (Networkx, 2023), employing the Dijkstra algorithm to find the shortest route between two cities (more details provided in Appendix A.6.). Subsequently, a normalized weight, represented as wij, was calculated to determine the level of travel between cities i and j relative to other city combinations (Equation 2).

$$g_{ij} = \frac{B_i B_j}{x_{ij}^2}$$

Equation 1. Weighting factor for each combination of cities,
using the population (B) per city (i and j) and the distance between city i and j (xij).

$$w_{ij} = \frac{g_{ij}}{\sum_{ij} g_{ij}}$$

Equation 2. Normalisation of the weighting factor.

To implement the network scan approach, the minimum travel time paths between origin-destination pairs that were calculated before, were used again. Subsequently, the model iteratively deleted each edge, one at a time, to analyse the change in travel time (Δt^{e}_{ij}) for all city combinations. In other words, only one edge was deleted in each iteration to observe its impact on travel time for all pairs of cities. This process was repeated for each edge in the network, allowing a comprehensive analysis of the effects each edges on travel time across all city combinations.

Informed by insights from interviews, the study recognized that official speed limits are often disregarded, and actual speeds can vary significantly based on circumstances. Consequently, a pragmatic approach was adopted, assuming an average speed limit of 70 kilometres per hour for the entire network, with a primary focus on intercity travel. This decision was made to ensure practicality in the absence of precise speed data and to emphasize the analysis of travel between cities rather than within them. While this approach may introduce some level of inaccuracy, it provided a feasible and reasonable solution given the limited availability of data on specific speed variations.

When deleting edges, certain cities became inaccessible as only one paved road provided access. Initially, an infinite increase in travel time was considered, but this adversely affected criticality values and rendered them difficult to interpret after normalization. Based on insights from interviews, it was found that detours on unpaved roads are commonly taken in such situations. Therefore, a reasonable two-hour increase in travel time was implemented as a practical solution.

By aggregating these calculations across all origin-destination pairs and incorporating the weights wij from Equation 3, an overall increase in weighted network travel time per edge (Te) was determined. This value, Te, is the criticality of an edge as stated by the network scan approach.

$$T_e = \sum_{ij} w_{ij} \Delta t_{ij}^e$$

Equation 3. The criticality value per edge based on the change in travel time (Δteij) when deleting the edge and the normalised weighted factor per city pair.

3.4. RESOURCE ALLOCATION

The subsequent step in the methodology involves constructing the game theoretical model, where the criticality values obtained per edge serve as the pay-offs for this model. Based on the results of the interviews, which are discussed in Chapter 4.1. several choices were made for the model development. It was decided that the resource allocation would solely take place in the region of Segou. It was found that geopolitical situations per region differ significantly. The two-player zero sum game found in the literature can best be applied to a situation where the defender is the controlling actor and the attacker executes a guerilla like strategy of hit and run attacks. This description fit the situation in Segou best, therefor the resource allocation will solely take place in this region.

On top of that, it was found in the results of the interviews that effective measures for road protection mainly involve military patrols in combination with EOD units to protect the road network. The defender’s strategy in the game theory model therefore resembles the allocation of these military patrols. Attacks on the other hand, entail IED placements, armed attacks, artillery attacks, suicide bombings and abductions as they all affect the connectivity of the road network.

After slicing the graph to retain only the Segou region, as explained in Chapter 3.2.1., the game matrix is formed. The game matrix serves as the foundation for running the game theory model, and in this case, a zero-sum two-player matrix is built. In a two-player game, the matrix is two-dimensional, with the defender's options listed on the rows, and the attacker's options on the columns. The outcome of the game is determined by the cell indicated by the defender's choice (row number) and the attacker's choice from the columns (column number). Solely one matrix is built, which showcases the defender’s payoffs. The attacker pay-offs are represented by the same matrix, however multiplied by -1 as the game is zero-sum. Zero-sum means one player's win corresponds to the other player's loss. Both players aim to maximize their respective pay-offs. Both players have the flexibility to distribute their choices across multiple options.

Specifically, in this study, the matrix consists of all the edges within the Segou region, with the edges serving as options for both players to distribute their resources. This results in a matrix of dimensions 207 by 207 for the Segou region. Along the diagonal, the criticality values of the column edges are displayed, and the rest of the column is filled with the negative criticality value. An example of this arrangement is demonstrated in Equation 4 for a network comprising three edges. As mentioned earlier, the pay-off in this matrix indicates the pay-off for the defender.

In Equation 4 for instance, if the defender allocates resources to edge 1 and the attacker selects edge 3, the outcome of the game would be -0.012 for the defender. The rationale behind this is that the defender has invested resources in a road where the attacker is not present. Conversely, the pay-off for the attacker would be -0.012 * -1 = 0.012, indicating a positive outcome for the attacker. This positive pay-off implies a win for the attacker, as they have successfully attacked a road without facing any resistance.

$$\begin{matrix} 0.003 & -0.0004 & -0.012 \\ -0.003 & 0.0004 & -0.012 \\ -0.003 & -0.0004 & 0.012 \end{matrix}$$

Equation 4. Example of a 3x3 zero sum two player matrix

The determination of the optimal strategy was achieved by calculating the Nash equilibrium of the game. In a Nash equilibrium, no player has an incentive to unilaterally deviate from their chosen strategy, as doing so would not lead to an improvement in their individual payoff. In essence, a Nash equilibrium represents a state where, with knowledge of their opponents' strategies, no player can enhance their own position by altering their strategy alone. This mutual best-response condition among players results in a stable and self-reinforcing outcome.

To compute the Nash equilibrium, the game matrix was processed using a game solver provided by the University of California (UCLA, 2023). This decision was made as the Python library NashPy had an exceedingly long runtime. Consequently, the Nash equilibrium of the game was obtained through the University of California's website.

The optimal strategies for the players are thus determined by the Nash equilibrium of the game. A positive value in the game indicates that the defender earns a higher criticality compared to the attacker, while a negative value signifies the opposite, implying that the attacker gains greater criticality.

3.5. COMPARATIVE ANALYSIS

Lastly, a comparative analysis was conducted to compare the obtained optimal strategies with the ACLED data of political violence incidents in the Segou region during 2022. To enable this comparison, the distribution of incidents needed to be extracted from the extensive ACLED dataset. For each incident, the closest edge was determined using the distance.nearest_edges function of OSMnx. This function utilizes a spatial indexing technique based on the R-tree algorithm, which effectively reduces the Euclidean distance between individual points and their potential matches. Further details on the R-tree algorithm are provided in Appendix A.6.

Only incidents that occurred within 10 kilometres of the road network were considered for inclusion. Incidents happening further away were deemed to have minimal impact on the network's connectivity. The choice of a 10-kilometer range aligns with ACLED's accuracy, which is at the village level, not street level. Since the model examines the largest highways and does not operate at a detailed level, this range corresponds to the village level utilized in the ACLED data.

The incidents were assigned to the closest edge, and the number of incidents per edge was divided by the total incidents in the region to establish the distribution per edge. This process allowed for a comprehensive comparison of the incident distribution with the optimal strategies obtained from the model.

4 | RESULTS

4.1. RESULTS OF INTERVIEWS

This chapter shows the results of the conducted interviews in Mali in the period of April, May and June 2023. The chapter has been dissected into different sections that discuss the different topics discussed during the interviews; types of attacks, measures to secure the road network and payoff analysis. These sections are divided in to subsections that discusses summarizes interviewees views on specific types of attacks or security measures. Discussion of these results has been done per subsection for the sake of readability, each subsection thus ends with a discussion.

4.1.1. TYPES OF ATTACKS

In order to deepen comprehension of the dynamics within the road network, individuals were interviewed regarding the various types of incidents occurring on the network.

IEDs / Bombings / Explosives

One of the firstly mentioned types of attacks are IED encounters. Many different types of IEDs are used in Mali to attack the road network.

1. Landmines are officially not regarded as an IED as they are not improvised. Landmines are however included in this list, because they are often used as a part of an IED. A landmine is a destructive device intentionally created to harm vehicles, injure, kill, or hinder people's movements. These mines can be activated by their intended target, such as being stepped on or struck, or triggered through various means like direct pressure, tripwires, tilt rods, command detonation, or a combination of the above. 5 of the 31 interviewees mentioned these landmines as a type of attack.
2. Direct pressure IEDs are devices that explode because of the pressure moving onto the pressure plate of the IED. All interviewees mentioned these direct IEDs as a type of attack.
3. Tripwires are spanned across a path in order to cause damage when the wire gets disrupted. All interviewees mentioned these tripwired IEDs as a type of attack.
4. Radio connected IEDs are placed near the road and are designed to explode on the signal of a mobile phone or any other electronic signal. They can thus be triggered from a distance and can target specific individuals. All interviewees mentioned these radio connected IEDs as a type of attack.

IEDs can thus directly attack and damage the infrastructure, but it mainly causes fear and therefore restriction of movement.

Besides IEDs, it was found that suicide bombings are a type of violent incident that affect the connectivity of the road network in Mali according to 21 of the 31 interviewees. Suicide bombings are violent acts in which individuals carry out attacks with the intention of causing mass casualties by detonating explosive devices strapped to their bodies. These bombings are typically perpetrated by extremist groups like JNIM and IS. The primary goal of suicide bombings in Mali is to instil fear and destabilize the state, as well as to advance the perpetrators' ideological agendas, which often involve imposing strict interpretations of Islamic law and challenging foreign influence. These attacks have a profound impact on the connectivity of the road network in Mali, as they target critical transportation arteries and intersections, disrupting the flow of goods, services, and people. Fear of potential attacks hinders civilian mobility, leading to reduced traffic and restricted movement. The destruction of infrastructure resulting from suicide bombings exacerbates the challenges of maintaining a stable and connected road network in the country.

Armed Attacks

An armed attack refers to a deliberate and organized act of aggression or use of force by one party against another. It typically involves the use of weapons or military means to cause harm, destruction, or injury. Armed attacks can take various forms, including but not limited to direct military confrontations, missile strikes, bombings, armed invasions, or acts of terrorism. The intent behind an armed attack is to cause significant damage, subdue or eliminate the opposing party, or achieve specific military or political objectives through forceful means. According to interviewees, the overarching goal of armed attacks are to show and pressure power in a certain region. 29 of 31 interviewees mentioned these armed attacks as a type of attack.

One specific form of armed attacks is that has been observed in Mali are artillery attacks according to 12 of 31 interviewees. An artillery attack is a military operation in which large-calibre weapons, known as artillery pieces, are used to launch explosive projectiles over long distances towards a specific target or area. Artillery is a form of indirect fire, meaning that the weapon's operator does not need to see the target directly to engage it. Instead, calculations are made based on distance, direction, and other factors to adjust the firing angle and trajectory, allowing the projectiles to reach their intended destination. Artillery attacks can be used for various military objectives, such as suppressing enemy positions, providing cover for advancing troops, destroying enemy fortifications or equipment, and disrupting movements. These attacks can be devastating, inflicting heavy casualties and significant damage to infrastructure and facilities. Therefore it is considered an influence on the network’s connectivity.

Kidnappings

Kidnapping refers to the unlawful act of capturing and holding someone against their will, typically for ransom, political motives, or other illicit purposes. Kidnappings are thus not a direct attack on the road network like IEDs are but cause fear among civilians and therefore restricts their movement.

According to interviewees, reasons for kidnappings are multifaceted. Firstly, financial motivations are a reasons for kidnappings. Criminal groups and terrorist organizations may conduct kidnappings as a means to demand ransom payments from the victims' families, employers, or governments. Ransom payments serve as a lucrative source of funding for these groups. A second type of motivation that was mentioned were of political nature. Armed groups may target individuals to gain leverage, exert pressure on governments, or make political statements. Thirdly, terrorism is a motivation for kidnappings. It is the type where kidnappings are used to advance their ideological objectives, gain publicity, and sow fear within the population. Lastly, kidnapping can be affiliated to criminal activity, meaning it can be involved in human trafficking, smuggling, or other illicit activities. Victims may be abducted for forced labour, exploitation, or as a commodity in illegal trades. All interviewees mentioned kidnappings as a type of attack.

4.1.2. PROTECTIVE MEASURES

To enhance understanding of the dynamics on the road network in Mali, interviewees were asked about current security measures on the Malian network.

Military Patrols and Convoys

A military patrol, or military patrol mission, refers to a specific task assigned to military personnel or units to conduct reconnaissance, surveillance, security, or combat operations in a designated area. The primary purpose of military patrols is to gather information, maintain situational awareness, deter potential threats, and provide security for friendly forces. Military patrols are seen as a way to secure the road network. Patrol can not be present continuously but showing presence regularly is seen as way to provide security. Using military patrols was mentioned by all interviewees as a way of securing the road network in Mali.

To make a distinction in terminology, a military convoy is a group of vehicles, often armoured and accompanied by armed personnel, that travel together for the purpose of transporting troops, equipment, or supplies (Hussain et al., 2019). The use of military convoys was mentioned by 23 of 31 interviewees as a measure for securing the Malian road network.

While military patrols and convoys are thus seen as a securing factor, 7 out of 31 interviewees noted that military presence can provoke violence. Especially because in Mali, state actors or international missions are the target. Diving deeper into the topic, it was found that civil actors prefer routes that are used by military patrols and convoys over ones that are not. It can be said that in general these routes are perceived safer in comparison with routes that do not have regular military present. However, civil transports try to keep a lot of distance from military convoys and patrols in order to circumvent becoming collateral in a possible fight. It was added that civil transports perceive routes safe that have been used by military patrols that same morning as the chance of driving into unexploded IEDs is smaller.

While military patrols and convoys seem to have a positive effect on the security of the Malian road network, interviewees indicated that these are not consistently deployed due to capacity limitations. The Malian forces, given their relatively small size compared to the country's expanse, face challenges in effectively safeguarding the road network. International missions primarily use their convoys and drones for camp resupply, attributing no further road protection initiatives because of capacity constraints. During interviews it was even revealed that the situation had deteriorated that far, that some units of international missions refuse to leave the military bases because of insufficient resources. This means less military presence on the roads, which makes the situation even worse. One of the interviews drew the deteriorating situation as shown in figure 13.

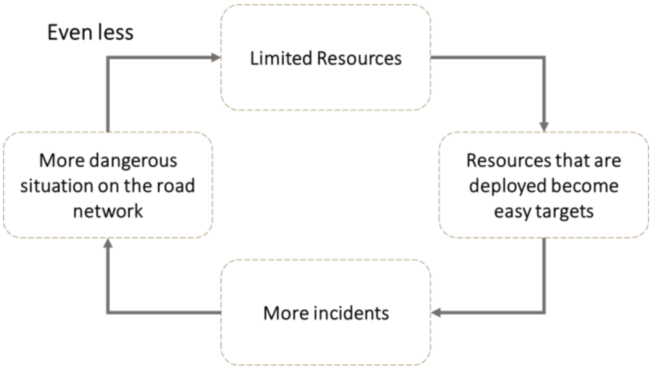

Figure 15. Sketch of the detrimental circle of safety on the road network in Mali as explained by one of the interviewees. It starts by the deployment of too little resources, which causes deployed assets to be easy target. Subsequently, more incidents occur which creates a more dangerous situation on the road network. The deteriorated situation on the road network then causes missions to be more hesitant to deploy assets or units even refuse to leave the bases, which means the resources deployed are even more limited.

All in all, military convoys and patrols are deemed to increase security on the Malian road network, however the capacity is highly limited causing the situation to deteriorate.

EOD units

Besides military patrols and military convoys, Explosive Ordnance Disposal (EOD) units' deployment are mentioned by 23 of 31 interviewees as a road network securing measure.
An EOD unit is a specialized military team equipped with expertise and equipment to identify, assess, and safely neutralize explosive hazards, including IEDs and other hazardous materials. EOD personnel are extensively trained in rendering safe and disposing of explosive devices in a controlled manner, minimizing potential harm to both personnel and civilians.

According to interviewees EOD units play a critical role in enhancing road security. They contribute to securing the road network by conducting regular patrols and inspections, especially in areas with a high risk of insurgent activity. OEOD units proactively search for and remove potential explosive threats, such as IEDs planted along roadways, which could disrupt traffic flow, endanger civilians, and impede the movement of goods and services. On top of that, are EOD units often attached to other military patrols and convoys that enables the military movement to overcome EOD attacks. EOD teams employ advanced detection and disposal techniques to mitigate the risk of roadside bombs and other explosive hazards. Their presence and interventions are deemed to offer a deterrent to potential attackers, as the risk of immediate detection and neutralization discourages extremist elements from placing improvised explosives along the road network.

Additionally, EOD units may engage in capacity-building efforts by training local security forces in explosive hazard recognition and disposal techniques. Such training empowers local forces to respond effectively to potential threats and enhance their ability to maintain road network security independently, thus creating a sustainable and resilient security environment.

However, it was found during interviews that the EOD units of international missions do not always work like they should. Interviews revealed instances where soldiers designated as explosive ordnance disposal experts in their contracts were actually newly enlisted soldiers in their respective national armies. EOD units therefore are not always reliable.

In conclusion, EOD units are instrumental in safeguarding the road network in Mali by diligently detecting, neutralizing, and disposing of explosive hazards. Their expertise and presence contribute to reducing the risk of improvised explosive attacks, ensuring safer transportation routes and thus providing security on the road network. However, a side note has to be made that EOD units are not always reliable resources in Mali.

Checkpoints

Compared to military patrols and convoys, checkpoints are a static security element that was mentioned by 29 of 31 interviewees. From interviewees experiences, checkpoints are often weakly armoured and protected and therefore are often targets of attacks. Checkpoints are usually occupied by the police.
Interviewees explained there are different types of check points in Mali. Firstly, a type for controls, they check IDs and customs, often placed on roads leading to and from neighbouring countries. Secondly, there are checkpoints with protection purposes. Entrances to cities are supposed to have check points. These check points are trying to prevent arms and explosives transportations.

The staticity of checkpoints causes the resources to cover only a limited area of the road network which weakens the effect of the checkpoints on securing the Malian network. On top of that are checkpoints usually at fixed locations, meaning that they do not change their position. This makes them easier to circumvent when planning a violent incident. All in all, do checkpoints protect the road network, however interviewees agree that this is less effective than military patrols.

Military Drones

The use of military drones can help in securing a road network according to 21 of the 31 interviewees. Military drones, also known as Unmanned Aerial Vehicles (UAVs), are remotely piloted aircraft equipped with advanced sensors and cameras. Drones can conduct surveillance and reconnaissance missions, detect threats like roadside bombs, and monitor roads for illicit activities. Their rapid deployment and ability to provide real-time intelligence make them invaluable for enhancing the response of ground forces to security threats. Moreover, drones minimize the risk to personnel by reducing the need for foot patrols in hazardous areas.
According to interviewees, the Malian armed forces do not have any military drones but MINUSMA does. The measure is effective but highly costly and which makes availability an issue.

Well-constructed and maintained roads

An important statement that was made by numerous interviewees (27 of 31) that the state of the road affects the likelihood of IED placements. As explained above, IEDs can be placed anywhere, but are

often placed under the road surface. Well paved roads make it more complicated to place IEDs for multiple reasons.
Firstly, well-paved roads, the placement of an IED more time consuming. Asphalt has to be heated in order to dig under the surface and place an IED. More time-consuming makes the associated risk for the attacker larger. Secondly, in well paved roads create less opportunities for simple IED placement, there are less holes etcetera. Lastly, well paved roads make IED spotting, meaning the recognition of IEDs is easier as irregularities in well paved roads are less common.

On top of the paving of roads, two of the interviewees mentioned that building a proper water drainage system also demotivates insurgent groups to place IEDs. The water drainage systems mitigates the impact of IED blasts by directing the force through the water tunnels instead of to potential targets on the roads. Water drainage systems are thus deemed to minimize harm to targets.

Another aspect that was mentioned by one of the interviewees was that the installation of street lights also has a decreasing influence on the placement of IEDs. IEDs are typically placed during the night time and traffic lights make surreptitious placement of IEDs more difficult.

While well-constructed and maintained roads can make the placement of IEDs more difficult, one interviewee explained that the more advanced measures become, there is an inherent likelihood of attackers developing more sophisticated tactics in response. As an example was the installation of wires in the road surface was mentioned which was done in Afghanistan. This caused insurgent actors not to stop but to further advance their methods. Therefore, it is important that these measures are mitigating but not preventing actions.

4.1.3. GEOPOLITICAL SITUATION IN MALI

During interviews it was found that there are notable regional variations in terms of dynamics on the road network. In certain regions, certain insurgent groups are more dominant than the governmental actor already is. It was found that in some regions hardly any incidents occur on the road network, this is for example the case in the region of Bamako. It was found that in the region of Segou the government still is the most dominant actor, meaning that they are the controlling force. The insurgent actor JNIM, is the most dominant insurgent actor in this region, regularly acting violently on the road network and restricting freedom of movement with their actions.

4.1.4. OTHER CONSIDERATIONS

During the semi-structured interviews some important considerations came up which will be discussed in this section.

It is interesting to note that several NGOs base their security assessment not only on the number of attacks that have been conducted in the past. The acceptance of the NGO by the local community is used as important addition to the analysis. It is an important side note to make, that security can be affected by more than armed security.

An important note was made by several interviewees regarding a policy implementation within international mission currently in Mali. It was stated that however excellent a policy advice may be, the likeliness of actual proper implementation is nihil.

The reasons behind the incapacity of international missions are twofold. Firstly, interviewees indicate that outdated mandates create a disconnect with the local government's requirements. Secondly, operational challenges within the diverse environment exacerbate limitations. Language barriers and cultural disparities hinder effective communication, fostering conflicting viewpoints and interests that hinder consensus on policy decisions. For instance, uniform payment scales for UN officers fail to account for substantial salary variations in their home countries. This discrepancy overshadows other considerations, making participation financially impractical for some countries. Moreover, varying interpretations of agreements result in inconsistencies, such as soldiers designated as explosive ordnance disposal experts who are actually new recruits in their national armies.

In addition to incapability, the Western perspective significantly influences the execution of international peace missions. The stark contrast between the reality in Mali, characterized by hunger, extreme violence, and poverty, and the reality of decision-makers in New York and Brussels cannot be overlooked. International missions primarily prioritize stabilization and peace-building efforts, while research such as the Malimetre (2023) reveals that the immediate physical security of the population is their most pressing need. The idea of creating a stable and peaceful society may be too far-fetched for the Malian people in their current circumstances. This fundamental mismatch between the priorities of international missions and the actual needs of the population forms the underlying cause of their frustration.

Lastly, while explaining the idea of the research and the goal of the model to interviewees, 3 of the 31 made a remark on the military culture. It was said that the current international military culture is not very data-driven and that it should be considered how a model like this would be handled. Military leaders usually have not learned to deal with or interpret data or a model. Warnings were given that military leaders might be sceptical on implementing such policy advice. This is especially the case for Malian armed forces where purely the digitalisation of data is not far reaching yet.

4.2. CRITICALITY RESULTS

This chapter provides a comprehensive analysis of the model's results concerning sub question 4. It commences with an examination of the criticality outcomes of the network, encompassing both national and regional dimensions. Subsequently, the chapter delves into the optimal strategies derived from the model. Moreover, the chapter entails comparative analyses between the model's optimal attacker strategies and the actual incidents that transpired in the Segou region during the year 2022. Additionally, it includes a comparative analysis between the model-generated optimal strategies and the incidents carried out by the insurgent group JNIM in Segou during the same period.

4.2.1. NATIONAL CRITICALITY AND EDGE BASED BETWEENNESS CENTRALITY

Figure 16 illustrates the criticality of the Malian road network, presented per road segment using the network scan approach. To establish a baseline for comparison, the criticality results are contrasted with the edge betweenness centrality degree in Figure 1Figure 16Figure 17. Several noteworthy observations can be drawn from these figures, providing a valuable baseline for further analysis and interpretation.

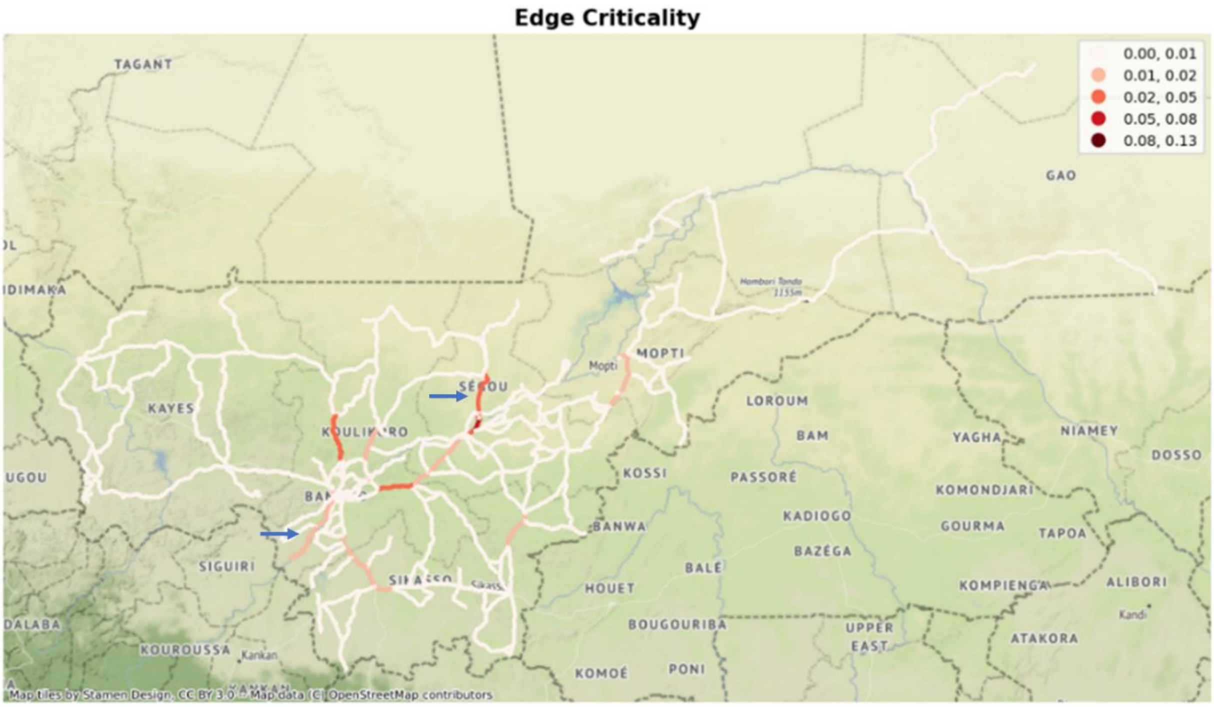

Figure 16. Edge criticality based on the Network Scan Approach. The darker red, the higher criticality values the road segment received. The blue arrows indicate the ‘forgotten roads’, the roads that are indicated as critical by the Network Scan Approach but not by the edge based betweenness centrality measure (Figure 17).

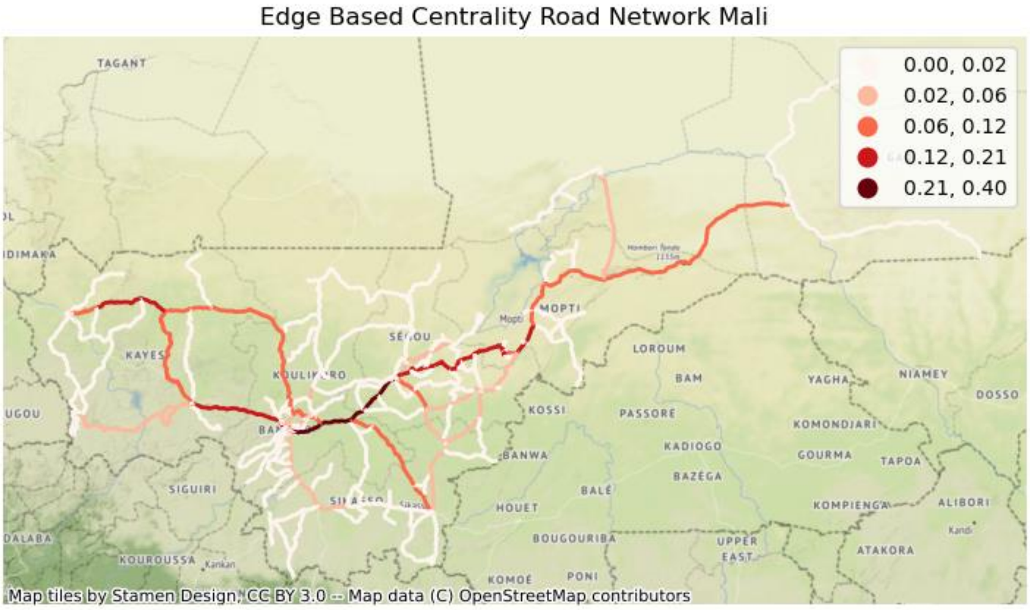

Figure 17. Edge Based Betweenness Centrality in Mali.

A fist observation is that the network scan approach assigns criticality values to roads that also receive high criticality scores in the edge-based betweenness centrality approach. The two approaches complement rather than contradict each other. The network scan approach seems to highlight road segments within the roads that the edge based betweenness centrality significant roads.

Secondly, the network scan approach yields higher values in the central region of the country, in contrast to the betweenness centrality results. In contrast, the degree centrality measure identifies many roads throughout the country as highly important, creating a network-wide "artery" of significance, which is crucial for determining shortest routes. The centred high values of the network scan approach indicate that the roads in the central region are vital not only due to their presence in numerous shortest routes but primarily because they connect significant cities that are relatively close to each other. The prominence of most cities in the centre of the country further underscores this pattern.

On top of that, the network scan approach stands out with more distinct criticality values, leading to clearer prioritization. This distinction allows the network scan approach to pinpoint which roads are truly indispensable, even among those considered important by the betweenness centrality measure. It is found that the majority of values fall within the range of 0 – 0.025. Only a highly limited number of road segments exhibit criticality values between 0.025 and 0.13. This outcome can be attributed to the weighting process applied in the network scan approach.

Finally, the network scan approach highlights a few roads that distinguish themselves, indicating their significance according to this method but not according to the betweenness centrality degree. Notably, these include the roads to the South-West of Bamako, connecting Bamako to Kangaba, and the road just North of Segou, linking Segou to multiple other cities. Considering the populations residing near these roads, these roads should indeed be regarded as important. In essence, the network scan approach emphasizes the roads already identified as crucial by the betweenness centrality measure and also brings attention to a few "forgotten roads" that are equally essential.

4.2.2. CRITICALITY IN THE SEGOU REGION

Figure 18 presents the criticality values for the Segou region, which encompass the values calculated using the national graph. Notably, the road to the North of Segou stands out with high criticality in particular.

Figure 19 displays the criticality of roads within the Segou region, calculated solely based on the network within that specific area. It is evident that the road to the North of Segou carries significant criticality. This observation can be attributed to the concentration of most cities in that particular region.

Another noteworthy observation is that the less centralised roads receive less weight compared to the national-based criticality. This phenomenon can be attributed to the fact that the national-based criticality places emphasis on the connections between regions rather than solely within a specific region. As a result, roads with local significance are given relatively lower importance in the national context.

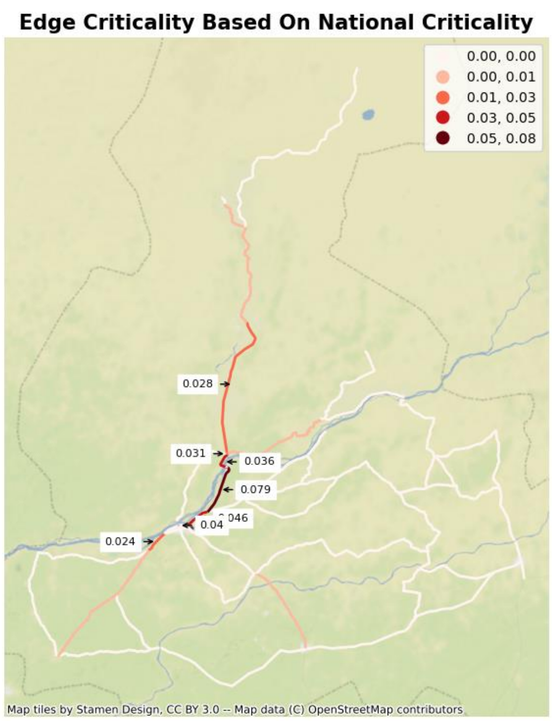

Figure 18. Nationwide criticality values in the Segou region (only > 0.01 has been put explicitly).

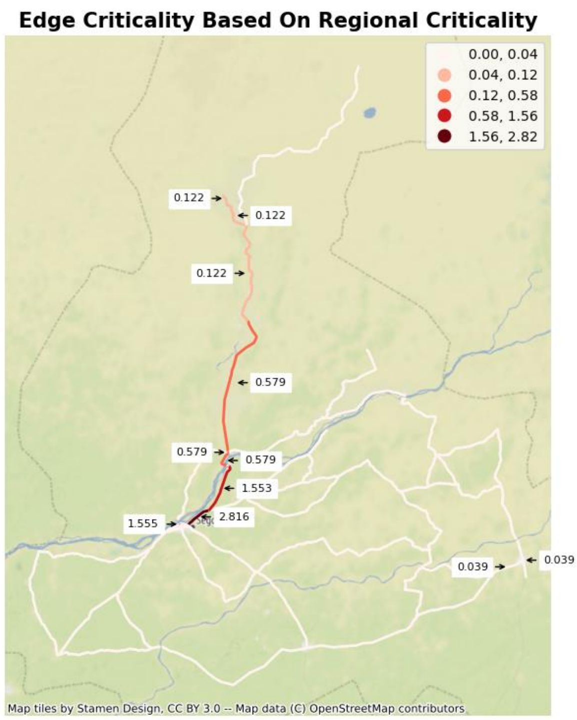

Figure 19. Regional criticality values in the Segou region (only > 0.01 has been put explicitly).

The distribution of criticality values within the Segou region based on regional criticality values are similar to the national criticality values. A considerable proportion of the values are skewed towards the lower end of the criticality scale, while only a limited number of road segments exhibit significantly high importance. Notably, the distribution of criticality values within the Segou region appears to be somewhat denser compared to the distribution observed at the national level. This phenomenon can likely be attributed to the relatively similar population sizes within the Segou region, resulting in a more compact distribution of criticality values.

4.3. RESULTS GAME THEORY MODEL

4.3.1. OPTIMAL STRATEGIES BASED ON NATIONAL CRITICALITY VALUES

Based on the national criticality values, the model has computed an optimal distribution strategy for both the defender and the attacker. Figure 20 provides a graphical representation of the attacker and defender's distributions, respectively. It is evident that both players prioritize the most critical road segments. Nevertheless, the attacker's optimal strategy allocates more weight to the most Northern part of the route to the North of Segou. Conversely, the defender assigns greater weight to road segments closer to Segou. This emphasis can be attributed to the region's highest criticality (Figure 21), which prompts the defender to prioritize the defense of these essential road segments.

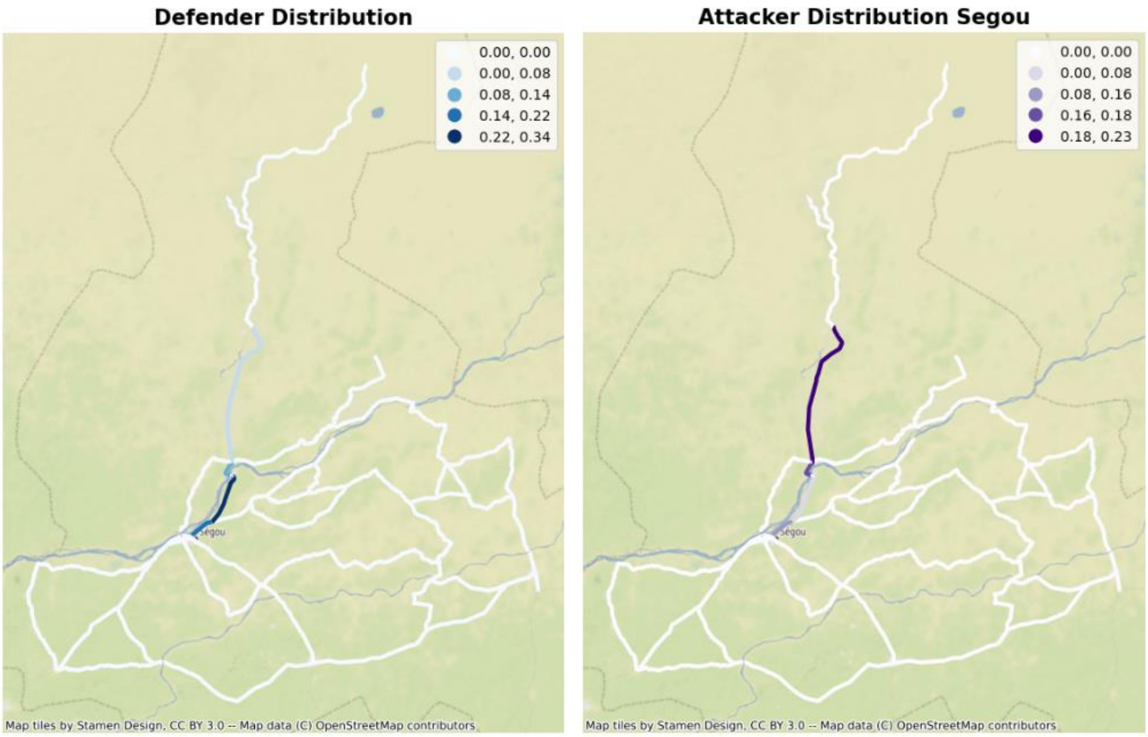

Figure 20. Optimal defender (left) and attacker (right) distribution according to the model based on nationwide criticality values. The darker the colour, the more distribution has been assigned to that road segment.

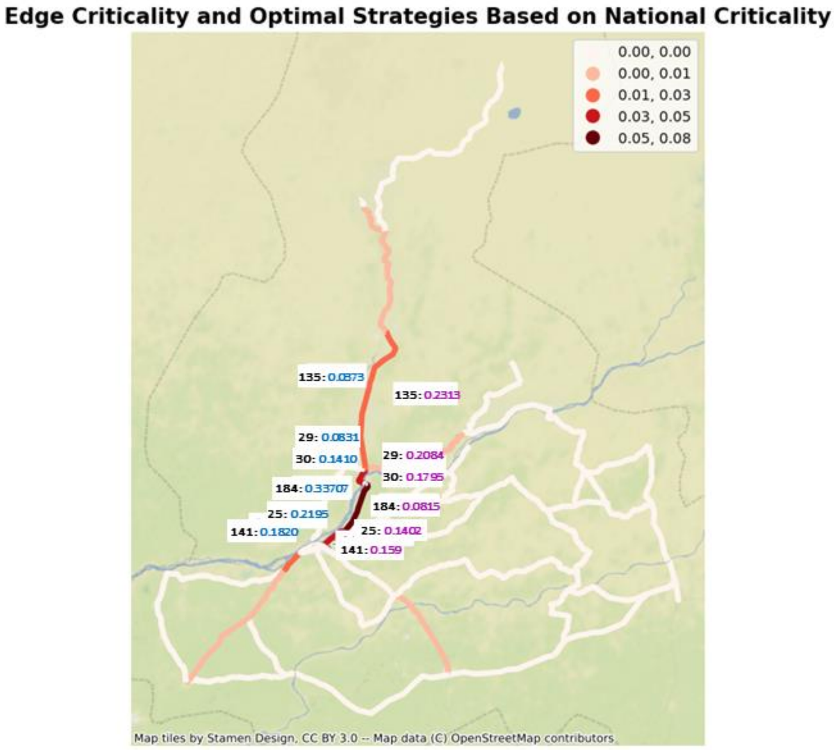

Figure 21. Detailed map of player's optimal strategies and national criticality values. Defender's distribution in blue annotation and attacker's distribution in purple annotation. The national criticality is visualised in red intensity on the roads

Table 3 displays the distribution of optimal strategies per road and the corresponding differences between the players' distributions and the criticality values for each road. An examination of the table reveals that the defender's and attacker's optimal strategies share identical road selections. Nonetheless, a notable contrast arises in their approach to weight allocation. The defender places more significance on roads with the highest criticality values. In contrast, the attacker opts for roads with comparatively lower criticality values, potentially seeking strategic advantages.

Road	Criticality	Defender	Attacker	Difference
184	0.0788	0.3371	0.0815	0.2556
25	0.0458	0.2195	0.1402	0.0793
141	0.0404	0.1820	0.1590	0.0230
30	0.0358	0.1410	0.1795	-0.0385
29	0.0308	0.0831	0.2084	-0.1253
135	0.0278	0.0373	0.2313	-0.1940
146	0.0242	0.0000	0.0000	0.0000
138	0.0103	0.0000	0.0000	0.0000
173	0.0103	0.0000	0.0000	0.0000
139	0.0095	0.0000	0.0000	0.0000

Table 3. Overview of the 10 roads with the highest national criticality values in Segou, the assigned distribution of optimal strategies and differences in players' distribution per road. Highest values relative to their column receive the darkest colour, while the lowest receive white colouring.

The value of the game was found to be -0.02568, meaning that with even resource capacities. The value of a game represents the expected payoff that the defender can achieve by following the optimal strategy. The defender can thus expect an effective loss. A negative value is unsurprising as the attacker minimizes the over the distribution of the defender, which will always be negative.

4.3.2. OPTIMAL STRATEGIES BASED ON REGIONAL CRITICALITY VALUES

Derived from the previously discussed regional criticality values, the model computed an optimal distribution strategy for both the defender and the attacker. Figure 22 presents the visual representation of the optimal distribution of the attacker and the defender. Notably, both players strategically allocate their resources to focus on the most critical road segments within the region. However, the attacker's optimal strategy places greater emphasis on the most Northern part of the route. Conversely, the defender allocates even more weight to road segments closer to Segou. This emphasis can likely be attributed to the fact that the highest criticality is situated in this specific region (Figure 23).

An intriguing observation emerges when comparing the optimal strategies based on national criticality values with those derived from regional criticality values. Notably, the regional optimal strategies exhibit a considerably closer proximity to Segou. This discrepancy can be attributed to the fact that the national-based perspective places more emphasis on the connection to cities in other regions, whereas the regional view exclusively focuses on the Segou region.

Furthermore, it is worth noting that the strategy based on regional criticality values is constrained to a distribution of three roads as can be seen in Table 4, while the national-based strategy is distributed over six roads. This distinction can also be attributed to the variance in criticality values. The regional criticality values' higher dispersion allows for clear prioritisation of solely three roads, whereas the relatively closer values in the national perspective allow for a distribution across six roads.

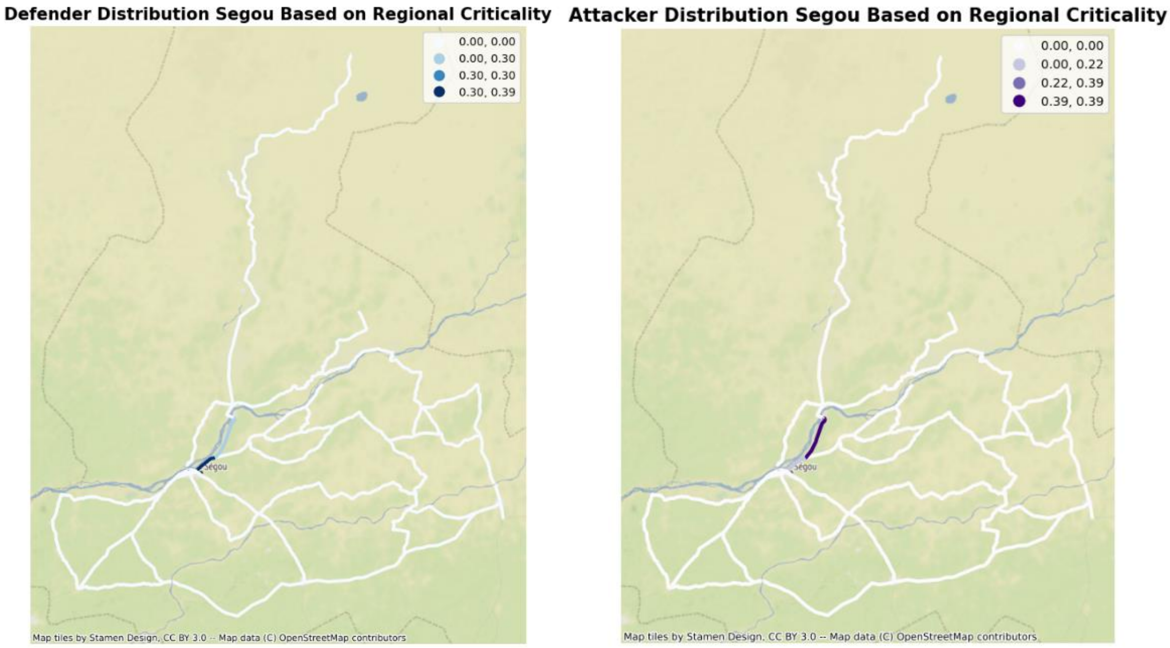

Figure 22. Optimal defender (left) and attacker (right) distribution according to the model based on regional criticality values. The darker the colour, the more distribution has been assigned to that road segment.

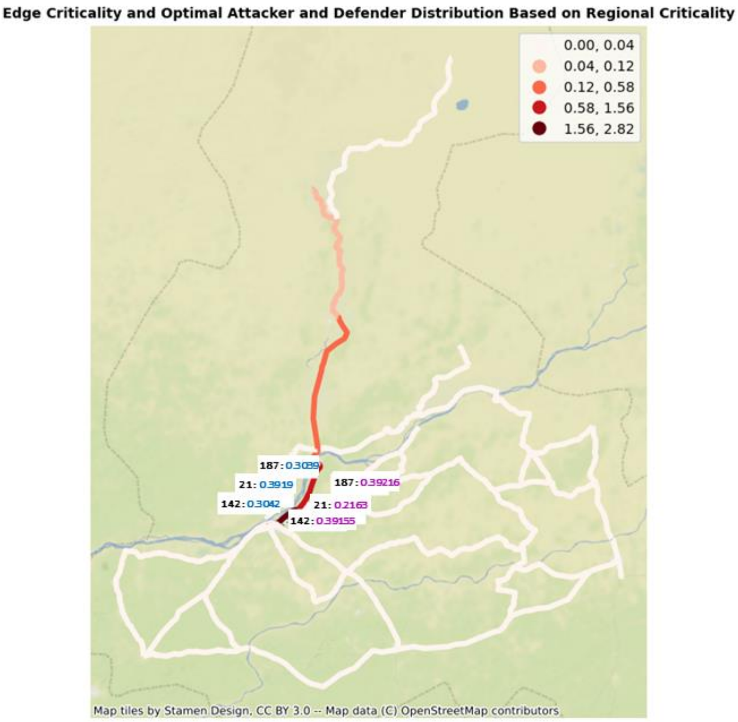

Figure 23. Detailed map of player's optimal strategies and regional criticality values. Defender's distribution in blue annotation and attacker's distribution in purple annotation. The regional criticality is visualised in red intensity on the roads.

Road	Criticality	Defender	Attacker	Difference
21	2.8160	0.3919	0.2163	0.1756
187	1.5530	0.3039	0.3922	-0.0883
142	0.8031	0.3042	0.3916	-0.0874
29	0.5793	0.0000	0.0000	0.0000
30	0.5793	0.0000	0.0000	0.0000
135	0.5793	0.0000	0.0000	0.0000
142	0.1220	0.0000	0.0000	0.0000
144	0.1220	0.0000	0.0000	0.0000
169	0.1220	0.0000	0.0000	0.0000
77	0.0385	0.0000	0.0000	0.0000

Table 4. Overview of the 10 roads with the highest regional criticality values in Segou, the assigned distribution of optimal strategies and differences in players' distribution per road. Highest values relative to their column receive the darkest colour, while the lowest receive white colouring.

The value of the game based on regional criticality was found to be -0.60899. In comparison to the model based on national criticality values this is higher. However, this might not be surprising as the regional criticality values were higher as well.

4.3.2. COMPARATIVE ANALYSIS OPTIMAL STRATEGIES AND INCIDENT DATA 2022

Figure 24 illustrates the distribution of actual reported incidents in the Segou region in 2022 per type of incident and the obtained optimal attacker strategies based on national criticality values (left) and regional criticality values (right). Figure 25 displays an aggregate view of the incidents of 2022, meaning that the roads have been coloured to the intensity of attacks happening on and around the road (<10km). To emphasize the difference in data displayed, a different colour coding has been used compared to previous visualizations.

The figures reveal that a significant portion of the attacks is concentrated in the North of the region. Solely armed clashes seem to be happening in the South as well. It can also be seen that the road part where the optimal strategy based on regional criticality values is concentrated, is not that heavily subject to actual attacks. However, it is very interesting to see that the optimal strategy based on national criticality values puts most weight on the same road segment as the actual incidents (figure 27).

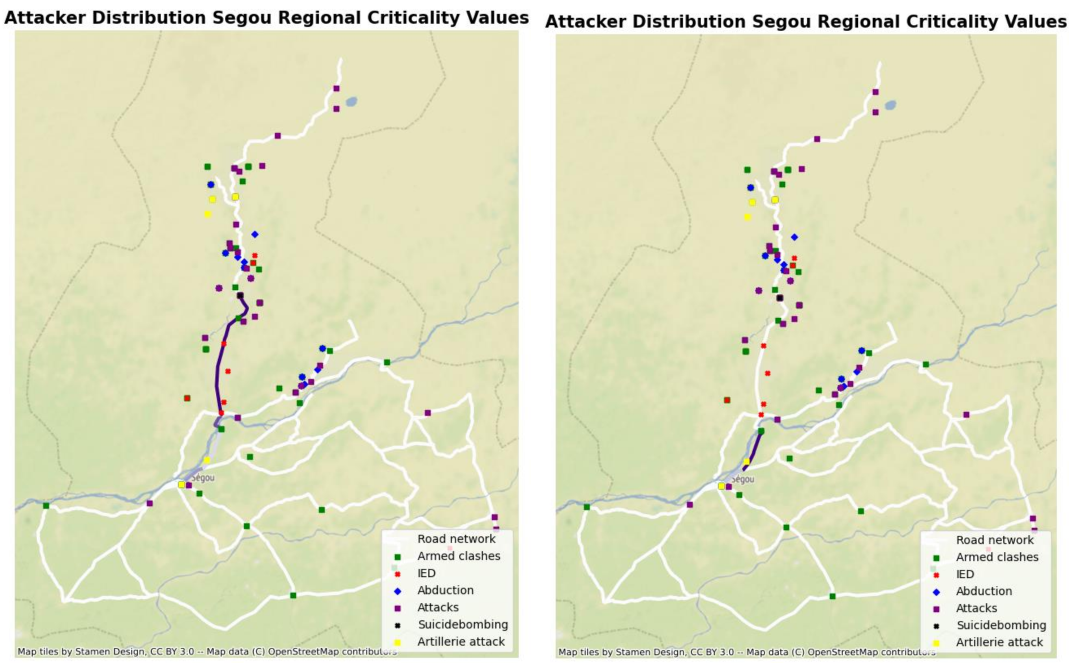

Figure 24. Plot of exact location of incidents per type in the Segou region in 2022 based on ACLED data. The colouring of the road is the visualisation of the optimal attackers strategy based on the national based criticality values (left) and based on the region.

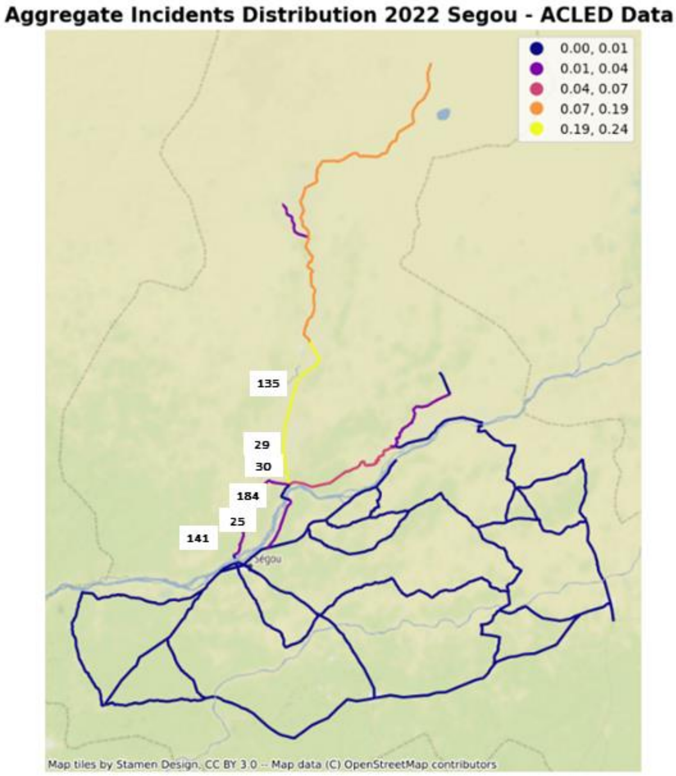

Figure 25. Aggregate view (assigned to the closest road) of reported incidents in the Segou region in 2022 based on ACLED.

In order to explore similarities and dissimilarities further, in Table 5 the defender and attacker distribution is compared to the aggregate distribution of incidents reported in 2022. It can be observed that in the model, the national based optimal attacker strategy puts emphasis on roads 25, 29, 30, 135, 141 and 184. On four of these 6 roads, no attacks have been reported in 2022. However on road 135, where the model puts most emphasis, the most incidents were reported as well, even the distribution numbers are relatively similar (0.2313 compared to 0.2388). Results of the model based on regional criticality values, distributed optimal attacker strategy over roads 25, 141 and 184. On two of these three roads, no attacks have been reported in 2022. However on road 187, some incidents took place. Moreover, many roads receive in reality a small portion of the incident distribution but are all disregarded by the model. What must be noted, is that from real world data, it can be seen that attacks have put an heavy emphasis on roads 143 and 144, while the model has neglected these roads. A possible reason for this might be that the model regards roads of different lengths similarly. While in reality, longer roads might be attacked more because there simply exists more road relative to very short roads.

It can be said that both strategies found by the model differ significantly from the actual incident distribution. Many roads that have been subject to incidents in 2022 are not accounted for in the optimal strategies found by the model. However, it can be said that the optimal attacker’s strategy found by national criticality values is less dissimilar to actual distribution compared to the optimal attacker's strategy found by regional criticality values.

Road Number	National Based Attacker Distribution	Regionally Based Attacker Distribution	Actual Incidents Distr
3	0	0	0.0373
6	0	0	0.0075
16	0	0	0.0075
25	0.1402	0.21629	0
28	0	0	0.0746
29	0.2084	0	0
30	0.1795	0	0
40	0	0	0.0075
43	0	0	0.0075
55	0	0	0.0075
75	0	0	0.0149
83	0	0	0.0075
91	0	0	0.0075
102	0	0	0.0075
109	0	0	0.0075
110	0	0	0.0075
119	0	0	0.0224
130	0	0	0.0075
131	0	0	0.0075
133	0	0	0.0224
134	0	0	0.0373
135	0.2313	0	0.2388
141	0.159	0.39155	0
142	0	0	0.0224
143	0	0	0.1567
144	0	0	0.194
145	0	0	0.0075
146	0	0	0.0075
169	0	0	0.0448
184	0.0815	0.39216	0.0299

Table 5. Display of the optimal strategies obtained by the model based on national (column 1) and regional (column 2) criticality values and the actual distribution of incidents in 2022 according to ACLED per road segment. The columns have been colour coded to assign darker red colours to higher values in the column to simplify visual comparison.

To compare optimal strategies with the incidents further, table 8 shows the incident distribution per type of incident in 2022 in the Segou region in comparison the optimal strategies. It was found above that road 135 was identified by the optimal strategy based on national criticality as most significant and the data of incidents revealed that this was also the most attacked road in 2022. It can be observed that on road 135, there are solely IEDs, armed clashes, attacks and suicide bombings. No abduction or artillery attacks were taken place on this road.

Lastly, the model referred to road 184 as slightly important and a few armed clashed were reported on these roads. It is interesting to note that many roads that received a small aggregate distribution in table 7 are roads that received this small portion solely because of armed clashes (6, 16, 55, 83, 91, 102, 109, 131, 145). While the model seems to catch the violent incidents overall not too well, it seems like especially the armed clashes are not well caught by the model.

	National Based Attacker Distribution	Regionally Based Attacker Distribution	IED distr	Armed Clashes Distr	Abduction Distr	Attack Distr	Suicide Bombdistr	Artillery Attack distr
3	0	0	0	0.0299	0	0	0	0.0075
6	0	0	0	0.0075	0	0	0	0
16	0	0	0	0.0075	0	0	0	0
25	0.1402	0.21629	0	0	0	0	0	0
28	0	0	0.0075	0.0299	0.0149	0.0224	0.0224	0
29	0.2084	0	0	0	0	0	0	0
30	0.1795	0	0	0	0	0	0	0
40	0	0	0.0075	0	0	0	0	0
43	0	0	0	0	0	0.0075	0.0075	0
55	0	0	0	0.0075	0	0	0	0
75	0	0	0	0	0	0.0149	0.0149	0
83	0	0	0	0.0075	0	0	0	0
91	0	0	0	0.0075	0	0	0	0
102	0	0	0	0.0075	0	0	0	0
109	0	0	0	0.0075	0	0	0	0
110	0	0	0	0	0	0.0075	0.0075	0
119	0	0	0.0075	0.0149	0	0	0	0
130	0	0	0	0	0	0	0	0
131	0	0	0	0.0075	0	0	0	0
133	0	0	0	0.0075	0.0075	0.0075	0.0075	0
134	0	0	0	0.0149	0.0149	0.0075	0.0075	0
135	0.2313	0	0.0522	0.1194	0	0.0522	0.0522	0
141	0.159	0.39155	0	0	0	0	0	0
142	0	0	0	0.0075	0	0	0	0.0149
143	0	0	0.0224	0.0672	0	0.0597	0.0597	0.0075
144	0	0	0.0224	0.0672	0.0522	0.0522	0.0522	0
145	0	0	0	0.0075	0	0	0	0
146	0	0	0	0	0	0.0075	0.0075	0
169	0	0	0.0075	0.0299	0.0075	0	0	0
184	0.0815	0.39216	0	0.0149	0	0	0	0.0075

Table 6. Overview of the optimal strategies obtained by the model based on national (column 1) and regional (column 2) criticality values and the actual distribution of incidents per type in 2022 according to ACLED per road segment. The columns have been colour coded to assign darker red colours to higher values in the column to simplify visual comparison.

4.3.3. COMPARATIVE ANALYSIS TO INSURGENT GROUP JNIM

For further analysis, the ACLED data has been filtered for solely the most dominant insurgent group in the region, JNIM. In Figure 26 the different types of attacks performed by JNIM in 2022 are plotted on top of the optimal distribution according to the model based on national criticality values. It can be observed that this insurgent group performs all types of attacks. Moreover, it can be seen that the most of the dispersed attacks that occurred in the South of the region can be attributed to JNIM. In Figure 27, an aggregate view of the JNIM incidents of 2022 are displayed. Compared to all the incidents that happened in the Segou region in 2022 (Figure 24) it can be said that JNIM is focussed on the centre part of the route to the North of Segou as well (yellow segment). However, more segments in the south and east (purple and orange) are lighting up more than before.

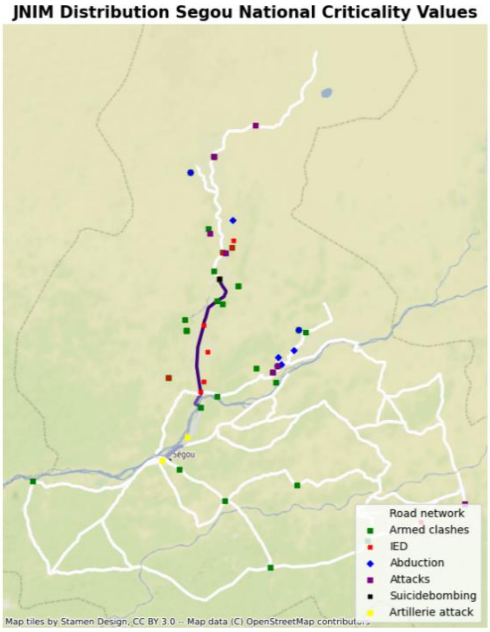

Figure 26. Plot of exact location of JNIM incidents per type in the Segou region in 2022 based on ACLED data. The colouring of the road is the visualisation of the optimal attackers strategy based on the national based criticality values (left) and based on the regional criticality values (right).

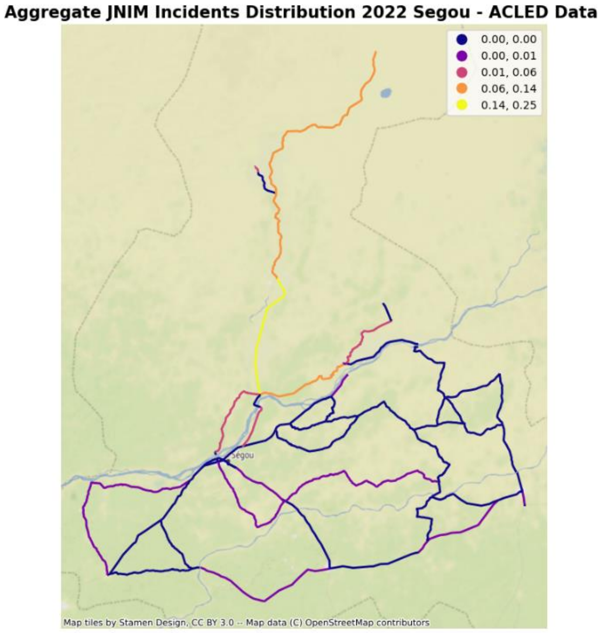

Figure 27. Aggregate distribution of JNIM attacks in 2022 based on ACLED data.

In order to explore the comparison to JNIM data further, the distribution of the optimal strategy based on national criticality values is displayed in Table 7 next to JNIM's incidents' distribution of 2022. It can again be observed that the optimal attacker distribution puts the most weight on the same road where JNIM puts the most weight on (road 135). It can be seen now that the high aggregate distribution for JNIM on this road can be attributed mainly because of the high rate of IED strikes. Armed clashes and IED strikes seem to occur on multiple geographical locations, however abductions, attacks and suicide bombings are more geographically focussed on a few roads. Furthermore, it seems like the total distribution of incidents in the Segou region in 2022 (Table 6) is not very different from the distribution of JNIM attacks. This indicates that JNIM is the insurgent actor responsible for most of the incidents in the region.

	National Based Attacker Distribution	JNIM Actual Total Incidents Distr	JNIM IED distr	JNIM Armed Clashes Distr	JNIM Abduction Distr	JNIM Attack Distr	JNIM Suicide Bombdistr	JNIM Artillery Attack distr
3	0.0000	0.0145	0.0000	0.0000	0.0000	0.0000	0.0000	0.0075
6	0.0000	0.0145	0.0000	0.0075	0.0000	0.0000	0.0000	0.0000
16	0.0000	0.0145	0.0000	0.0075	0.0000	0.0000	0.0000	0.0000
25	0.1402	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
28	0.0000	0.1304	0.0075	0.0299	0.0149	0.0149	0.0149	0.0000
29	0.2084	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
30	0.1795	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
40	0.0000	0.0145	0.0075	0.0000	0.0000	0.0000	0.0000	0.0000
55	0.0000	0.0145	0.0000	0.0075	0.0000	0.0000	0.0000	0.0000
75	0.0000	0.0145	0.0000	0.0000	0.0000	0.0075	0.0075	0.0000
83	0.0000	0.0145	0.0000	0.0075	0.0000	0.0000	0.0000	0.0000
91	0.0000	0.0145	0.0000	0.0075	0.0000	0.0000	0.0000	0.0000
109	0.0000	0.0145	0.0000	0.0075	0.0000	0.0000	0.0000	0.0000
119	0.0000	0.0435	0.0075	0.0149	0.0000	0.0000	0.0000	0.0000
133	0.0000	0.0145	0.0000	0.0000	0.0075	0.0000	0.0000	0.0000
134	0.0000	0.0580	0.0000	0.0149	0.0149	0.0000	0.0000	0.0000
135	0.2313	0.2464	0.0448	0.0746	0.0000	0.0000	0.0000	0.0000
141	0.1590	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
143	0.0000	0.1159	0.0224	0.0149	0.0000	0.0224	0.0224	0.0000
144	0.0000	0.1449	0.0224	0.0299	0.0075	0.0149	0.0149	0.0000
145	0.0000	0.0145	0.0000	0.0075	0.0000	0.0000	0.0000	0.0000
169	0.0000	0.0435	0.0075	0.0075	0.0075	0.0000	0.0000	0.0000
184	0.0815	0.0580	0.0000	0.0149	0.0000	0.0000	0.0000	0.0075

Table 7. Overview of the optimal strategies obtained by the model based on national criticality values (column 1) and the distribution of JNIM incidents in 2022 (column 2) and distribution of JNIM incidents per type according to ACLED per road segment. The columns have been colour coded to assign darker red colours to higher values in the column to simplify visual comparison.

5 | CONCLUSION & DISCUSSION

In this final chapter, the convergence of the game theory model, network science analysis, on-site interviews, and literature review culminates in a comprehensive examination that sheds light on road network protection in conflict areas and the imperative task of preserving connectivity. By addressing the sub-questions, a cohesive and nuanced answer to the main research question emerges, providing a deeper understanding of effective strategies for maintaining road network connectivity in conflict zones. After providing comprehensive answers to the research questions, this chapter will delve into a detailed discussion of the methodology employed and the obtained results. Furthermore, it will explore the implications of the findings for policy-making, highlighting their significance in scientific contexts as well as their broader societal relevance.

5.1. RESEARCH QUESTIONS

The primary focus of this thesis revolves around addressing the main research question:

"How can road network protection be strengthened to minimize the impact of terrorist attacks through the allocation of protective resources in conflict areas?"

To effectively answer this research inquiry, several sub-research questions were identified. By delving into these sub-questions, a cohesive and nuanced response to the main research question is achieved.

SQ1: What is the state of the art Malian road network protection against terrorist attacks?

It was found through interviews that the current protection of the road network in Mali is implemented through various measures. Military patrols, convoys, explosive ordnance disposal (EOD) units, intersection checkpoints, and the use of drones contribute to maintaining connectivity on the road network. Interviewees agreed that checkpoints are less effective than military patrols because of the staticity. On top of that did interviewees agree that military patrols accompanied by EOD units create the most security on the road network. Additionally, the construction and maintenance of well-paved roads have been found to enhance security passively by facilitating the identification of improvised explosive devices (IEDs) through quick detection of irregularities. Similarly, it was found that the installation of street lights can be effective in reducing IED incidents as they are typically placed during night-time. Furthermore, the implementation of advanced water drainage systems mitigates the impact of IED blasts by directing the force through water tunnels, minimizing harm to targets. However, the implementation of these measures carries substantial costs and necessitates time-intensive processes. For instance, road paving, due to its geopolitical and cultural considerations, requires significant time and resources which are often not at hand.

Despite the current existence of these measures, it became evident during the interviews that identified measures are not consistently deployed due to capacity limitations. Malian forces, given their relatively small size compared to the country's expanse, face challenges in effectively safeguarding the road network. Security checkpoints in particular, are reported to be ill-equipped and vulnerable to attacks. International missions primarily use their convoys and drones for the resupply of military bases, attributing no further road protection initiatives because of capacity constraints. Consequently, the road network protection has entered a detrimental cycle wherein insufficient resources on the network render deployed assets as easy targets, resulting in highly precarious situations. As a consequence, actors exhibit increased reluctance in allocating resources to the network, leading to decreasing security presence on the network which has made the situation even more dangerous. A visualisation of this detrimental circle has been portrayed in Figure 28. Interestingly, links can be made between this detrimental circle and the so called 'broken window theory'. The broken window theory from the field of criminology explains that visible signs of disorder and neglect in an environment can lead to an increase in crime and anti-social behaviour (Wilson & Kelling, 1982). It attributed the enhancement of crime to the lack of signals that the situation is monitored. This is comparable to the lack of resources that is placed on the road network which enhanced an unsafe environment.

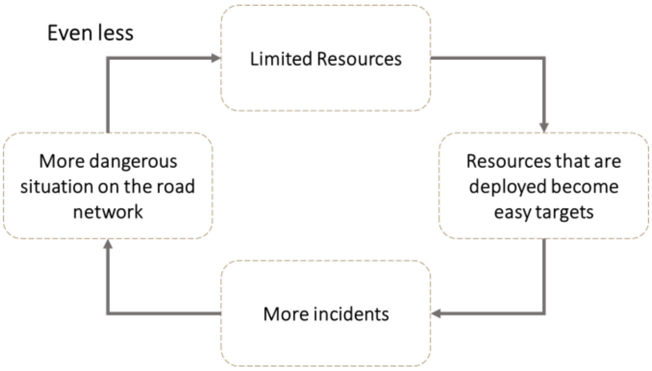

Figure 28. Detrimental circle of safety on the road network in Mali as explained by interviewees.

It is crucial to note that even if these measures were fully executed and implemented with sufficient capacity, they would not completely prevent attacks or the placement of IEDs. The identified security measures serve as mitigating factors, making it more challenging for attacks to be executed or IEDs to be planted. However, it was found in interviews as security measures become more advanced, there is an inherent likelihood of attackers developing more sophisticated tactics in response. Therefore, these measures are mitigating but not preventing actions.

Lastly, an important aspect raised in numerous interviews is the potential for military or armed presence on the roads to potentially worsen the security situation. The rationale behind this argument is that insurgent groups often target military or state actors, potentially escalating violence. While this viewpoint was supported in multiple interviews, civilian organizations still perceive roads where military or state actors are regularly present as relatively safer compared to areas where insurgent groups have freedom of movement.

In summary, the state of road network protection in Mali, as revealed through the interviews, entails a multifaceted approach involving various measures such as military patrols, convoys, EOD units, intersection checkpoints, drones, well-paved roads, street lights, and advanced water drainage systems. While these measures contribute to security, their effectiveness varies, with military patrols and EOD units seen as particularly impactful. Nonetheless, capacity constraints and resource limitations hinder consistent deployment, leading to a detrimental cycle of decreasing security presence and increased vulnerabilities. It is important to recognize that even fully executed measures won't completely prevent attacks or IED placements, as attackers may adapt to more advanced security methods. Despite challenges, the presence of armed forces on roads is still considered as relatively safer, despite the potential for escalating violence. Based on these findings, the model will be based on the distribution of military patrols accompanied by EOD units accompanied by the policy advice of the detrimental cycle.

SQ2: How can protective resources be allocated over critical road segments?

To address the question of allocating protective resources to critical road segments, a comprehensive investigation involving two distinct literature reviews was conducted. The aim was to identify optimal methods for assessing road segment criticality and selecting an appropriate game theory model for resource allocation.

Criticality measures were categorized into four classes based on their applicability and sophistication. Unfeasible approaches, primarily due to data limitations, comprised the first class. The second category encompassed basic centrality methods, which were deemed overly simplistic. More advanced methods formed the third category. Two of the methods in this category focussed on node criticality. The network scan approach however, especially designed for road networks, emerged as a balanced choice, integrating shortest paths, population sizes, travel distances, and travel times within a manageable computational framework. In the final category, Agent-Based Modelling (ABM) was considered inapplicable due to its demanding development process. Ultimately, the network scan approach was deemed most suitable for the Mali case due to its balance in simplicity and comprehensive analysis.

Secondly, literature reviewed on game theoretical resource allocation showed a very limited number of articles closely related to the topic. Among these, three utilized the Stackelberg game framework, due to the inherent complexity of modelling the Stackelberg game however, a time constraint renders it less feasible for this research. Consequently, a two-player zero-sum game structure, where optimal strategies can be ascertained through Nash equilibrium calculations as proposed by Chen (2022) emerges as the most pragmatic choice. Chen et al. (2022) corroborated these optimal strategies with risk assessment approaches, affirming that Nash equilibrium provided the most effective strategies. Given its simplicity, applicability, and seamless integration into the Malian case, the two-player zero-sum game stands out as a fitting method for this study.

Regarding game theoretical resource allocation, limited literature directly related to the topic was identified. Of the few relevant articles, three employed the Stackelberg game framework, though its complexity and time requirements posed challenges. As a result, a two-player zero-sum game, as suggested by Chen (2022), emerged as a pragmatic choice. Chen et al.'s (2022) findings, which aligned optimal strategies with risk assessment, reinforced the viability of Nash equilibrium calculations. This approach, characterized by its simplicity, applicability, and seamless integration with the Mali context, was considered an appropriate fit for the study.

In this model, the criticality of road segments serves as the basis for determining the payoff. No literature was found on integrating criticality values of a network into a game theoretical model, this will therefore be assumed to be an innovative approach.

While identified literature falls within the context of terrorist attacks, none of the found literature had application to conflict areas. It is thus important to note that application to this case needs to be conducted with care and a critical perspective.

SQ3: How can the allocation of protective resources over critical parts of the road network be modelled taking into account adversary actions in the case of Mali?

The second sub-question centred around identifying suitable approaches for model development, while the third sub-question focused on implementing these approaches within the specific context of Mali and to make the step from conceptual model to the formal game.

The network scan approach proves to be a useful additional tool for the criticality evaluation of the road network. Edge based betweenness centrality was used as a benchmark to compare to the results of the network scan approach. The comparison revealed that the former provides a different perspective on the criticality of road segments for connectivity, but the results rather complement than contradict each other. The edge based betweenness centrality identifies numerous roads throughout the country as highly important, creating a network-wide "artery" of significance. The network scan approach however highlighted specific segments of these “arteries” mostly in the centre of the country, around Bamako and to the North of Segou. The network scan therefore proves that these roads in the central region are vital not only due to their presence in numerous shortest routes but primarily because elimination heavily impacts society. Furthermore, the network scan approach yields more distinct criticality values, resulting in a clearer prioritization. This distinction allows the network scan approach to pinpoint which roads are truly indispensable, even among those considered important by the betweenness centrality measure. Especially in an resource scarce environment like Mali, a greater distinction is valuable. Lastly, the network scan approach also introduced two additional edges to the ranking of importance that edge-based centrality overlooked.

To explore the impact of the modeler's chosen network boundaries on criticality values, an analysis was performed using both national and regional network configurations. The findings indicated that criticality values in both cases exhibited a notable skew towards the lower end of the criticality scale. However, regional criticality values demonstrated a higher density compared to national values, largely due to substantial variations in population sizes at the national level. Furthermore, it was observed that criticality values based on the national network highlighted the significance of decentralized roads within the Segou region. This outcome was expected, given that regional criticality values do not consider connections to cities outside the region. It is thus essential to acknowledge that the boundaries selected by the modeler have a substantial impact on resulting criticality outcomes, with broader boundaries placing greater emphasis on less centralized roads and a wider range of population sizes leading to lower criticality values.

To develop a comprehensive formal model, careful consideration had to be given to the insights garnered from the interviews regarding the geopolitical situation in Mali. It was found that the interplay between the defender (representing the state actor) and the attacker (insurgent groups) differs significantly across regions in Mali. In some regions, the insurgent party becomes the defendant rather than the attacker. The turning of roles does not fit with the model as the governmental actors are less likely to pursue rebellious strategies that involve attacking roads and disrupting connectivity, as they are assumed to prioritize the interests of the population higher on their agenda. Hence, the roles of the two players in the model, defender and attacker, cannot be interchanged freely. The formal game was deliberately tailored to focus on a region where the state actor holds a dominant position, while insurgent groups adopt guerilla-like tactics. This alignment was substantiated by the insights gleaned from the interviews, which clearly indicated that the Segou region exemplified this dynamic.

An element of innovation in this study lies in the application of these methods to a conflict area, which introduced certain challenges within the formal game due to limited available data. Addressing concerns related to unpaved roads, discrepancies in the geographical locations of cities, and other associated limitations stemming from these decisions are elaborated upon in Chapter 5.3.

In conclusion, it was found that the network scan approach is a valuable addition for criticality measurements while it is however heavily subject to the boundaries set by the modeller. It is important to note that the game theory model is specific and does not fit to all geopolitical situations. Lastly, especially in a conflict area, data can oppose issues like choices around unpaved roads, mismatches between city locations and network locations.

RQ4: How can protective resources be optimally distributed over the road network in Mali according to the developed model?

By running the game based on both national and regional criticality values in the Segou region in Mali, optimal distributions were obtained for both the defendant player and the attacking player.

In both cases, the defender finds optimal strategies putting most weight on the roads with the highest criticality values. In the regional criticality values these are just North of Segou but very close to the city and in national based criticality values these lie on the route from Segou further North, to Niono. The closer to Segou (the higher the criticality values) the more resources the defender should put on protection of the roads according to the optimal strategies.

In both scenarios, the attacker's distribution focuses on the same routes as the defender, albeit with almost mirrored weights compared to the defender's. The attacker's optimal strategy indicates a preference for placing the most weight on the route to the North of Segou, but with a notable emphasis on the upper North rather than closer to the city of Segou. In the national distribution strategy, this translates to the highest weight being assigned to the road segment between Niono and Markala, whereas in the regional distribution, it pertains to the road segment just South of Markala. As a result, the roads where the defender allocates significant resources receive relatively fewer resources from the attacker, while the roads where the defender allocates fewer resources are assigned higher importance by the attacker. Notably, both players allocate resources to the same set of roads; there are no roads that only one of the two players prioritizes for resource allocation this indicates that the model expects a lot of confrontation between the two parties. On top of that, it can be stated that it would be advisable to place most resources on these roads as it forms the optimal strategy, meaning that the defender can not reach a better outcome than as portrayed in the equilibrium.

An intriguing contrast between the two optimal strategies lies in the number of roads that are prioritized. The strategy based on national criticality values focuses on six different roads, whereas the alternative strategy concentrates solely on three roads. This distinction can likely be attributed to the disparities in criticality values between the regional and national approaches. In the national approach, the populations of cities in the Segou region are relatively close to each other, in contrast to outliers such as Bamako with its larger population. As a result, the criticality values around the cities within the Segou region exhibit a more comparable range. On the other hand, the regional approach solely considers cities within the Segou region, leading to a greater differentiation of criticality based on the relative population sizes of those cities. Consequently, the differences in criticality values within the region exhibit more significant variations than the criticality values based on national considerations. This observation highlights that not only do the boundaries of criticality calculations influence the criticality values but they also impact the resulting optimal strategies.

A comparative analysis was conducted between the obtained optimal strategies and the reported data of conflict related incidents in the Segou region during 2022. The analysis revealed that the incidents in 2022 occurred on a greater number of roads than what the optimal strategies prescribed. Specifically, of the six roads that the optimal strategy based on national criticality values recommended for resource allocation, only two were actually subject to conflict related incidents in reality. Similarly, among the three roads chosen by the optimal strategy based on regional criticality values, only one road was used as a location for attacks. The substantial difference between the model's outputs and the actual distribution of incidents can be attributed to various factors. Firstly, the model's simplicity may not account for all the complex factors at play (see Chapter 5.3. for further elaboration). Secondly, the behaviour of the insurgent actor might not adhere to strict rationality, leading to deviations from the optimal strategy bounded by rational decision-making. Thirdly, the state actor (defender) may not act rationally, thereby influencing the attacker's response and the equilibrium. Moreover, both players might not exhibit rational behaviour, leading to entirely different outcomes. Finally, it is possible that the real-life situation has not yet reached its equilibrium, implying that the players are still in the process of finding the equilibrium.

It was however very interesting to observe that the road assigned by the national view as by far most significant, was found to receive the highest weight of violent incident distribution in reality as well. This means that the attacker’s optimal strategy of the nationwide criticality calculations is more similar to the attackers real distribution in 2022 than attacker’s optimal strategy based on regional criticality calculations. It is surprising as it might be expected that an insurgent group is more regionally oriented and therefore would coincide with a regional cost benefit analysis. Therefore this might be an indication that insurgent groups plan their attacks with a nationwide approach to connectivity. However, it is also possible that the nationwide criticality distribution is more similar to the attacker’s actual active region.

Lastly, a comparative analysis was executed for the insurgent group JNIM specifically to check whether optimal strategies resembled with their activity in 2022 in the region of Segou. No more similarity was found with this specific insurgent group than with the aggregate data. This might indicates that the dissimilarity between the optimal strategies and reported incidents in 2022 do not stem from the fact that the model is not actor specific.

In both games, a negative value was observed, signifying that, the attacker emerges victorious in the region of Segou when optimal strategies would be played. Consequently, the defender can anticipate experiencing a net loss. This negative value aligns with expectations, as the attacker strategically minimizes over the defender's distribution, leading to an inherent negative outcome. However, it is challenging to draw further conclusions about the game's value as it appears to have limited resemblance to real-world scenarios. This discrepancy arises from the fact as the attacker's strategies in reality differ from the optimal strategy. The value of the game is however based on the optimal strategies. As a result, the practical implications of the game's value become less informative in understanding the dynamics of the actual conflict situation in Segou.

To conclude, it was found that the boundaries of criticality measures impact optimal strategies. It was found that optimal attacker's strategies are not very similar to empirical data of attacks in Mali. Multiple reasons could contribute to that finding including the model's over simplification of reality, or irrational behaviour of one (or both) of the players or a state of non-equilibrium. It was however found that the optimal strategies based on national criticality values were more similar to empirical data than optimal strategies based on regional criticality values. This could be an indication that insurgent groups plan their attacks with a nationwide view to connectivity rather than solely focussed on the region.

RQ5: How can results be generalised for allocating resources to protect road networks against terrorist attacks?

The aspects of this research that hold potential for generalization are the use of the network scan approach in conflict area, the use criticality measures as input for a game theoretical model and the developed model overall.

A resemblance was observed between roads with elevated criticality values and those experiencing a high frequency of reported incidents in 2022. This discovery suggests that the network scan approach holds promise as a method that effectively captures road criticality, even from the perspective of insurgent groups.

Using criticality values as input for a game theoretical model is a novel approach. However it is not yet proven that combination of the network scan approach and game theory obtain optimal strategies that resemble reality. Further research is needed for further validation. For generalisation, it is crucial to recognize that the boundaries selected by the modeller influence the resulting criticality outcomes and obtained optimal strategies. For the generalisation of the model it would therefore be advised to use national border for criticality valuations and to use the active region of the insurgent group as area for obtaining optimal strategies.

It is important to acknowledge that the model is limited to a two-player zero-sum game (see Chapter 5.3.) for further information on limitations. The form of the game in this model means that application to a different geopolitical setting has clear requirements. These are called the rules of the game:

- The defender in the situation should have dominance in the region.
- The attacker has a modus operandi that fits with a zero sum game. Meaning that a win for one player is the loss for another player.
- Both players should be rational.
- Players should not cooperate

In summary, the model requires additional refinement to achieve readiness for widespread application. While the existing model can be considered rudimentary and somewhat detached from real-world complexities, it is believed to have laid down essential foundational principles.

All sub research questions above lead to the following answer to the main research question:

"How can road network protection be strengthened to minimize the impact of terrorist attacks through the allocation of protective resources in conflict areas?"

Although the effectiveness of utilizing the network scan approach as input for a two-player zero-sum game to enhance road network protection against terrorism is yet to be validated, several insights can be drawn from this study to reinforce road network protection.

Firstly, the complexity of dynamics in conflict area road networks was acknowledged through expert interviews, which concluded that a combination of military presence such as patrols and convoys, coupled with explosive ordnance disposal (EOD) units, has a positive impact on road network safety. Insufficient allocation of resources for road network protection was found to adversely affect safety and could potentially thus be worse than placing no resources.

Secondly, it was found that the network scan approach can be a useful tool for criticality measures as it provides a clear identification of indispensable roads. Especially in conflict areas which are usually resource scarce, this approach can provide valuable insights.

In conflict areas, where often little to no empirical traffic data is available, it would be advisable to focus network protection on the roads named in the obtained optimal strategies, as these mean that no better outcome can be obtained.

Moreover, the model's criticality values can fortify road network protection against terrorist attacks by providing insights into insurgents' behavioural patterns. By comparing optimal strategies based on regional and national criticality values with real-world data, it becomes possible to discern whether insurgent groups plan attacks with a nationwide perspective or focus on regional connectivity. Additionally, when the model would be utilized by state actors equipped with empirical defender distribution information, the model can shed light on the rationality behind insurgent behaviour, facilitating more informed decision-making.

5.2. POLICY IMPLICATIONS

The goal of this thesis is to shed light on road network protection in conflict areas and the imperative task of preserving connectivity. In this section, the potential input for security policy making is provided.

One highly significant aspect that the EPA programme focusses on transparent communication of the limitations of the model and the assumptions made. In line of that thought, first and foremost, as previously discussed, it is important to acknowledge that the developed model represents an initial stride towards a comprehensive framework that could effectively inform policymakers and military leaders. While the current model may be considered simplistic and distant from reality, it serves as a foundational starting point.

Another crucial insight gained from the EPA program is the necessity for policy advice to withstand the challenges of the political arena in order to have a meaningful impact on policy-making. In the case of this model and its specific context, significant obstacles are anticipated in the political sphere. This thesis examines several policy options where the model could be effectively employed, and each of these options will be thoroughly discussed.

5.2.1. MALIAN FORCES

Firstly, the model (or a future version) could potentially be used by the Malian army to distribute military protective resources. However, there may be resistance or scepticism from military leaders and personnel towards relying solely on data-driven models which was obvious in interviews. The human element in military operations, such as experience, intuition, and leadership, is highly valued. Some may perceive data-driven models as overly deterministic or undermining the role of human judgment and expertise. It is essential to note that military leaders in Mali are typically not extensively trained in handling large datasets or models of this nature, which could lead to a clash of cultures. Therefore, introducing and implementing the model requires a delicate approach, characterized by patience, interactivity, and careful consideration.

Furthermore, implementing this type of model within the armed forces in Mali poses significant complexities. The final model would need to be fed with data specific to the organization intending to use it. Through conducted interviews, it became evident that the intelligence branch of the Malian army differs from that of The Netherlands, creating potential challenges in terms of acquiring the appropriate data, identifying individuals capable of managing the data input, and interpreting the model's results accurately.

5.2.2. INTERNATIONAL MISSIONS

An additional avenue for implementing the policy advice lies within international missions operating in Mali. However, alongside the expected scepticism and resistance within a military context discussed above, political complexities further complicate the implementation process. These political complexities revolve around the activities of international missions and their misalignment with the government's needs. Interviews revealed a noticeable disconnect between the missions' actions in Mali and the needs of the government. This disconnection can be attributed to the incapacity faced by the missions in fulfilling requested actions and the influence of Western perspectives that shape their operational approaches. Consequently, interviewees emphasized that despite the development of an excellent policy advice regarding the distribution of protective resources, the likelihood of effective implementation by international missions remains highly uncertain.

The explanation for the incapacity of international missions is two-fold. Firstly, their mandates appear to be outdated, resulting in a mismatch with the needs of the local government. Secondly, operational challenges stemming from the highly multicultural environment contribute to their limitations. Language barriers and cultural differences not only impede effective communication but also give rise to conflicting perspectives and interests, making it difficult to find common ground and consensus on policy matters. A concrete example is the uniform payment scales for all UN officers, which fail to account for the significant salary differences with their home countries. Consequently, for some countries, participating in a UN mission leads to an extreme change in income, overshadowing other considerations. Furthermore, different countries may have varying interpretations of contractual agreements, causing inconsistencies. Implementing policy within such an environment becomes exceedingly challenging. The outdated mandate and cultural differences ultimately contribute to the mission's incapability to meet the needs of the local government, resulting in frustration among the local population. This frustration has escalated to the point where officers have faced harassment, and demonstrations against these missions have taken place.

In addition to incapability, the Western perspective significantly influences the execution of international peace missions. The stark contrast between the reality in Mali, characterized by hunger, extreme violence, and poverty, and the reality of decision-makers in New York and Brussels cannot be overlooked. International missions primarily prioritize stabilization and peace-building efforts, while research such as the Malimetre (2023) reveals that the immediate physical security of the population is their most pressing need. The idea of creating a stable and peaceful society may be too far-fetched for the Malian people in their current circumstances. This fundamental mismatch between the priorities of international missions and the actual needs of the population forms the underlying cause of their frustration.

Following the completion of Phase II, conducting interviews, in June 2023, the Malian representative in the UN Security Council made a declaration in New York, expressing Mali's desire for MINUSMA to withdraw from the country. This development highlights how frustrations can escalate to the extent that implementing any policy becomes an unviable option.

5.3. LIMITATIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

Limitations are applicable to the model, findings, and analysis conducted in this study. This section will discuss limitations per topic.

An overarching limitation of this research, as discussed in Chapter 1.5.5, pertains to its scope. The research does not encompass a quantitative analysis involving specific resource distribution figures; instead, it is confined to relative distribution represented in percentages. This limitation is attributed to the unavailability of precise data regarding the exact quantity of resources at the disposal of national and international forces, along with their associated costs. The scarcity of such data originates from two main factors. Firstly, information of this nature is highly classified due to its potential to compromise individuals' safety. Secondly, there is a significant likelihood that comprehensive data concerning resource availability and associated costs is simply absent. Insight from interviews revealed that the intelligence capabilities of mainly Malian forces are relatively rudimentary, possibly leading to the absence of such data. A remark should be made that even if such data were accessible to the author, its public disclosure within this research would be deemed unethical, as it could jeopardize lives.

5.3.1. DATA LIMITATIONS

Firstly, the data used is subject to limitations. One of the primary limitations of OpenStreetMap is the potential for data inaccuracies and inconsistencies. Since OSM relies on crowd-sourced data, the quality of information can vary significantly. While many contributors diligently validate and update data, others may unknowingly introduce errors or fail to maintain accuracy over time. Consequently, certain regions or features might be better mapped than others, leading to discrepancies in data reliability. Furthermore, the temporal aspect of data in OSM can be both a strength and a limitation. The real-time nature of contributions allows for rapid updates and the incorporation of new developments. However, it also means that certain data might quickly become outdated, especially in rapidly changing environments like Mali that is heavily subject to seasonality.

Secondly, is the population data in Mali not very trustworthy, validation was sought in different sources but findings varied heavily. The decision was made to stick to one source that seemed to have a reliable source as SimpleMaps. However, data is likely to be inaccurate as populations measurements are often imprecise in developing countries (Stoto, 1983).

Lastly, ACLED data on violent incidents in 2022 might be subject to several limitations as well. Firstly, ACLED data is based on media reports. Therefore, ACLED data may suffer from geographical coverage bias. It tends to have more extensive coverage in conflict-prone regions or areas with higher media and data reporting accessibility. This bias can result in underrepresentation of conflicts in remote or less media-covered locations, leading to potential gaps in the understanding of armed conflicts on a global scale. In general, the country of Mali is prone to conflict however it can be assumed that not all incidents are reported, especially in more remote areas. Secondly, as ACLED primarily relies on media reports, NGO publications, and other open-source materials to gather information on conflict events. While this approach allows for real-time updates, it can also introduce issues of data accuracy and reliability. Some conflicts might go unreported or may be inaccurately documented, leading to potential discrepancies and incomplete information.

5.3.2. INTERVIEW LIMITATIONS

Semi-structured interviews, while a valuable research method, come with inherent limitations that should be considered when reading the results of this thesis.

One significant limitation lies in the lack of standardized questioning. The flexibility of semi-structured interviews allows participants to freely express their views and experiences. However, this variability in question format can impede direct comparisons of responses across participants. Another crucial aspect to acknowledge is the potential for interviewer bias. The interviewer's presence and behaviour can subtly influence participants' responses, leading to unintentional biases in question framing or follow-up prompts. Next to that, it is important to acknowledge that purposive sampling introduces some degree of bias, as the sample selection is not random. Furthermore, the resource-intensive nature of semi-structured interviews limits the sample size researchers can work with effectively. This smaller sample may not fully represent the entire a 360 degree view of the topic. Lastly, a potential for social desirability bias is present as well. Participants might modify their responses to present themselves favourably or in line with perceived societal expectations. Examples of this could include that Malian are less likely to speak negatively about their country or governance because of pride or because of fear.

5.3.3. NETWORK SCAN APPROACH LIMITATIONS

Although the network scan approach aligns well with the complexity requirements of this case, it has certain limitations. Firstly, ideally real world traffic data should be used to base a criticality measure on. However, that was not a possibility for the case of Mali where this data is unavailable. In the network scan approach, solely populations are regarded as a factor of importance. It might however, be the case that in regions where population is lower, agricultural activity is higher which has a large effect on traffic streams and on the wellbeing of the country. Since this could also be said about for example industrial activity, education accessibility or medical accessibility, it was decided to keep the model general. However, in further research developing the model for specific needs would be recommended to even further increase the societal impact. Secondly, the network scan approach does has some limitations regarding the road network. Firstly, maximum road capacity is not taken into consideration. This might be an issue in Mali as traffic, especially within cities can be very intense.

Calculating travel times presented further challenges. Interviews revealed that official speed limits are often disregarded, and actual speeds vary significantly based on circumstances. To address this, an average speed limit of 70 kilometres per hour was adopted for the entire network, with the understanding that the model calculates almost all travel times between cities rather than within them. While this decision introduced some inaccuracies, particularly in calculating criticality values, it provided a practical solution given the limited data availability.

Furthermore, the computational intensity of the network scan increases significantly when applied to large networks which poses a limitation of the method.

Another drawback is that the network scan approach does not consider attacks on multiple locations simultaneously. It solely considers scenarios where one edge is removed but not multiple at the same time. A well-coordinated attack could however do this. It means that in some cases an edge does not seem highly critical according to the network scan approach, because another road lies parallel to it. However when these two roads would be attacked at the same time the travel distance time could increase immensely. This would mean that all possible sets of edges should be incorporated in the model as well which would heavily increase the computational demand of the model. Analysis of the ACLED database revealed a low incidence of simultaneous attacks occurring across multiple places, which justified excluding this aspect.

One significant challenge encountered was the predominance of unpaved roads, which presented issues of unreliable knowledge of accessibility, capacity, and traffic speed.
Consequently, the decision was made to focus the model solely on paved roads, as interviews confirmed that inter-city transportation primarily utilizes these roads. However, this decision resulted in the potential disconnection of a city called Tessalit, which is solely connected to rest of the road network via an unpaved road. To address this, Tessalit was manually placed at the starting point of the unpaved road, granting the paved roads leading to it the appropriate weighting. Nonetheless, this approach inadvertently resulted in a shorter distance to Tessalit in the model compared to reality, potentially influencing the criticality values.

An additional difficulty arose when removing an edge from the network to assess its criticality. In some cases, this rendered a city inaccessible as only one paved road provided access to that city. Initially, an infinite increase in travel time was considered, but this significantly impacted criticality values, making them unreadable after normalization. In the interviews, it was discovered that detours on unpaved roads are commonly taken in such scenarios. Thus, a two-hour increase in travel time was implemented as a reasonable solution. However, this adjustment still has a substantial impact on the distribution of criticality values, as observed in the histograms displaying their distribution.
Additionally, the model's border settings posed challenges. The model is respective to a specific region and takes only the roads into account that fall inside that region. Shifting the region thus has an effect on the results. For the Segou region it was checked whether the results differed with a small change in borders but no changes in results were to be found. Adjusting the model to account for specific actors and their respective regions of activity would provide a more accurate representation of their modus operandi and thus of the accompanied optimal strategies. In further research it would be advised to investigate purely the active region.

5.3.4. GAME THEORY LIMITATIONS

It is important to note that a game theory model represents a highly simplified version of reality. Firstly, it assumes rational behaviour from both players, which may not always be the case. This might indicate that the obtained optimal strategies are not close to what is happening in reality at all. Additionally, the model focuses primarily on optimizing strategies for preserving and attacking network connectivity. It does not encompass attacks with different goals, such as spreading fear or gaining publicity. These attacks are likely to be placed on different geographical locations than given by the optimal strategies. As a result, comparing the optimal attacker distribution obtained by the model to real-world scenarios becomes complex, as it is often challenging to ascertain the underlying objectives of insurgent attacks. However, it was found in interviews that underlying goals of attacks are often showing presence in a region. While the goal of a specific attack thus might be to gain publicity, it is still likely to occur on a place where the insurgent group wants to show its presence. This is likely to be on places with a higher connectivity in general therefore it was expected that the comparison between real incidents and optimal strategies could still be made. However, in further research it would be recommended to examine further how to distinct the incidents that have the goal to attack connectivity.

Another limitation of the game theory approach is how pay-offs are distributed especially in the case of IED attacks. The game theory model views the situation as follows. When an attacker chooses a specific road segment to focus on and the defender does that as well, the defender wins and the attacker loses. However in the case of an IED, the attacker places an IED and the if the defender chooses this road as well there are two possibilities. The defender spots the IED and neutralizes it or the defender gets hit by the IED, which obviously means that the defender does not win in reality. The real life situation is more complex than the zero-sum game portrays. The model thus assumes that defenders always spot IEDs. It would be recommended for further research to explore this aspect further.

5.3.5. MODEL LIMITATIONS

As extensively explained earlier, this model remains susceptible to numerous assumptions and limitations. In order to provide a comprehensive and well-informed recommendation on the allocation of protective resources in Mali, further research is warranted. Specifically, it is crucial to refine the model by adapting it to the unique characteristics and operational strategies of specific actors, as well as considering the active region in which these actors operate. Instead of using administrative border of a region, it would be recommended to use the active region of a specific actor. It would be recommended to analyse previous incidents to understand the modus of operandi of the specific actor and adjust the model accordingly. If it is concluded that an actor does not operate rationally, it could be advised to regard the modus operandi as given and construct a game theory model around it that provides an optimal strategy for the defendant.

A further model limitation is its disregard for road length. The model treats vastly different road lengths equally, solely relying on the criticality value. However, real-world protection requirements differ for longer roads, necessitating more resources. Longer roads also have increased vulnerability due to their greater number. Future research should incorporate road length for more accurate optimal strategy determination.

Lastly, it is recommended for further research to validate the model's effectiveness and determine its applicability to different types of attacks. In the results it seemed like the model catches violent incidents like armed clashes less than other types of attacks. It is necessary to investigate this further and identify the specific types of attacks that should be considered when evaluating the model's performance.

5.4. SCIENTIFIC RELEVANCE

The scientific research contributions of this thesis, can be summarized as follows.

5.4.1. METHODOLOGICAL RESEARCH CONTRIBUTIONS

The developed model represents an initial endeavour to integrate network science in combination with game theory within the context of attacks on road networks and the preservation of road network connectivity. This innovative approach contributes to a deeper comprehension of the operational strategies employed by insurgent groups, as well as the potential applicability of game theoretical models in informing security policy decisions related to transportation networks. By bridging these disciplines, a more comprehensive understanding of the complex dynamics at play can be achieved, paving the way for enhanced security measures and informed policy-making in safeguarding transport networks.

Furthermore, this thesis has used the network scan approach and, in doing so, has made a valuable contribution to the ongoing exploration and understanding of this method. By applying the network scan approach within the context of a conflict area, novel insights and practical implications have emerged, enhancing knowledge of its effectiveness, potential applications and limitations. The findings and outcomes of this research not only provide valuable contributions to the existing literature but also serve as a foundation for future studies in this field.

On top of that, this thesis delves into an exploration of effectively handling the network scan approach within a highly data-limited environment. Recognizing the challenges posed by limited data availability, the research investigates innovative approaches and methodologies to overcome these constraints. The findings shed light on the potential avenues and adaptations required to leverage network science effectively, even in situations where data availability is restricted, fostering more robust and applicable research outcomes.

Lastly, scientific relevance of this research also lies in its innovative combination of quantitative methodologies, specifically network science and game theory, with qualitative methods such as interviews. Network science offers a data-driven quantitative foundation for evaluating criticality within road networks, facilitating a precise assessment of vulnerable segments. Game theory quantitatively models the intricate interactions and strategic decisions of the actors. The incorporation of qualitative interviews enriches the research by providing nuanced insights into the real-world dynamics, challenges, and contextual nuances associated with road network protection. These interviews enable a deeper exploration of the situation in Mali and enables to paint a full story behind the data. The synergy between these quantitative and qualitative methodologies enhances the robustness and applicability of the research outcomes. Ultimately, this integration contributes to a more informed, nuanced and holistic understanding of road network protection problem.

5.4.2. APPLICATION RESEARCH CONTRIBUTIONS

Lastly, this study has enhanced the understanding of the intricate dynamics of road networks in conflict areas. By conducting on-site interviews and engaging with individuals directly involved in these environments, valuable insights have been obtained regarding the types of attacks that occur, the security policy measures implemented, and the contextual factors that influence the effectiveness and implementation of such policies. The knowledge gained from these interviews has provided nuanced perspectives on the multifaceted challenges faced in securing road networks and has illuminated the complex interplay between various stakeholders and environmental factors. This comprehensive understanding serves as a foundation for the development of more effective and contextually appropriate security policies, fostering safer and more resilient road networks in conflict areas.

5.4.2. GEOGRAPHICAL RESEARCH CONTRIBUTIONS

To conclude, this thesis underscores the significance of scientific research in developing countries, particularly those affected by conflict. While it may be more convenient for the academic community to concentrate on other countries with fewer challenges in terms of gathering information (data collection or interview conduction), it is crucial to recognize the imperative for research and progress in these specific regions. Engaging in scientific research in developing countries subject to conflict is not only important but also essential for promoting sustainable development and fostering positive change.

On top of a moral obligation, conducting research in such diverse environments can provide valuable insights and lessons that can benefit the Western world as well. By exploring alternative perspectives and approaches, the academic community can gain a deeper understanding of how things are done differently, challenging existing assumptions and broadening our collective knowledge base. This reciprocal exchange of knowledge and experiences fosters mutual learning and growth, promoting a more inclusive and comprehensive approach to scientific research and global problem-solving. Therefore, it is not only important to conduct research in developing countries subjected to conflict due to moral obligations, but also because it holds the potential to teach the Western world valuable lessons about our own practices and perspectives.

5.5. SOCIETAL RELEVANCE

The societal research contributions of this thesis are discussed in the following section according to Bornmann (2013) division of social, cultural, environmental and economic impact of academic research. These are discussed in the following sections, the environmental impact of this research was found highly limited and therefore that section has been discarded.

5.5.1. SOCIAL IMPACT

According to Bornman (2013), social benefits encompass the valuable contributions that research makes to a nation's social capital. This includes its role in addressing pressing social issues, informing policymaking processes, and stimulating public discourse on critical matters. This thesis addresses a multi facet problem that relates to various grand challenges. The addressed problem, terrorism attacks on critical road segments, integrates the grand challenges of global peace and infrastructure resilience. This thesis enhances the understanding of terrorism dynamics on road networks in conflict areas and therefore contributes to these complex social issues. On top of that, hopes the developed model in this research to support policymaking on how to effectively distribute protective resources.

By contributing to safe transportation in conflict areas, this study also hopes to have an indirect influence on reducing inequalities as the two are highly related as explained by Kaplan and Teufel (2016). This thesis has therefore a social impact on the grand challenges of peace, infrastructure resilience and indirectly on reducing inequalities.

5.5.2. CULTURAL IMPACT

Cultural benefits involve the meaningful contributions of research to a nation's cultural capital, such as its impact on cultural preservation and heritage (Bornmann, 2013).

While the research does heavily not touch upon the Malian culture, the provided policy impact is of military nature. The military culture is a heavily set culture (Soesters et al., 2006) that is often very rigid and ill-integrated with modelling techniques like the one proposed in this study. This research might however, be another step towards a more data oriented military approach and might show military leaders that modelling can be highly valuable in the battlefield.

On top of that, it was shown in the literature reviews on terrorist attacks on critical infrastructure that most research on this topic is performed in the West while countries mostly plagues by terrorism are in the Middle East and the Sahel region. This means that regions that need this type of research the most are a bit neglected by the academic literature and therefore it is argued that this thesis contributes to 'inter-country' inequality.

Lastly, this research sheds light on how to perform network analysis and game theory analysis on a country like Mali. It elaborates on cultural aspects of international missions and how to implement a road network with many uncertainties into a model. An example of this is the real car speed that differs significantly from the official speed limits in the country or the challenge of unpaved road in a network scientific graph. This research tried to implement as many of these cultural implications as possible by going to Mali and having interviews with experts in the field. By documenting these findings, this research contributes to the nation's cultural capital.

5.5.3. ECONOMIC IMPACT

Economic impact encompass research that enhance a nation's economic capital (Bornmann, 2013). This thesis and the developed model impact the nation's economy in two distinct ways. Firstly, by using this model hopefully resources can be distributed effectively so less economic value goes to waste. Secondly, by putting the model to use, hopefully the safety situation on roads in Mali will improve. This will have an impact on trade and thus on stability, prosperity and economic welfare.

5.6. EPA RELEVANCE

In this final section, the research's significance within the EPA Program at TU Delft becomes evident.

Firstly, the study focuses on several multi-actor grand challenges by exploring the intersection of critical infrastructure protection and the global fight against terrorism. Secondly, the study has a multidisciplinary character by integrating diverse disciplines such as network science, game theory and security studies. On top of that, are the fundamental themes, modelling, simulation, policy, and politics, of the EPA program addressed. Additionally, the study presents cutting edge modelling techniques and takes an analytic stand towards the security domain which is characteristic for the EPA program. Moreover, while the study is technical in nature, the 'soft side' is not neglected. Key messages of the program are adhered to by placing emphasis on transparent communication of model limitations assumptions and on the survival of the policy advice in the political arena.

Concluding, findings contribute to the program's mission of fostering interdisciplinary policy analysis, showcasing the importance of tackling multifaceted challenges with integrity and efficacy in both policy and engineering realms.

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A | APPENDICES

A.1. BACKGROUND ON THE CONFLICT IN MALI

The conflict in Mali has been a long-standing and multifaceted struggle, characterized by deep-rooted ethnic tensions, political instability, and the rise of extremist insurgency. Since its outbreak in 2012, the conflict has had significant ramifications for the security, humanitarian situation, and regional stability in the Sahel. This appendix aims to provide a comprehensive overview of the Mali conflict, exploring its root causes, key actors, and the international community's efforts to resolve the crisis.

The Mali conflict's root causes can be traced back to a combination of historical, socio-economic, and political factors. First and foremost, longstanding ethnic tensions between the Tuareg and Fulani populations have played a central role (Klute & Mulugeta, 2016). These tensions have been fuelled by socio-economic disparities, marginalization, and competition over land and resources. The grievances stemming from these disparities have contributed to a sense of frustration and a desire for greater self-determination among certain ethnic groups.

Moreover, weak governance, corruption, and the inadequate provision of basic services have eroded public trust in the state institutions, creating an environment prone to conflict (Dijkzeul & Mulugeta, 2018). The Malian government's failure to address these issues effectively has widened the gap between the state and its citizens, further exacerbating tensions.

Another significant factor has been the proliferation of arms, which has been intensified by the fallout from the Libyan civil war. The influx of weapons into the region provided various armed groups with greater firepower, enabling them to challenge state authority and pursue their respective agendas (Lacher, 2017). Extremist groups, such as Al-Qaeda in the Islamic Maghreb (AQIM) and the Islamic State in the Greater Sahara (ISGS), capitalized on the power vacuum and the discontent within certain communities to gain influence and carry out acts of terrorism (Hoffman, 2018).

The Mali conflict involves a range of actors, each with their own interests and objectives. The Malian government, although initially ill-prepared to effectively respond to the crisis, has sought to regain control over the territory and restore stability (Mendy, 2020). Its efforts have been focused on enhancing security, promoting development, and fostering dialogue between conflicting parties. However, challenges such as weak institutions, corruption, and the limited presence of state authority in some areas have hindered the government's ability to establish its legitimacy and effectively address the root causes of the conflict.

On the other side, various armed groups have emerged, each with their own motivations and aspirations. The National Movement for the Liberation of Azawad (MNLA), predominantly composed of Tuareg fighters, has sought greater autonomy and self-determination for the northern region of Azawad (Lecocq, 2016). Ansar Dine, another significant group, has aimed to establish an Islamic state based on a strict interpretation of Sharia law. These groups have engaged in armed confrontations with the Malian government and have often clashed with each other over territorial control and resources.

In addition, transnational extremist organizations such as AQIM and ISGS have exploited the conflict to expand their influence and carry out terrorist activities. These groups have capitalized on grievances, socio-economic disparities, and the porous borders in the Sahel region to recruit fighters, conduct attacks, and undermine stability (Hoffman, 2018).
International Efforts:
The international community has responded to the Mali conflict through a combination of military intervention, diplomatic initiatives, and humanitarian aid. The United Nations Security Council authorized the establishment of the United Nations Multidimensional Integrated Stabilization Mission in Mali (MINUSMA) in 2013, aiming to stabilize the country and support the political process (UN Security Council, 2013). MINUSMA has been actively involved in promoting security, protecting civilians, and facilitating peace negotiations between the Malian government, armed groups, and other stakeholders.

Regional actors have also played a crucial role in addressing the Mali conflict. The Economic Community of West African States (ECOWAS) has led regional efforts by deploying the ECOWAS Mission in Mali (AFISMA), which later transitioned into the African-led International Support Mission to Mali (AFISMA) and subsequently the United Nations Mission for the Stabilization of Mali (MINUSMA). These regional initiatives have aimed to provide military support, facilitate dialogue, and foster cooperation among Sahelian states to counter the cross-border threats posed by extremism and instability (Bøås & Stiansen, 2018).

In addition to the United Nations and regional organizations, the European Union (EU) has been actively involved in addressing the Mali conflict. The EU launched the European Union Training Mission in Mali (EUTM Mali) in 2013. EUTM Mali has focused on enhancing the capabilities of the Malian Armed Forces through training and advisory support. Its efforts have aimed to improve the military's professionalism, effectiveness, and respect for human rights (European External Action Service, 2019). The mission has provided training in various areas, including military doctrine, command and control, logistics, and human resources management.

Furthermore, international donors, including both bilateral and multilateral actors, have provided significant financial assistance for humanitarian aid, development programs, and peacebuilding initiatives in Mali. These efforts have aimed to address the immediate needs of affected populations, promote sustainable development, and support the long-term stability and resilience of the country (European Union, 2019).

Resolving the Mali conflict remains a complex and ongoing challenge. The conflict's multifaceted nature, including deep-rooted ethnic tensions, governance issues, and the presence of extremist groups, requires a comprehensive and multidimensional approach. Efforts to address the conflict must include both short-term stabilization measures and long-term solutions that address the underlying causes.

Key challenges include the persistence of ethnic tensions, which require inclusive governance mechanisms that accommodate diverse identities and address historical grievances. Additionally, the proliferation of arms and the influence of extremist groups necessitate comprehensive security sector reforms, effective counter-terrorism measures, and initiatives to combat the illicit flow of weapons (Bøås & Stiansen, 2018).

Moreover, achieving lasting stability in Mali requires addressing socio-economic disparities, promoting equitable development, and improving access to basic services, particularly in marginalized areas. Enhancing the capacity of state institutions, combating corruption, and promoting the rule of law are essential for building trust between the government and its citizens (Berdal & Keen, 2016).

In conclusion, the conflict in Mali remains a complex and protracted struggle, involving deep-seated ethnic tensions, political instability, and the presence of extremist groups. Resolving the crisis requires a comprehensive and sustained approach that addresses the root causes, engages all relevant actors, and combines military, diplomatic, and developmental efforts.

International interventions, such as the United Nations Multidimensional Integrated Stabilization Mission in Mali (MINUSMA) and regional initiatives led by the Economic Community of West African States (ECOWAS), have played a crucial role in supporting the Malian government and promoting stability. Additionally, the European Union Training Mission in Mali (EUTM Mali) has provided training and advisory support to enhance the capabilities of the Malian Armed Forces.

However, significant challenges persist. Ethnic tensions, governance issues, and the influence of extremist groups continue to hinder progress towards lasting peace. It is essential to foster inclusive governance mechanisms that address the grievances of different ethnic groups and promote equitable development across the country. Additionally, efforts to combat the proliferation of arms and counter extremist ideologies must be sustained and reinforced.

International donors should continue providing financial assistance for humanitarian aid, development programs, and peacebuilding initiatives. These efforts should prioritize addressing socio-economic disparities, improving access to basic services, and supporting the resilience and livelihoods of affected populations.

Achieving lasting stability in Mali requires a long-term commitment from all stakeholders. The Malian government must strengthen its institutions, combat corruption, and ensure the provision of essential services to its citizens. Furthermore, regional and international actors should collaborate closely to coordinate their efforts, share intelligence, and support the political process.

Ultimately, the resolution of the Mali conflict will contribute not only to the stability and prosperity of the country but also to the broader Sahel region. It requires a comprehensive approach that addresses the complex interplay between security, governance, development, and reconciliation.

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A.2. RESEARCH DESIGN OVERVIEW

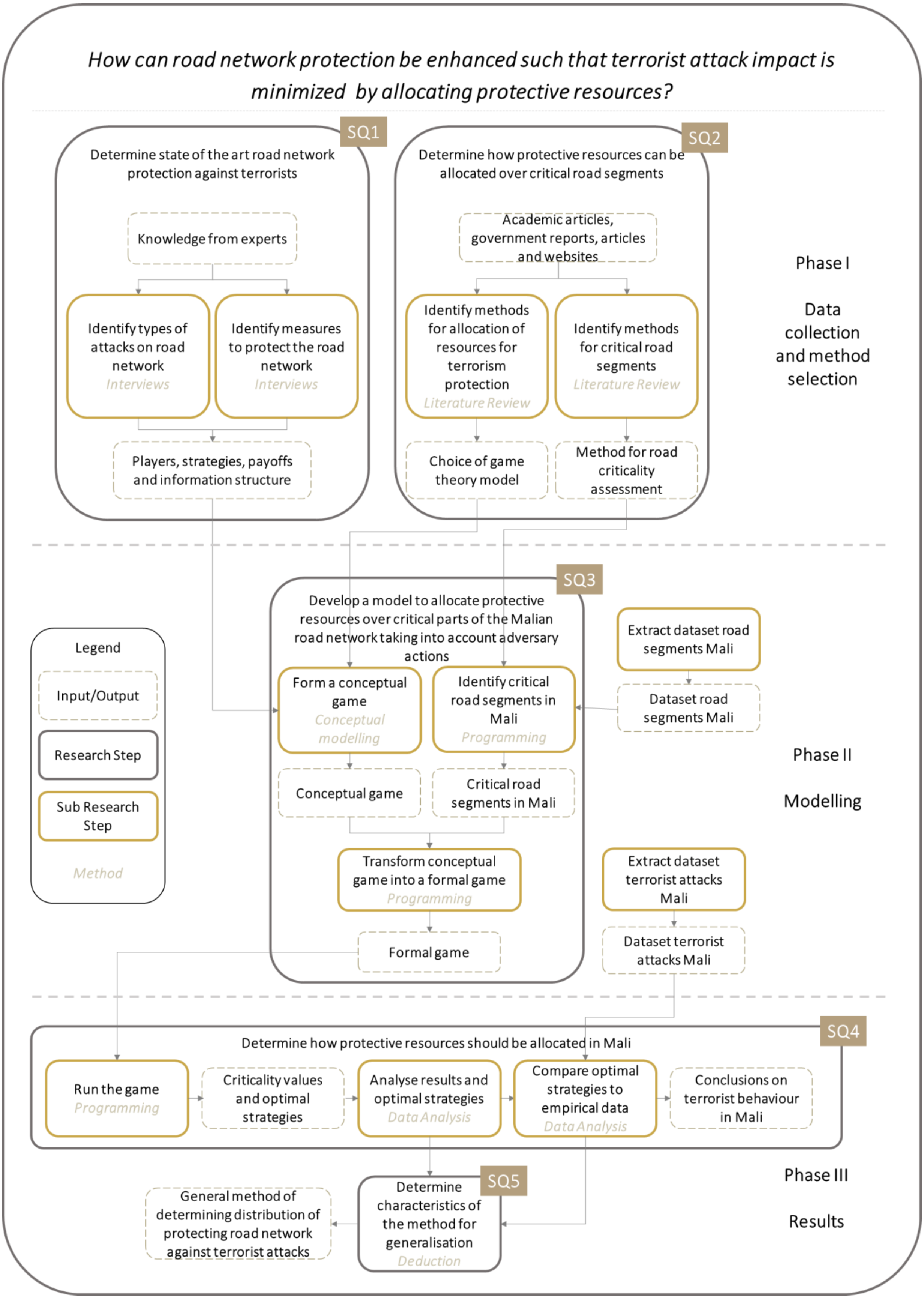

Figure 29. Overview of research design

A.3. LITERATURE METHODOLOGY

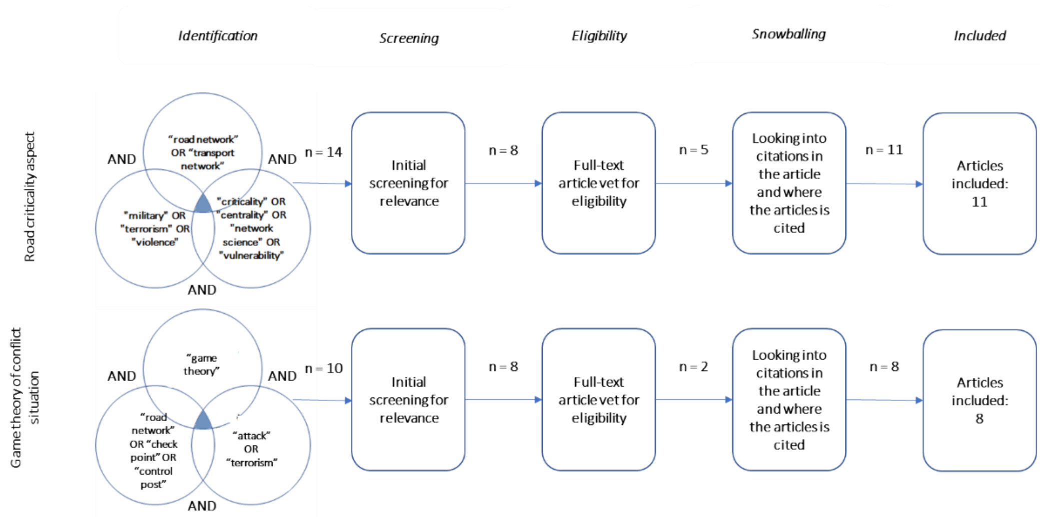

Figure 30. Overview of results of the PRISMA method

A.4. NETWORK STATISTICS

The Directed National Graph

The network under consideration is a directed graph with 1225 nodes and 2330 edges. The average node degree (k_avg) is approximately 3.80, indicating that, on average, each node has around 3.80 outgoing edges. The total length of the route network is approximately 24,531,599.57 units, with an average edge length of 10,528.58 units. On average, each node is connected to about 2.89 streets.

Looking at the counts of the number of edges connected to a node, we find that there are 103 nodes with no outgoing edges, 37 nodes with one outgoing edge, 977 nodes with three outgoing edges, 107 nodes with four outgoing edges, and only one node with five outgoing edges. These numbers are further represented as proportions, showing that the majority of nodes (79.76%) have three outgoing edges, while other categories make up a smaller proportion of the network.

There are a total of 1122 intersections in the network. The cumulative length of all streets in the network is approximately 12,466,915.86 meters, with an average street length of 7031.54 meters. The average circuity is approximately 1.15, indicating that routes in the network deviate slightly from the straight-line distance. Furthermore, there are no self-loops in the network, implying that no edges connect a node to itself.

Undirected Graph

The undirected graph in question has 1225 nodes and 1773 edges. The average node degree (k_avg) is approximately 2.89, indicating that, on average, each node is connected to around 2.89 edges. The total length of the route network is approximately 12,466,915.86 units, with an average edge length of 7031.54 units. On average, each node is connected to about 2.89 streets, which is consistent with the average streets per node in the directed graph.

Analyzing the counts of the number of edges connected to a node, we find similar results as in the directed graph, with 103 nodes having no connections, 37 nodes having one connection, 977 nodes having three connections, 107 nodes having four connections, and only one node having five connections. The proportions of these categories are also comparable, with the majority of nodes (79.76%) having three connections, and the other categories representing smaller proportions of the network.

The undirected graph contains a total of 1122 intersections, just like the directed graph. The cumulative length of all streets in the network is approximately 12,466,915.86 units, with an average street length of 7031.54 units, matching the average edge length. Additionally, the average circuity is calculated to be approximately 1.15, indicating that routes in the network tend to deviate slightly from straight-line distances.

There are no self-loops in the undirected graph, implying that no edges connect a node to itself.

Moreover, the average shortest path length within the network is approximately 29.17 units, reflecting the typical distance between nodes when navigating through the graph.

The diameter of the network, which represents the longest shortest path between any two nodes, is measured at 83 units. This parameter provides insights into the maximum distance required to traverse the network from one node to another.

Overall, these additional statistics further characterize the undirected graph, offering essential information for analysing its navigability, efficiency, and topological properties. These metrics are valuable in various practical applications, including transportation planning, network optimization, and assessing the overall robustness of the graph in real-world scenarios.

The attributed inherited from OSM are the following.

Attribute	Explanation	Type
osmid	unique ID number per node	Integers
y	y coordinate	Float
x	x coordinate	Float
street_count	Indication of how many edges are connected to the node	Integer 1-4
highway	Type of road the node is	Nan values
contraction	Indication of the node was contracted with any other nodes	Nan values
geometry	geometry of the node	Point value

Table 8. Node attributes of OSMnx

Attribute	Explanation	Type
u	Node ID	String
v	Node ID	String

X	X coordinate	Float
Y	Y coordinate	Float
highway	Indication whether road is a highway or not	Boolean
Name	Name of the road if present	String
contraction	Indication wether edges have been contracted	Boolean
geometry	geometry of the edge	Coordinates that form the road together

Table 9. Edge attributes of OSMnx

Figure 31. Closeness centrality of the whole network

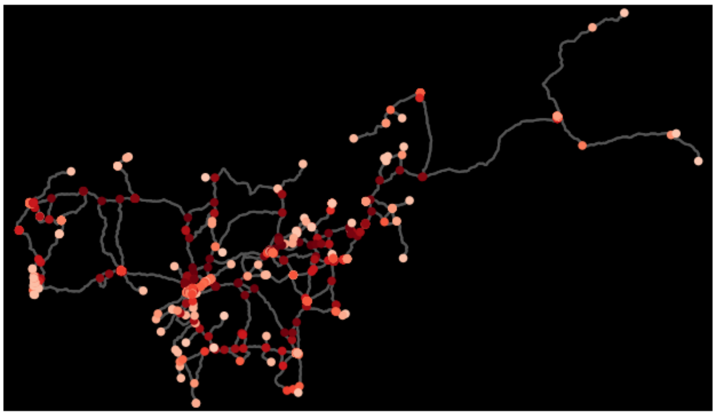

Figure 32. Node based betweenness centrality of the whole networks

A.5. ACLED DATA

ACLED (Armed Conflict Location and Event Data) is a prominent dataset widely used in conflict research and analysis. It provides detailed information on various events related to political violence and armed conflicts worldwide. The dataset captures a range of variables to facilitate comprehensive and nuanced analyses of conflict dynamics. Some of the key variables included in ACLED data are:

- Date and Time: The precise date and time of each reported event, enabling temporal analysis and trend identification.

- Location: Geographic coordinates (latitude and longitude) of the event's occurrence, facilitating spatial analysis and mapping.
- Actor Information: Identification of the actors involved in the event, such as government forces, rebel groups, militias, or civilians.
- Event Type: Categorization of the event type, such as battles, explosions/remote violence, protests, or violence against civilians.
- Fatalities: The number of people killed as a result of the event, helping to gauge the severity and impact of each incident.
- Casualties: The total number of individuals killed and injured, providing a broader perspective on the human toll of conflicts.
- Event Description: A brief narrative describing the event, providing context and additional details about the incident.
- Source: The origin of the reported information, helping to assess the reliability and credibility of the data.
- Subnational Information: ACLED data includes information at the subnational level, allowing for localized analysis of conflict events within specific regions or districts.
- Geographical and Political Context: Additional variables such as country, region, and administrative divisions are provided to contextualize the events within the broader geographical and political landscape.
- Event Latitude and Longitude Accuracy: Information on the precision of the geographic coordinates, indicating the accuracy of the location data.

These variables collectively enable researchers and analysts to explore various aspects of armed conflicts and political violence, including patterns, trends, and underlying drivers. ACLED's comprehensive and detailed dataset is valuable for policymakers, academics, and humanitarian organizations in understanding and responding to complex conflict situations worldwide.

A.6. ALGORITHMS

Dijkstra Algorithm

The Dijkstra algorithm works as follows.
Certainly! The Dijkstra algorithm is a widely used algorithm in computer science and graph theory. It is primarily employed to find the shortest path from a source node to all other nodes in a weighted graph. The algorithm is named after its creator, Dutch computer scientist Edsger W. Dijkstra.

Here's a step-by-step explanation of how the Dijkstra algorithm works:

1. Initialization: Begin by selecting a source node from which you want to find the shortest paths to all other nodes. Assign a distance value of 0 to the source node and infinity to all other nodes.
2. Selecting the Next Node: At each step, choose the node with the smallest distance value among the nodes that have not been visited yet. This node becomes the current node.
3. Update Neighbors: For the current node, examine all its neighboring nodes (nodes directly connected to the current node by an edge) that have not been visited. Calculate the distance

from the source node to each of these neighbors through the current node. If this distance is smaller than the previously recorded distance, update the neighbor's distance value with the new, shorter distance.

4. Mark as Visited: After updating the distances of all neighboring nodes, mark the current node as visited, indicating that its shortest path from the source node has been determined.
5. Repeat Steps 2-4: Repeat steps 2 to 4 until all nodes in the graph have been visited. The algorithm ensures that the shortest path from the source node to all other nodes is found.
6. Termination: The algorithm terminates once all nodes have been visited, and the shortest distance from the source node to each node is known.

By the end of the Dijkstra algorithm, you will have a collection of shortest distances from the source node to all other nodes in the graph. Additionally, it can provide information on the shortest path itself by keeping track of the predecessors of each node in the process.

It's important to note that the Dijkstra algorithm works efficiently for non-negative weighted graphs. In the case of graphs with negative weights, other algorithms like the Bellman-Ford algorithm should be used to find the shortest paths.

R-tree algorithm

A R-tree algorithm works as follows.

1. Node Structure: An R-tree consists of a hierarchical structure composed of nodes. Each node represents a rectangular bounding box that encloses a group of spatial objects or other child nodes.
2. Data Insertion: When inserting a spatial object into the R-tree, it starts at the root node. The algorithm searches for the node that can best accommodate the new object without causing excessive overlap with other objects. This is usually the node with the smallest enlargement needed to cover the new object.
3. Splitting Nodes: If a node becomes full after insertion, it is split into two nodes. The algorithm determines the best way to redistribute the objects between the two new nodes to ensure a balanced tree.
4. Querying: R-trees efficiently support spatial queries, such as range queries (finding all objects that intersect a given search window) and nearest neighbour searches (finding the closest object to a specified location). The algorithm uses the bounding boxes of nodes to efficiently prune unnecessary branches during the search, reducing the search space and improving query performance.
5. Node Merging: Over time, nodes may become under-utilized due to object deletions or frequent updates. To optimize the tree structure, the R-tree algorithm may perform node merging, combining two adjacent nodes if their contents can be efficiently accommodated in a single node.

The R-tree algorithm's effectiveness lies in its ability to quickly narrow down the search space during spatial queries, leading to faster query times compared to traditional data structures. It is widely used in various applications involving spatial data, such as database systems with spatial indexing capabilities, GIS software, and applications involving geographical data, like mapping and location-based services.