Brigade vehicle deployment problem

A quantitative brigade vehicle deployment optimisation on a multimodal transport network

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Abstract

Current geopolitical tensions mean that NATO countries must now make greater efforts to deter threats to their territories, having neglected this defence task for years. In case of a major conflict, brigades and their vehicles are ordered to immediately travel to the area of conflict. This vehicle deployment is researched and modelled in a Multi-Integer Linear Programme (MILP), with the objective to minimise the makespan of the deployment, e.g. the arrival time of the last convoy. In this deployment the strategic and operational movements are modelled, meaning the starting point is the Point of Embarkation (POE) and the end point is the Staging Area (SA) or Concentration Area (CA). The model is suited for deployments that use a double modal network, being road and rail transport. Two scenarios are established, distinguishable by their transport networks and vehicle types, and they are subjected to configurations in which parameters are varied. The research is conducted in cooperation with the Royal Netherlands Army (RNLA), and serves as a handle to obtain understanding on deployments when varying certain parameters. It is observed that the usage of the rail mode mainly should be motivated by vehicle suitability, rather than makespan oriented reasoning, as it hardly improves the makespan of the deployment. Furthermore, platooning is a promising technology to implement in the deployment, with the ability to decrease the makespan by at least 11%. The influence of traffic congestion halfway the deployment is highlighted, encompassing an increase in makespan of at least 7-15%. It is found that the convoy amount and the amount of vehicles does not influence the makespan by a lot (±1.9%). Lastly, the difference between the transport networks of the two scenarios is exposed with the use of a robustness examination, where the makespan of the first scenario improves substantially more (11.7%) than the makespan of the second scenario (0.4%). This research can be expanded in several directions, including the incorporation of additional modalities and a more comprehensive investigation into the robustness of transport networks within these deployments.

Key words: Convoy Movement Problem, Brigade vehicle deployment problem, Multi-Integer Linear Programme, Military logistics

Nomenclature

LIST OF ABBREVIATIONS

Abbreviation	Definition
AOR	Area of Operation
CA	Concentration Area
CMP	Convoy Movement Problem
EU	European Union
HB	Homebase
IED	Improvised Explosive Device
KPI	Key Performance Indicator
MILP	Mixed Integer Linear Programme
MSR	Main Supply Route
NATO	North Alantic Treaty Organisation
POD	Point of Disembarkation
POE	Point of Embarkation
RNLA	Royal Netherlands Army
RTT	Route Time Table
SA	Staging Area
UN	United Nations
VRP	Vehicle Routing Problem

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Introduction 1

1.1 Motivation for the research

Following a relatively stable period in the aftermath of the cold war, a new era of tensions has emerged. In this past era, the core tasks the Royal Netherlands Army (RNLA) were mainly equipped with core task two and three, providing safety and security in other countries, and providing emergency assistance during nature disasters. The first core task, keeping own territory and allied territory safe, was not in the picture due to the relatively low tensions [5]. Due to the increasing threat from Russia, the RNLA must put a great focus on this first core task again and increase defence budget.

A part of the first core task is the deployment of a great amount of vehicles in a certain deployment area. A brigade should be able to get to a certain conflict location as soon as possible from the moment it gets the orders. An immense operation, particularly when considering the size of this unit. A brigade includes up to 1000 vehicles, a mix of wheeled vehicles (Figure 1a), caterpillar vehicles (Figure 1b) and flatrack vehicles (Figure 1c).

(a) Wheeled vehicle (b) Caterpillar vehicle (c) Flatrack vehicle

Figure 1: Three vehicle types of a brigade [2]

The areas of conflict are situated throughout the eastern regions of Europe, since the threat is coming from Russia. Given the considerable geographical distances involved, there is a great need to ensure that this is well planned, especially in times of major conflict on the European continent. The mode of transport of the vehicles can be via road in the form of convoys, or via railroad, loaded on trains. Additionally, the transportation of the vehicles can be facilitated by water transport, specifically by (inland) barges. However, this is not a probable occurrence due to the geographical positioning of the sea and inland waterways relative to the Netherlands and eastern Europe.

There are a few operational aspects of road and rail deployments that can induce problems. Firstly, it is possible that hostile nations may try to interfere and disrupt the infrastructure, ensuring the deployment of these convoys are delayed or not possible. Secondly, the utilisation of these transport networks by allied forces to reach the conflict area is also necessary, adding another layer of complexity due to the limited availability of the infrastructure. This results in strict time windows during which modes of transport are available for utilisation.

In the case of a major conflict at NATO's eastern borders, all allies need to respond and send their troops. Therefore, every ally is assigned timeslots for specific roads, in order to prevent collisions or interference with other convoys. Due to the considerable distances that need to be travelled, the vehicles are obliged to stop while in-transit for purposes such as resting and re-fuelling.
In military terms, vehicle movement along the route can be divided into three categories: strategic, operational and tactical. These categories differ from each other with respect to important variables such as vehicle speed, length of convoys and transportation capacities. In essence, as the front line gets closer, vehicle speed, convoy lengths and transportation capacities decrease [3]. The magnitude of this undertaking, added to the number of vehicles that need to be transported makes it a highly complex problem.

1.2 Preliminary literature study

Vehicle routing problems (VRP) in transport networks is a subject that has been extensively researched, with numerous studies and theories having been developed in this field.

Magzhan Kairanbay et al, (2013) suggested that the shortest path from one place (node) in a transport network to another node in the network (Shortest Path Problem) is generally solved with the use of graphs, existing of nodes, and arcs, connecting the nodes. The lengths of the arcs are considered the weights [6].
In his book on algorithms, **Jeff Erickson, (2019)** includes an extensive description of transport network algorithms, as well as a number of useful algorithms for solving shortest path problems and maximum flow problems [7].
Nazimuddin Ahmed et al. (2012) proposed an algorithm to optimise the maximum flow based on capacities of arcs [8].

In a study conducted by **Nico Vandaele et al, (2000)** , a new analytical approximation is presented for modelling traffic flow based on queueing theory. The study's primary focus is on continuous traffic flows and heterogeneous arrival and service processes [9].

In their papers on Convoy Movement Problems (CMPs), **Byung Jun Ju & Byung Do Chung, (2024)** and **Byung Jun Ju & Byung Do Chung, (2023)** state that it is a variant of the VRP. CMPs are highly applicable to military applications. The travelling agent differs from the travelling agent in the VRP, as the former are significantly longer with lengths of up to 42 km. The first paper focuses on the coordinated movement of multiple convoys, with the objective of minimising total costs. In the second paper, the coordinated movement of multiple convoys is depicted while minimising total flow time, incorporating uncertainty in convoy travel times [10, 11].

A study conducted by **Mokhtar et al, (2021)** introduced a Generalised Convoy Movement Problem (GCMP) that embeds a wide range of considerations that occur in real scenarios. These considerations involve waiting times on nodes, permissible criss-crossings, inaccessible nodes or arcs, due to weight limits or security risks and lastly, non-uniform convoy lengths [12]. The theoretical and mathematical base used was proposed by **Ram Kumar et al, (2009)** , evaluating it in different studies. In these studies, they describe the Convoy Movement Problem, a problem in which convoys move from a starting point to a destination without overtaking, crossing or stopping

while in-transit. In the first paper, a first CMP is defined by modifying the Train Scheduling Problem. Also, a variable velocity per segment is introduced. The second paper focusses more on the multimodality of transportation [13, 14].
Akgün and Tansel, (2007) describe an optimisation model for a Deployment Planning Problem (DPP), in which units are transported from different starting locations to their destinations. Within the scope of this research, the availability of multimodal transport, including both road and rail transport, is taken into consideration. The emphasis is placed on the minimisation of costs [15].

1.3 Research gap

Evolving from the VRPs, a new type of problem has arisen, namely the Convoy Movement Problem (CMP). These are highly applicable to military operations, as multiple vehicles need to be transported in a convoy shape. The convoys are inherently different from a single agent, as they are equipped with a significant length compared to the lengths of the arcs. This makes calculating the optimal solution different, as avoiding collisions is evidently a priority. A lot of research has been done around VRPs and CMPs, and they are also used in the military domain for the transportation of military convoys, with each research having a certain focus. All literature consist of a base line with general convoy demands, such as preventing the crossing of convoys, or maintaining a headway time between convoys. Nevertheless, the distinct answer to transporting all vehicles of a brigade to a conflict area as soon as possible is yet to be researched. In this deployment, multiple transport modes should be included, in order to increase robustness and operational pace. It is of high interest in order to acquire an insight in what certain parameter changes regarding velocities and operation scale do with the deployment performance. Concrete contributions to the existing literature consist of additional transport modes, difference in objective function and in-transit rests. For the execution of these contributions, additional modelling aspects need to be established. For example, in-transit rests could be modelled with the use of a continuous driving time decision variable. These aspects are elaborated upon in Sections 3 and 4.

1.4 Research goal and scope

Following the acquisition of insight into the matter, the scope is defined, as it is of great importance to set the project to certain boundaries. The main goal is to develop a quantitative answer to the question how a brigade is transported to a conflict area, as soon as possible, using multiple transport modalities. A primary challenge in this regard is the coordination of vehicles to ensure their timely and effective deployment. Consequently, this research will exclusively focus on the vehicles themselves, disregarding factors such as their loading methods or intended purposes. The length of a vehicle is an important factor in this research, as vehicles with a shorter length will produce shorter convoys. The amount of vehicles of certain lengths within the brigade will be chosen for this research in a representative way, ensuring all types of vehicles are represented realistically. The brigade and the transport system need to be elaborated upon in order to get a sufficient understanding of the problem. After this, the current literature around similar problems are reviewed, in order to later implement these theories in the quantitative model. Several desired and undesired parameters need to be taken into consideration. These include enemy interference on the transport system, road capacity, demanded departure and arrival times, and convoy splitting.
This results in the answering of the following research question:

How can a brigade effectively be transferred to an area of conflict in case of a major conflict and what parameters are of influence?

Which can be broken down into these sub questions:

1. In what way is the current transport system for vehicle movement built up?
2. What is found in literature around these Convoy Movement Problems and the identified challenges?
3. What steps need to be taken for developing a model to simulate the brigade vehicle deployment?
4. How does the model perform under different scenarios and configurations?

1.5 Methodology

In order to address this research question, the stated sub questions need to be answered properly. For the first sub question, an analysis on the existing transport system is conducted. This includes the means of transport and their networks, the type of vehicles to transfer, and other variables that are either desired or undesired. This is done by interviewing the staff of the RNLA, and by consulting documents. For the second research question, literature is reviewed on similar problems; differences and similarities are identified, and eventually an answer is found by using, improving, and possibly combining different theories and implementations found in literature. The third research question is answered by developing a quantitative model in which the theories found in the literature study are implemented. A real-world scenario is established, for which the model is optimising the deployment. For the last research question, the model is tested in certain configurations, ranging from convoy velocities to a difference in convoy sizes and lengths.

1.6 Research structure

The research can be divided into four different phases, corresponding to the four different research questions. Section 2 elaborates on the current unit deployment within the RNLA and NATO. In this section, both the deployment chain and the convoy movement are outlined. Consequently, a more thorough examination of the existing literature is undertaken. The purpose of Section 3 is to provide a well-structured insight into the available literature, as the aspects to focus on are highlighted by the preceding section. In Section 4, the way the model is built up is outlined after the presentation of the modelling requirements, along with the assumptions that are considered to be necessary. This model is verified and validated in Section 5. The experimental plan is defined and executed in Section 6. Every section ends with answering the related sub question in the section overview. The paper ends with a conclusion and a discussion in Sections 7 and 8, respectively. The research structure is shown in Figure 2.

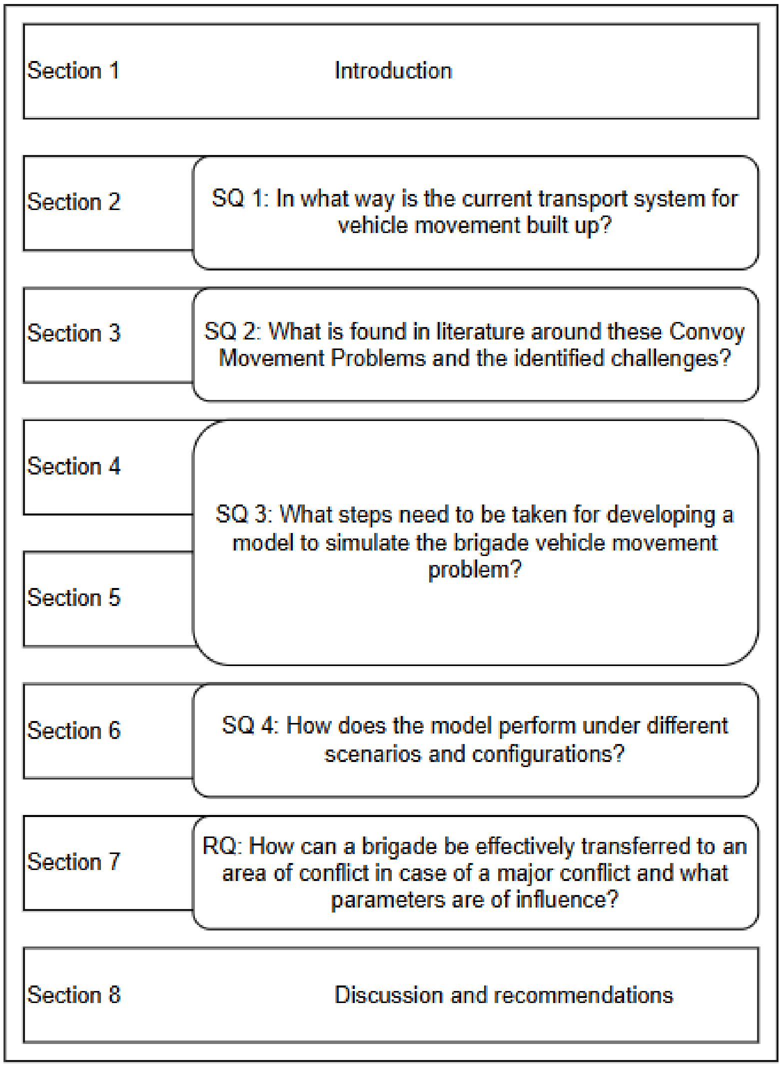


Figure 2: Research structure

Transport system 2

2.1 Introduction

The brigade movement problem is a problem which is present in the civil domain, as well as the military domain. There are numerous strategies for a well-structured and organised deployment for a brigade. For the purposes of the research, the military domain is researched. It is highly important to obtain a good understanding of the current operations done in this domain. Therefore, in this section, the current movement of equipment according to NATO and RNLA is described, both at the convoy level, in order to understand certain parameters that are necessary for implementation, and at the transport network level, in order to grasp a certain level of knowledge regarding the whole operation. The information described in this section will be gathered from RNLA and NATO literature as well as from an interview with an employee working with displacements. The section is divided into a number of sub sections, comprising the deployment chain and convoy movement.

2.2 Deployment chain

The deployment chain describes the sequence of modes and operations that are present within the total deployment of a brigade. The RNLA makes a distinction between administrative and non-administrative movements. The term administrative movement is used to denote a movement that prioritises efficiency. It is asserted that during the execution of this movement, there is an absence of any threat. A non-administrative movement is focused on an effective and protection based movement. During this movement, the possibility of a threat is expected. This threat may be posed by an enemy, heavy unpredictable weather, or even the local population. For the purposes of the research, the movements in question are non-administrative [3].

The deployment can be categorised into four different phases, national, strategic, operational, and tactical movement.

The national movement is a movement under national responsibility. The movement would be starting at the Homebase (HB) and ending at the Point of Embarkation (POE), where the strategic movement will start. Or, for redeployment, the starting point would be the Point of Disembarkation (POD) and ending point the HB. The HB obtains supplies from depots and suppliers. For the Netherlands, this national movement can be seen as a rearrangement of personnel and equipment before or after a major deployment is taking place. Therefore, this movement type is not in scope of this research.

Strategic movement consists of movements from designated POEs to PODs. This is mainly done with the utilisation of highways, allowing vehicles to drive with a velocity of up to 80 km/h. Within this type, normal traffic rules apply, as there is no risk of contact with the enemy. The length of the strategic movement is approximately $\frac{2}{3}^{\text{th}}$ of the total deployment route length. Subsequent to this phase, the operation will be overseen by an international coordinating organ. The aforementioned organ will be responsible for communicating the timeframes in which transport is both permitted and necessary. The organ in question may be affiliated with NATO, the UN, the EU, or an alternative international body, depending on the specific operational context.

Operational movement is defined as the movement of personnel and equipment into a phase line objective. In this phase, the probability of contact with the enemy is low, although this is not impossible. Consequently, the maximum permissible vehicle velocity is set at 50 km/h. Within the operational movement, Staging Areas (SA) and Concentration Areas (CA) are positioned to ensure the optimal preparation of convoys for battle-ready deployment. From the CA onwards, a multinational commander will be responsible. In some occasions, the SA and CA coincide. The operational movement is estimated to account for approximately $\frac{1}{4}^{\text{th}}$ of the total deployment route length.

Lastly, tactical movement is the movement of personnel and equipment within their Area of Operation (AOR). Due to the movement within the AOR, the probability of contact with the enemy is anticipated. It is therefore evident that, in order to reduce the visibility of the enemy, a network of smaller roads is necessary to use to reach the final objective. This approach further reduces the maximum vehicle velocity to 20 km/h. The deployment chain can be seen in Figure 3.

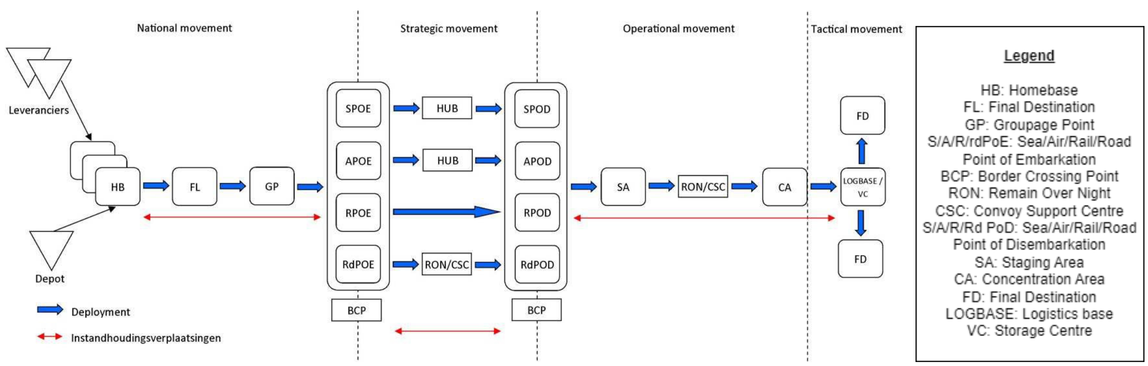


Figure 3: Deployment chain [3]

2.3 Convoy movement

The movements are executed in convoy formation, where a convoy is not necessarily constrained to any kind of form. Improving the safety of convoys is considered a high priority, not in the last place due to the vulnerability of convoys. It is evident that the convoy's vulnerability is attributable to its size and limited velocity, as well as its role in supplying the army. This vulnerability is further compounded by the convoy's predictable route. Finally, the destruction of convoys is a highly effective propaganda tactic for the opposing side. Consequently, the total vehicle fleet is divided into smaller 'convoy packs' of approximately 5 to 10 km in length. This, and following quantitative information is gathered during an interview with Simon Bijzitter, deputy head of movements at the 43 mechanised brigade. Assuming an average vehicle length of 7 m and maintaining an inter-vehicle distance of 50 m, a convoy pack of 5 km would accommodate approximately 80 to 90 vehicles. Given that the deployment is expected to encompass 1000 vehicles in total, it is estimated that the number of convoy packs required will fall within the range of 5 and 12. The interval between convoy packs is referred to as the 'headway time', a term which is also widely mentioned in literature. This interval is crucial in ensuring sufficient space between convoys to provide enough safety and flexibility. The headway time for road convoys is 30 minutes.

In the context of transporting convoys on rails, it is possible to transport the convoy packs as a whole. At present, the train carriages have a capacity to transport half a convoy pack. However, in the event of a conflict, the regulations permit the RNLA to increase the carriage capacity to a whole convoy pack. Loading a whole convoy pack on a train is estimated to take 6 hours, whereas unloading a convoy pack is estimated to take 3 hours, both durations can be influenced by weather conditions.

Convoys are exposed to various threats, including irregular and conventional enemy forces, mines, improvised explosive devices (IEDs), and other vulnerabilities. With irregular enemies, militias or opponents of the RNLA are meant. For example, irregular enemies are composed of a local population that is against the presence of the RNLA in their region. Often, these enemies are more difficult to locate. Conventional enemies can be seen as a 'normal' opposing army [16].

Rests are planned throughout the deployment. This is necessary to not only to prevent the personnel from getting exhausted, but they can also be utilised for commanding by the commander. There are two types of rests, short rests, which last up to 10 minutes, and long rests, which last at least 30 minutes. The location and duration of the long rests will depend on the strategic goal of the rest. During administrative movements, the long rests will occur approximately every six hours. This resting frequency will be used as a guideline in the model [3].

2.4 Transport network

2.4.1 Introduction

Following the description of the deployment chain and convoy movements, the transport network is elaborated upon. The subsection ends with a more detailed insight into the project boundaries.

2.4.2 Road network

Road transport possesses an impressive degree of transport capability, a fact owed to the diversity of road transport vehicles and their respective loading capacities. Road transport is characterised by speed, which is especially useful for urgent transport. Moreover, this mode of transportation is distinguished by its exceptional adaptability, given the extensive network of roads available for reaching the desired destination. This modality is characterised by its accessibility, as it is the only method of direct transportation between the initial and final points. The deployment of personnel is contingent upon two primary factors: the availability of personnel and the geographical boundaries of the area in question. In the event of undesired weather, only delays are to be expected due to the robustness of the network. Consequently, it can be deduced that the continuity is relatively high [3].

2.4.3 Rail network

Rail transport is extensively utilised by military forces in Europe, as the network is regarded as being of a high standard. The velocity of the trains is between 60 and 120 km/h, assuming normal conditions. In environments characterised by a relatively dense network, rail transport systems exhibit a high degree of flexibility. However, as with road transport, it is imperative to consider the varying timetables and schedules that may be in effect. Consequently, the timeframes established by the international coordinating organ are adhered to. In contrast to road transport, additional transportation is required to reach the destination. Furthermore, the utilisation of transshipment locations and additional transshipment time is necessary. Any type of cargo within the designated volume and weight parameters can be transported due to the enormous variety in rail vehicles. Lastly, the utilisation of rail transport reduces the emission of carbon dioxide relative to road transport [3].

2.4.4 Project boundaries

As mentioned in Section 2.3, the convoy form is not of importance during brigade movement. Despite this fact, there is a difference in the vehicle types used by the RNLA, as explained in Section 1. Vehicles that are not designed for driving on highways are preferred to be transported by train. These include caterpillar vehicles, as well as other heavy vehicles. Important to note that it is possible to transport them via road, however unwanted due to road damage, or having the necessity for extra transport equipment.
The boundaries of the project are stated in Figure 4. A generic transport network graph is established, showing the starting node and the end node connected by three Main Supply Routes (MSR) drawn in bold. In order to establish a connection between the MSRs, vertical and diagonal arcs are drawn on nodes in between the starting node and end node. The type of movement is also detailed, showing that the operation is mainly focused in the strategic and operational domain. The starting node is thus at the edge of the national movement, at a POE. The end node can be considered a SA or CA, and can be placed in the operational movement. The whole network can be used by all modalities, as it is a generic network. This means that the arcs drawn are both rail and road arcs. In Section 6, the transport network is adapted to a real-world scenario.

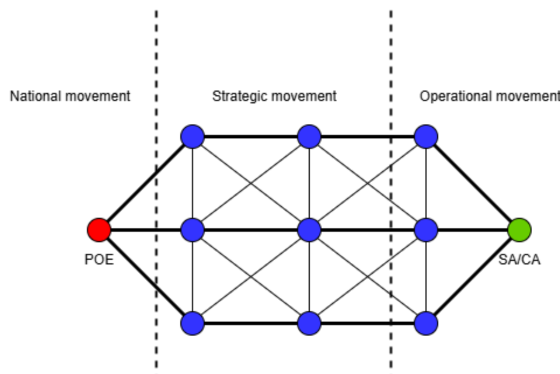


Figure 4: Generic outline of the network

2.5 Section overview

The current movement of equipment is stated in NATO and RNLA literature, which has been researched extensively. The deployment chain depicts a schematic representation of the different types of movement and the different types of points within the chain. Consequently, the research can be put into perspective. The movements considered are non-administrative, meaning the deployment is focused on effectiveness and protection. Throughout the deployment, the threat levels are expected to increase and so will the safety measures, resulting in a reduction of the maximum allowable velocity. During a deployment, the vehicles are transporting in convoy form. The convoy is split up into 'convoy packs' that are travelling in succession and separated by a headway time. The length of the convoy packs can extend up to 10 km.

The potential threats discussed can result in disruption to the arcs and/or nodes. With regards to the arcs, it is important to note that this may result in a reduction or even termination of transport capacities. The nodes within the network are only able to function as a throughput for a limited number of arcs, or they may be terminated entirely. This has the potential to have disastrous consequences for the pace of the operation, as there are a large number of arcs that cannot be used. Furthermore, it is widely acknowledged that rail networks are considered to be a more vulnerable target for enemy disruption, primarily due to their convenience in facilitating the transfer of assets and their relative predictability in comparison to alternative transportation routes such as roads. Lastly, a generic transport network is discussed in which nodes and arcs are depicted which correspond to hubs and the transportation ways (road and rail, respectively). This generic transport network provides a well-understanding of the fact that the strategic and operational movements are optimised in the research.

Literature 3

3.1 Introduction

The literature review aims to gather the existing knowledge and use or modify it in order to serve the purpose of the present research. CMPs emerge from VRPs, having certain fundamentally different aspects, such as a nonzero vehicle (or convoy) length compared to the arc, a non-crossing constraint and a headway time. The VRPs are considered to be common knowledge, and therefore CMPs are the focus of the literature research. The selection of CMP literature is made based on addressing certain aspects within the problem. These aspects encompass the challenges that have emerged from the previous sections, consisting of the following:

- **Convoy packs:** The vehicle fleet is divided into convoy packs, which should avoid collisions and provide headway time. These convoy packs will be referred to as convoys in the remainder of this thesis.
- **Starting points and destinations:** For the total vehicle fleet there is one starting point and one destination. This will have an influence on the arc capacities.
- **Multimodality:** This aspect focuses on multiple ways to transport the vehicles at transshipment locations. Transshipment time needs to be included.
- **Rests and pauses:** Rests and pauses need to be kept in mind.

The relevant literature is found by utilising online websites such as ScienceDirect, Google Scholar or the repository of TU Delft. Several terms have been searched, such as 'Convoy Movement Problem optimisation', and possibly added with terms that indicate the problems scoped in this research. Literature to which is cited in the found literature is also reviewed as it is considered to be valuable as well.

In Section 1.2, a big portion of the literature has briefly been introduced. This section will elaborate upon the aforementioned literature, in order to be able to develop a mathematical formulation for the present research. The section concludes with a comprehensive comparison of the literature, addressing certain challenges these papers handle.

3.2 Convoy Movement Problem base equations

In their work, **Mokhtar et al, (2020)** presented a Generalised CMP (GCMP), a theoretical framework that has since been widely adopted in the field. In order to solve this, a model is introduced. This Linear Convoy Movement Problem-Node (LCMP-Node) model utilises a nodal approach in order to ensure crossing of convoys is not occurring. It has been demonstrated to accommodate all common variants, thus establishing a comprehensive foundation for addressing the convoy movement problem. A mixed-integer linear programme (MILP) is established with several constraints, including general CMP constraints that ensure no-crossing or overtaking, headway time, as well as convoy-specific velocity, timeframes and waiting on specific nodes. The LMCP-Node mathematical formulation is compared with three current formulations and tested. It is important to note that the model does not incorporate disruptions; however, it is possible to manually manipulate the nodes and arcs in order to induce disruptions and observe the subsequent rerouting of the deployment. Furthermore, the convoy length is not specified, and the amount of convoys are modelled up to 15 convoys. It can be concluded from these numbers that Mokhtar et al. utilise a smaller inter-vehicle distance than RNLA. In the context of the research, multimodality is not a factor that has been taken into consideration, since the only mode of transportation utilised is road transport. Moreover, it is important to note that the starting points and destinations of the convoys can be either unique or shared by multiple convoys. The LCMP-Node mathematical formulation is outperforming existing methods found in papers from **Ram Kumar et al, (2009)** [13, 14], especially with denser networks and increasing amounts of convoys [12].

The following constraints and parameters describe the core elements of the LCMP-Node model by Mokhtar et al, (2020) structured as a mixed-integer linear programme (MILP):

Notation	Description
N	Set of n nodes i, j
A	Set of arcs (i, j)
U	Set of u convoys
N'	Subset of nodes where waiting is permitted $N' \subseteq N$
N_i^u	Subset of all nodes convoy u can reach from node i, $N_i^u \subseteq N$
N^u	Subset of nodes that are situated on a path for convoy u, $N^u \subseteq N$
W	Set of convoy pairs (u, v) that can conflict
c_{ij}^u	Travel time of convoy u on arc $(i, j) \in A$
h^{uv}	Headway time of convoy u after convoy v
s^u	Origin of convoy u
d^u	Destination of convoy u
b^u	Earliest start time for travel of convoy u
f^u	Latest finish time for travel of convoy u
g^u	Maximum allowed delay for convoy u to start travel after b^u
l^u	Maximum allowed time for travel of convoy u

Table 1: Overview of variables and parameters in the LCMP-Node model by Mokhtar et al, (2020)

A number of decision variables are used:

$$X_{ij}^u = \begin{cases} 1 & \text{if convoy } u \text{ traverses arc } (i, j), \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

$$V_i^u = \begin{cases} 1 & \text{if path of convoy } u \text{ visits node } i, \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

$$Z_i^{uv} = \begin{cases} 1 & \text{if convoy } u \text{ reaches node } i \text{ before convoy } v \text{ when both pass node } i, \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

$$L_i^u \geq 0 \quad \text{(arrival time of convoy } u \text{ at node } i, \text{if it visits } i \text{ at all)} \tag{4}$$

Objective function:

$$\min \sum_{u \in U} L^u_{d^u} \tag{5}$$

Subject to:

$$\sum_{j \in N^u_i} X^u_{ij} = V^u_i, \quad u \in U, i \in N, \ i \neq s^u, d^u \tag{6}$$

$$\sum_{j \in N^u_i} X^u_{ji} = V^u_i, \quad u \in U, i \in N, \ i \neq s^u, d^u \tag{7}$$

$$\sum_{i \in N^u_i} \sum_{j \in N^u_i} X^u_{ij} = V^u_i - 1, \quad u \in U \tag{8}$$

$$2(X^u_{ij} + X^u_{ji}) \leq V^u_i + V^u_j, \quad u \in U, i \in N^u, j \in N^u_i \tag{9}$$

$$\sum_{u \in U} (V^u_i + V^u_i) = 2m \tag{10}$$

$$2V^u_i \leq \sum_{j \in N^u_i} V^u_j, \quad u \in U, i \in N^u, i \neq s^u, d^u \tag{11}$$

$$(b^u + g^u)V^u_i \leq L^u_i, \quad u \in U, \ i \in N^u \tag{12}$$

$$\sum_{i \in N^u} \sum_{j \in N^u_i} c^u_{ij} X^u_{ij} \geq \sigma^u, \quad u \in U \tag{13}$$

$$V^u_i + V^v_i \leq Z^{uv}_i + Z^{vu}_i + 1, \quad (u,v) \in W, \ i \in N^u \cap N^v \tag{14}$$

$$V^u_i + V^v_i \geq 2(Z^{uv}_i + Z^{vu}_i), \quad (u,v) \in W, \ i \in N^u \cap N^v \tag{15}$$

$$L^u_i + h^{uv}(1 - Z^{uv}_i) \leq L^v_i, \quad (u,v) \in W, \ i \in N^u \cap N^v \tag{16}$$

$$X^u_{ij} + X^u_{ji} + Z^{uv}_i + Z^{vu}_j \leq 2, \quad (u,v) \in W, \ i \in N^u \cap N^v, \ j \in N^u_i \cap N^v_j \tag{17}$$

$$X^u_{ij} + X^v_{ji} + Z^{vu}_i + Z^{uv}_j \leq 2, \quad (u,v) \in W, \ i \in N^u \cap N^v, \ j \in N^u_i \cap N^v_j \tag{18}$$

$$X^u_{ij} + X^v_{ij} + X^v_{ji} + Z^{vu}_i + Z^{uv}_j \leq 4, \quad (u,v) \in W, \ i \in N^u \cap N^v, \ j \in N^u_i \cap N^v_j \tag{19}$$

Equation (5) describes the objective function, which is to minimise the sum of the arrival times of convoy u to its destination d^u. In Equation (6) to Equation (11), the flow through the network is modelled. This is done with the decision variable V^u_i in order to improve computational time by

reducing the branch and bound tree. Equation (6) and Equation (7) guarantee the conservation of flow, e.g. what enters the nodes must leave the node as well, except for the origin and destination. Equation (8) makes sure the convoy uses one arc between two nodes, and Equation (9) makes sure that if two neighbouring nodes are on the optimal path of a convoy, they are connected with an arc. The constraint in Equation (10) ensures that the origin and destination of the convoys are on the path of the convoy. Nodes on the path of a convoy are all neighbours, which is stated by Equation (11). Furthermore, Equations (12) and (13) are controlling arrival times, Equations (14) and (15) determine the order of convoys that visit the same node. In Equations (16) to (19), the headway time is implemented, as well as crossing rules are adhered to.
Most CMP literature is built-up in this way. The papers previously mentioned in Section 1.2, and authored by **Byung Jun Ju & Byung Do Chung, (2024)** and **Byung Jun Ju & Byung Do Chung, (2023)** are also embedded with these base equations. A number of decision variables are defined, which include the traversal of certain arcs, in this case it consists of decision variable X_{ij}^u in Equation (1). In order to be able to model the headway time and the prevention of collisions, a decision variable such as Z_i^{uv} in Equation (3) is needed. An optional improvement can be made by implementing a decision variable such as V_i^u in Equation (2), which reduces the branch and bound tree by constraining decision variable X_{ij}^u. The literature diverges in the goals it needs to fulfil. These goals include the adherence to objectives such as timeframes or no stopping orders.

3.3 Specific challenges

In the paper written by **Akgün and Tansel, (2007)**, an approach for implementing multimodality within convoy movement is sketched. The paper begins with a similar well-known basis of mathematical formulation of the CMP. After that, a number of nodes N_{TR} are modelled as transfer points, resulting in a limited number of nodes where a switch from transport mode can take place. At these nodes, the transshipment time is modelled using so called 'mode free arcs' (i, i') and (i', i). The transshipment time is modelled as the travel time at these nodes [15].

$$\sum_{l \in AF_i} CT_{l,c,v,t} - \sum_{l \in AB_i} CT_{l,c,v,t-tr_{lb}^{\text{loaded}}} = 0, \quad i \in N_T,\ c \in CT_i,\ v,\ t \tag{20}$$

$$\begin{gathered} IV_{i,v,t} + \sum_{l \in AF_i} (TF_{l,v,t} + TE_{l,v,t}) - IV_{i,v,t-1} - \sum_{l \in AB_i} \left(TF_{l,v,t-tr_{lb}^{\text{loaded}}} + TE_{l,v,t-tr_{lb}^{\text{empty}}} \right) = 0, \\ i \in (N \setminus n_d),\ v,\ t \end{gathered} \tag{21}$$

$$\begin{gathered} IC_{i,c,t} + \sum_{l \in AF_{i,v}} CT_{l,c,v,t} - IC_{i,c,t-1} - \sum_{l \in AB_{i,v}} CT_{l,c,v,t-tr_{lv}^{\text{loaded}}} = 0, \\ i \in N_{TR},\ c \in CTR_i,\ c \in CFIRST,\ t \end{gathered} \tag{22}$$

Equation (20) encompasses the net flow of an item c on a transshipment node. For every transshipment node i at time t, the flow should be equal to zero. In contrast to transfer nodes, there is not a transshipment happening. Similarly, in order to ensure the flow of other nodes, Equation (21) is established. Equation (22) ensure the right flow on transfer points. In these points, the transshipment time is represented by the loading and unloading times trv_{lv}^{loaded}, as well as additional waiting time at transfer nodes IC_{ict}.

Mayerle et al, (2020) presented a mathematical formulation of the Vehicle Routing and Truck Driver Scheduling Problem with Intermediate Stops (VRTDSPIS). This is done in order to give advice to policy makers to help define policy around long-distance transport with intermediate stops. An optimisation model is written, consisting of a graph with nodes and arcs. The goal of the optimisation is to minimise the total costs, while adhering to all regulatory restrictions. Several types of rests are being researched, including maximum continuous driving time, maximum daily driving time, minimum over-night rests. The continuous driving time h_n^1 is subject to a maximum value L_{drv}, which is determined by law. The essence of the theory is that the value for h_n^1 cannot exceed L_{drv}. After a rest, the continuous driving time is set to zero, and will count up again [17].

3.4 Section overview

In this chapter, the base equations for CMPs have been described, following from the work **Mokhtar et al, (2020)** performed. Sets of nodes, arcs and convoys are defined, and a number of decision variables arise. In order to implement multimodality, **Akgün and Tansel, (2007)** described adding 'mode free' arcs (i, i') and (i', i), in order to 'travel' between modes on a node, e.g. transship from one mode to the other. **Mayerle et al, (2020)** authored a research for policy makers in order to help them define polices within the long distance transport sector. A continuous driving time variable is established which cannot not exceed the maximum driving time. This variable is reset when a rest has happened. With the knowledge gathered in this section, the creation of a mathematical model can commence. This model is described in Section 4.

Modelling 4

4.1 Introduction

Following a comprehensive review of the relevant literature and the acquisition of knowledge regarding movement and convoy operations, the modelling stage is to be started. In this section, the modelling requirements that follow from the previous two sections are depicted, as well as assumptions, followed by a mathematical formulation of the problem. In Section 5, the model is verified. Validation will take place in Section 5.6.

4.2 Modelling requirements and assumptions

First, the goal of the model is defined. *The model should calculate the route for every convoy to take while minimising the total makespan of the deployment.* In order to achieve this, a transport network is used, with different modalities. Furthermore, the model should adhere to the realistic aspects sketched in Section 2, such as headway times and velocities. It is imperative to note that rests need to be taken into account as well. The model is obliged to prioritise train transport for certain convoys. The requirements of the model are stated here:

- Convoys may not cross each other or overtake each other.
- A headway time is maintained between convoys when traversing the same arc.
- When traversing by road modality, rests should be implemented.
- Switching transport modes is possible on certain transshipment nodes, with the costs of transshipment time.

A number of assumptions have been made, and are described in the following bullet points:

- A convoy consists of the same vehicles with the same lengths. This parameter represents the average vehicle length. There is a distinction between vehicles that are prioritised to be transported via rail instead of road.
- Convoys always traverse arcs with a constant speed, which is set for every arc.
- All nodes within the network are equipped with enough space to serve as a waiting/resting area for every convoy.
- Only long rests are modelled. The minimum rest time is 30 minutes. It is assumed that the time lost from a rest is one hour. In this assumption, the time to leave the highway and enter the resting location and vice versa is included.
- The road and train network are considered to consist of the same nodes and arcs for generic purposes. This can be varied in order to comply with a specific scenario.
- A train can always transport a whole convoy, despite the fact that the convoy length varies. For a vehicle amount of 1000, the amount of convoys will fall between the range of 6 and 12, as mentioned in Section 2.3. The convoy length for train transport will fall between 583 m and 1167 m.

- When a convoy is transported by a train, there always is a train present to serve this transportation, which is capable of moving that convoy.

4.3 Mathematical model

The model starts with the known CMP elements elaborated upon in Section 3.2. Sets for nodes, arcs and convoys are established in order to be able to create a general single modal CMP, as seen in the work **Mokhtar et al.** authored. This is elaborated with the multimodal graph information obtained from **Akgün and Tansel**. Extra arcs (i, i') are added on nodes, which represent transshipment arcs. Extra sets are added which represent modes and transshipments. The sets and parameters, as well as the decision variables of the MILP can be seen in Table 2. For resting purposes, a new set of decision variables and constraints are established, based on the information obtained by the paper written by **Mayerle et al.**

Notation	Description
N	Set of n nodes i, j
A	Set of arcs (i, j, m)
U	Set of u convoys
U'	Subset of u' train convoys $U' \subseteq U$
P	Set of transport modes
O	Set of transshipments
W	Set of transshipment nodes $W \subseteq N$
v_{ijm}	Convoy velocity on arc $(i, j, m) \in A$
h_m	Headway time for mode $m \in P$
τ_t	Transshipment time $t \in O$
o	Origin of the convoys $u \in N$
e	Destination of the convoys $\in N$
f	Max amount of road arcs for convoys u'
k	Max amount of convoys on one arc
a	Max continuous driving time on road
b	Min rest time on road
l_{ijm}	Length of arc (i, j, m)
l_{um}	Length of convoy u in mode m
n^v	Amount of vehicles in the fleet
n^c	Amount of convoys
$d^i_{m_1}$	Inter vehicle distance within a road convoy
l^v	Average vehicle length

(a) Sets and parameters

Decision variables	Description	
X_{ijmu}	Binary value which determines if convoy u traverses arc (i, j, m)	$u \in U$, $(i, j, m) \in A$
Y_{ijmuv}	Binary value which determines if convoy u traverses arc (i, j, m) sooner than convoy v	$u, v \in U$, $(i, j, m) \in A$
V_{iu}	Binary value which determines if convoy u visits node i	$i \in N$, $u \in U$
Z_{itu}	Binary value which determines if convoy u is performing a transshipment t on node i	$i \in N$, $t \in O, u \in U$
R_{iu}	Binary value which determines if convoy u rests on node i	$i \in N$, $u \in U$
L_{imu}	Arrival time of convoy u in mode m on node i	$i \in N$, $u \in U$, $m \in P$
D_{imu}	Departure time of convoy u in mode m on node i	$i \in N$, $u \in U$, $m \in P$
C^{arr}_{iu}	Continuous road driving time upon arrival at node i by convoy u	$i \in N$, $u \in U$
C^{dep}_{iu}	Continuous road driving time upon departure from node i by convoy u	$i \in N$, $u \in U$
T	Arrival time of the last convoy at e	

(b) Decision variables

Table 2: Model notation overview

The convoy length for a mode is calculated using Equation (23):

$$l_{um} = \begin{cases} \frac{n^v}{n^c} \cdot (d^i + l^v), & \text{if } m = m_1 \\ \frac{n^v}{n^c} \cdot l^v, & \text{if } m = m_2 \end{cases} \tag{23}$$

Objective function

$$min\ T \tag{24}$$

Subject to:

$$\sum_{(i,j,m)\in A} X_{ijmu} + \sum_{(j,i,m)\in A} X_{jimu} = V_{iu} \quad \text{if } i = o,\ \forall j \in N,\ \forall u \in U,\ \forall m \in P \tag{25}$$

$$\sum_{(i,j,m)\in A} X_{ijmu} + \sum_{(j,i,m)\in A} X_{jimu} = V_{iu} \quad \text{if } i = e,\ \forall j \in N,\ \forall u \in U,\ \forall m \in P \tag{26}$$

$$\left.\begin{array}{l} \sum_{(i,j,m)\in A} X_{ijmu} = V_{iu}, \\ \sum_{(j,i,m)\in A} X_{jimu} = V_{iu}, \end{array}\right. \quad \forall u \in U,\ (i,j) \in N,\ i \neq o, e,\ m \in P \tag{27}$$

$$\sum_{u\in U} X_{ijmu} \leq k, \quad \forall (i,j,m) \in A \tag{28}$$

$$\sum_{(i,j,m_1)\in A} X_{ijm_1u'} \leq f, \quad \forall u' \in U' \tag{29}$$

$$\left.\begin{array}{l} Y_{ijmuv} \leq X_{ijmu}, \\ Y_{ijmuv} \leq X_{ijmv}, \end{array}\right. \quad \forall\,(i,j,m) \in A,\ (u < v) \in U,\ m \in P \tag{30}$$

$$\left.\begin{array}{r} X_{ijmu} + X_{ijmv}\ -\ 1\ \leq\ Y_{ijmuv} + Y_{ijmvu}, \\ Y_{ijmuv} + Y_{ijmvu}\ \leq\ 1, \end{array}\right. \quad \forall\,(i,j,m) \in A,\ (u < v) \in U,\ m \in P \tag{31}$$

$$\left.\begin{array}{r} Z_{it_1u} \leq \sum_{j\in N:(j,i,m_1)\in A} X_{jim_1u}, \\ Z_{it_1u} \leq \sum_{k\in N:(i,k,m_2)\in A} X_{ikm_2u}, \\ Z_{it_1u} \geq \sum_{j\in N:(j,i,m_1)\in A} X_{jim_1u} + \sum_{k\in N:(i,k,m_2)\in A} X_{ikm_2u} - 1, \end{array}\right. \quad \forall (i,j,k) \in N, u \in U \tag{32}$$

$$\left.\begin{array}{r} Z_{it_2u} \leq \sum_{j\in N:(j,i,m_2)\in A} X_{jim_2u}, \\ Z_{it_2u} \leq \sum_{i\in N:(i,k,m_1)\in A} X_{ikm_1u}, \\ Z_{it_2u} \geq \sum_{j\in N:(j,i,m_2)\in A} X_{jim_2u} + \sum_{i\in N:(i,k,m_1)\in A} X_{ikm_1u} - 1, \end{array}\right. \quad \forall (i,j,k) \in N, u \in U \tag{33}$$

$$Z_{itu} = 0, \quad \forall i \in N \notin W,\ t \in O,\ u \in U \tag{34}$$

$$D_{imu} + \frac{l_{ijm} + l_{um}}{v_{ijm}} \leq L_{jmu} + M \cdot (1 - X_{ijmu}), \quad u \in U, (i,j,m) \in A \tag{35}$$
$$D_{imu} + \frac{l_{ijm} + l_{um}}{v_{ijm}} \geq L_{jmu} - M \cdot (1 - X_{ijmu}),$$

$$D_{imu} \geq L_{imu}, \quad (i,j,m) \in A,\ i \in N, i \neq e \tag{36}$$

$$D_{imu} \geq L_{im'u} + \tau_t - M_t \cdot (1 - Z_{itu}), \quad \forall i \in N, u \in U,\ t \in O,\ (m,m') \in P \tag{37}$$
$$L_{imu} \geq D_{im'u} + \tau_t - M_t \cdot (1 - Z_{itu}),$$

$$D_{imv} \geq D_{imu} + h_m + \frac{l_{um}}{v_{ijm}} - M_{hw} \cdot (1 - Y_{ijmuv}), \quad \forall (i,j,m) \in A, u < v \in U,\ m \in P \tag{38}$$
$$D_{imu} \geq D_{imv} + h_m + \frac{l_{um}}{v_{ijm}} - M_{hw} \cdot (1 - Y_{ijmvu}),$$

$$C_{ju}^{arr} \geq C_{iu}^{dep} + \frac{l_{ijm_1} + l_{um_1}}{v_{ijm_1}} - M_C \cdot (1 - X_{ijm_1u}),$$
$$C_{ju}^{arr} \leq C_{iu}^{dep} + \frac{l_{ijm_1} + l_{um_1}}{v_{ijm_1}} + M_C \cdot (1 - X_{ijm_1u}), \quad \forall i < j \in N,\ (i,j,m_1) \in A,\ u \in U$$
$$C_{iu}^{dep} + \frac{l_{ijm_1} + l_{um_1}}{v_{ijm_1}} \leq a + M_C \cdot R_{ju} + M_C \cdot (1 - X_{ijm_1u}), \tag{39}$$

$$C_{iu}^{arr} \leq a \cdot (1 - \sum_{(j,i,m_2) \in A} X_{jim_2u}), \quad \forall i > j \in N,\ (j,i,m_2) \in A,\ u \in U \tag{40}$$

$$R_{iu} \geq \frac{C_{iu}^{arr} - a}{M_R},$$
$$C_{iu}^{dep} \leq a \cdot (1 - R_{iu}), \quad \forall i \in N,\ u \in U \tag{41}$$
$$C_{iu}^{dep} \leq C_{iu}^{arr} - a \cdot R_{iu},$$

$$D_{im_1u} \geq L_{im_1u} + b \cdot R_{iu}, \quad \forall i \in N,\ u \in U \tag{42}$$

$$R_{iu} \leq V_{iu}, \quad \forall i \in N,\ \forall u \in U \tag{43}$$

$$C_{iu}^{dep} \leq C_{iu}^{arr} + M_R \cdot (1 - V_{iu}), \quad \forall i \in N, i \neq o,\ \forall u \in U \tag{44}$$

$$T \ \geq \ L_{emu}, \quad \forall\, u \in U,\ m \in P \tag{45}$$

The objective function stated in Equation (24) minimises the arrival of the last convoy at the end node. In Equations (25) to (27) , the conservation of flow is determined and the binary decision variable X_{ijmu} is defined. In order to add extra robustness in the deployment, the maximum amount of convoys u on one arc (i, j, m) is constrained by k in Equation (28). Similarly, in Equation (29), the prioritisation for train transport for certain convoys $u' \in U'$ is secured. Parameter f determines how many road arcs can be traversed by these convoys. The decision variable Y_{ijmuv} is set to 1 only if X_{ijmu} is equal to one in Equation (30). The constraints presented in Equation (31) guarantee that, in the event of convoy u and convoy v traversing the same arc, it is possible for only one of the Y decision variables to take the value of 1. This makes the model force to choose an order for these convoys to traverse that specific arc. In Equation (32), the binary decision variable Z_{it_1u} is equal to 1 if a transshipment t_1 from mode m_1 to mode m_2 is performed at node i by convoy u, Similarly, the constraints in Equation (33) ensure the decision variable Z_{it_2u} is equal to 1 when a transshipment t_2 from mode m_2 to mode m_1 is performed at node i by convoy u. A set W for transshipment nodes is established, and in Equation (34), the Z_{itu} is set to zero for all convoys at a non-transshipment node i. The arrival time of convoy u at node j with mode m is determined by the constraints in Equation (35) and 36. It is calculated as the departure time at node i plus the travel time on arc (i, j, m). The constraints in Equation (37) ensure the departure time on node i after transshipment t from mode m to mode m' is calculated by adding the transshipment time τ to the arrival time with mode m before transshipment on node i. Additionally, the arrival time at node i after transshipment t is calculated by adding the transshipment time τ to the departure time at node i. The equations in Equation (38) provide the headway time, the first equation ensures that if convoy u is before convoy v on the same arc (i, j, m), the departure time of convoy v at node i is greater than or equal to the arrival time of convoy u at node j plus the headway time h_m for that specific mode. The second equation ensures that if convoy v is before convoy u on the same arc (i, j, m), the departure time of convoy u at node i is greater than or equal to the arrival time of convoy v at node j plus the headway time h_m for that specific mode. Furthermore, the term $\frac{l^c_m}{v_{ijm}}$ ensures the whole convoy has left the node upon initiating the arc traversement. In Equation (39), the decision variable C^{arr}_{iu} and C^{dep}_{iu} are related to each other. Equation (40) ensures that C^{arr}_{iu} is set to zero if the arc (j, i) is traversed in mode m_2. The equations written in Equation (41) describe the situation for when R_{iu} should be equal to 1, and the reset logic for the C values. Then, in Equation (42) the resting time b is added to the departure time D_{im_1u}. In Equation (43), the binary rest variable R_{iu} can only be equal to one if the node is visited by that convoy u. In order to execute correct continuity for the C values, Equation (44) is implemented. Finally, the decision variable T is set to the arrival time of the last convoy in Equation (45).

Five big M values are utilised in order to correctly define the if then constraints. The values for these Ms need to be defined in a proper way. For Equation (35) and 42, the value for M should comply with:

$$M \geq max(D_{imu} + \frac{l_{ijm} + l_{um}}{v_{ijm}})$$

In this equation, the maximum departure time needs to be guessed generously, the other term can be provided via the parameters. For M_t in Equation (37), the value should comply with:

$$M_t \geq max(\tau_t) + 0.1$$

In this equation, the M_t should be greater than the largest τ value and therefore an additional 0.1 is added. For the M_{hw} in Equation (38), the value should comply with:

$$M_{hw} \geq max(h_m + \frac{l_{um}}{v_{ijm}} + D_{ijm})$$

For M_C in Equation (39), the values should comply with:

$$M_C \geq max(C_{iu}^{arr} + \frac{l_{ijm_1} + l_{um_1}}{v_{ijm_1}})$$

For M_R in Equation (41), the value should comply with:

$$M_R \geq max(a + \frac{l_{um_1}}{v_{ijm_1}})$$

In summary, the big M values are based on input parameters, as well as expected latest departure times, which differ per scenario or configuration.

4.4 Section overview

The requirements and assumptions are defined, and a mathematical model is stated. Elements from **Mokhtar et al, (2020)**, **Akgün and Tansel, (2007)** and **Mayerle et al, (2020)** are utilised in order to mathematically describe the required aspects of the model. In order to ascertain that this model is (1) working in accordance with the mathematical model and (2) is providing the right answers with sufficient accuracy, the model is verified and validated in Section 5.

Verification and validation 5

5.1 Introduction

After introducing the mathematical model, the model implementation needs to be verified and the conceptual model as well as the output of the model needs to be validated [4]. This modelling process is depicted by Robert G. Sargent, (2011) in Figure 5.

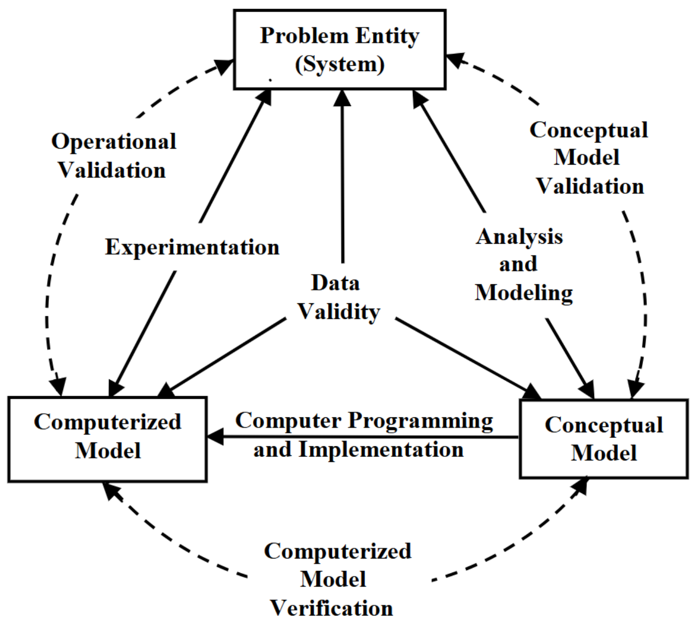


Figure 5: Modelling process [4]

In order to build a qualitatively good computerised model, first, a conceptual model is to be established. This is done by analysing the system to be modelled, and recognising aspects to be translated into mathematics. Then, the conceptual model is translated into a computer, making it a computerised model. If all steps are taken correctly, the computerised model should be sufficiently accurate for the implementation it was intended for.

Sargent states that conceptual modal validity ensure that (1) the theories and assumptions underlying the conceptual model are correct and (2) the model's representation of the problem entity and the model's structure, logic, and mathematical and causal relationships are "reasonable" for the intended purpose of the model. For computerised model verification, the goal is to ensure the computer programming and implementation of the conceptual model are correct, i.e. the concept model is translated to the computer. Operational validation is determining whether the output of the simulation consists of the required accuracy for the intended purpose of the model [4].

The mathematical model described in the previous section needs a proper implementation. The model is programmed in Python, and Gurobi version 12 is used in order to solve the MILP. Optimisations are run on a HP Zbook G5, with 16 GB RAM and an 8^{th} gen Intel Core i7 processor. Additionally, Gurobi offers a MIPFocus parameter, allowing the user to modify their solution strategy. The default value is zero. Setting the value to 1 incentivises the solver to focus on obtaining feasible solutions quickly, whereas the value of 2 encourages the solver to proving optimality, reducing the gap between the best solution and the best bound. Lastly, setting the value to 3 ensures the model to focus on increasing the best bound [18]. The MIPFocus parameter is changed in the experimental phase, in order to decrease runtime. The relative difference between the current best solution and the best bound is the optimality gap, which is stated as a percentage. If this number is greater than 0%, there is a possibility that the current best solution is not the best solution. In this case, the solver needs more time in order to calculate the best solution. In all experiments, the optimality gap is 0%, unless stated otherwise. This means that the given solution is always the best possible solution.

5.2 Test run

In order to verify the implementation, a test network is established, which can be seen in Figure 6. The figure shows a modified version of the generic network shown in Figure 4. An eight-nodal network is connected by arcs, showing the MSRs in bold, and other vertical and diagonal arcs connecting the MSRs. All drawn arcs represent both modalities, meaning that an arc can be traversed in road and rail modality. The input data can be seen in Table 3. There are a couple aspects necessary to test, predominantly being the headway time, transshipments, and resting capabilities. The transshipment nodes are node C, F and H.

Notation	Description	Value
M	Big M for travel time	14
M_t	Big M for transshipment	8
M_{hw}	Big M for headway time	18
M_C	Big M for C value	13
M_R	Big M for rests	12
MIPFocus	MIPFocus parameter	0
v^{road}	Vehicle velocity in km/h	70
v^{rail}	Train velocity in km/h	80
l^{MSR}	Arc length for MSR arcs in km	300
$l^{vertical}$	Arc length for vertical arcs in km	150
$l^{diagonal}$	Arc length for diagonal arcs in km	350
τ_1	Transshipment time road → rail in h	6
τ_2	Transshipment time rail → road in h	3
h_1	Headway time for road transport in h	0.5
h_2	Headway time for rail transport in h	2
n^v	Total vehicle amount to deploy	1000
u	Amount of convoys	10
l^v	Average vehicle length in m	7
d^i	Inter vehicle distance in m	50
a	Max continuous driving time on road in h	8
b	Min rest time on road in h	1
k	Max amount of convoys on one arc	4

Table 3: Overview of values of parameters for verification

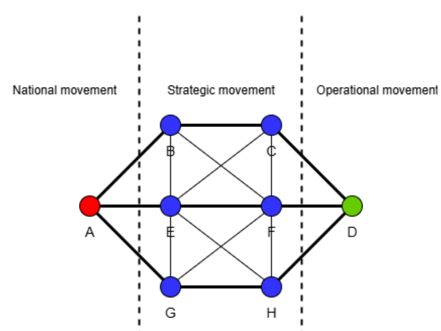


Figure 6: Test network

First, a test run is executed in order to get used with the model and its outputs. The performance and arrival times are stated in Table 4a and 4b.

Indicator	Value
Runtime	185.59 s
Best objective	16.85
Best bound	16.85
Gap	0.00 %
Cumulative arrival time (sum of all L_{eu})	159.74

(a) Overall performance

Convoy	Arrival Time (h)
1	15.68
2	16.26
3	16.26
4	15.68
5	16.85
6	15.68
7	16.26
8	15.10
9	15.10
10	16.85

(b) Arrival times per convoy

Table 4: Test run performance and arrival time details

The results are as expected when looking at the input parameters. In this case, the model makes the decision to transfer all convoys via road, as this solution generates the fastest makespan. A more detailed description of the route and a visualisation of the convoys are shown in Appendix B.

5.3 Headway time and transshipment time

In order to ensure that the headway time and transshipment time are modelled correctly, it is necessary to remove the vertical and diagonal arcs from the model. This results in only MSR arcs being used. The MSR arcs are alternating between modes, meaning that the arcs originating at A are only serving convoys that are in mode T, and the subsequent arcs can only be traversed in mode W. In order to trigger the other transshipment, the arcs going in node D are only traversable in mode T. The detailed description of the route and a visualisation of the convoys can be seen in Appendix C. In Table 5a and 5b, the performance and arrival times can be seen. Furthermore, a segment of the convoy paths is presented in Table 6 in order to demonstrate headway and transshipment times.

Indicator	Value
Runtime	3.48 s
Best objective	26.91
Best bound	26.91
Gap	0.00 %
M	30
M_t	30
M_{hw}	30
M_C	30
M_R	30
Cumulative arrival time (sum of all L_{eu})	232.95

(a) Overall performance

Convoy	Arrival Time (h)
1	24.90
2	26.91
3	24.90
4	22.89
5	20.88
6	24.90
7	22.89
8	22.89
9	20.88
10	20.88

(b) Arrival times per convoy

Table 5: Headway and transshipment verification results

Convoy	Path [mode]	Departure Times (h)	Arrival Times (h)
2	**A** [T] → **B** [T→W] → **C** [W→T] → **D**	6.03, 12.79, 23.15, 0.00	0.00, 9.79, 17.15, 26.91
3	**A** [T] → **B** [T→W] → **C** [W→T] → **D**	4.02, 10.78, 21.14, 0.00	0.00, 7.78, 15.14, 24.90
4	**A** [T] → **B** [T→W] → **C** [W→T] → **D**	2.01, 8.77, 19.13, 0.00	0.00, 5.77, 13.13, 22.89
5	**A** [T] → **B** [T→W] → **C** [W→T] → **D**	0.00, 6.76, 17.13, 0.00	0.00, 3.76, 11.13, 20.88

Table 6: Segment of Table 17

From the values stated in Table 6, the observation can be made that the headway times and transshipment times are adhered to. The headway time is 2 hours, and the time it takes for the train to leave the node is $\frac{0.7}{80} = 0.009$ hours. Therefore, the difference between departure times on the train arcs should be greater than or equal to 2.01 hours, which holds.

Now, the model is run with 20 convoys, and excluding the rail arcs C-D, F-D, H-D and C-F, F-H in order to induce transshipments. Due to the high number of convoys, there is a significant overlap in the routes traversed. Consequently, the headway time constraints can be evaluated. It is important to note that the substantial optimisation gap between the best objective and the best bound is not problematic in terms of verification, since the objective of this run here is only to observe whether the constraints are functioning correctly. In Appendix C.1, the visualisation and convoys paths can be seen. The performance of the model can be seen in Table 7, and in Table 8, a segment of the convoy paths can be seen, in order to verify headway time constraints.

Indicator	**Value**
Runtime	60.12 s
Best objective	18.22
Best bound	4.33
Gap	76.26 %
M	30
M_t	30
M_{hw}	30
M_C	30
M_R	30
Cumulative arrival time (sum of all L_{eu})	333.45

Table 7: Overall performance for headway and transshipment validation for 20 convoys

Convoy	**Path [mode]**	**Departures (h)**	**Arrivals (h)**
5	**A** [T] → **G** [T] → **H** [T→W] → **D**	2.00, 5.76, 12.82, 0.00	0.00, 5.76, 9.51, 17.14
11	**A** [W] → **G** [REST W] → **H** [REST W] → **D**	0.54, 5.87, 11.19, 0.00	0.00, 4.87, 10.19, 15.52
19	**A** [W] → **G** [REST W] → **H** [REST W] → **D**	1.08, 6.41, 11.73, 0.00	0.00, 5.41, 10.73, 16.06
17	**A** [W] → **E** [REST W] → **H** [REST W] → **D**	0.54, 5.87, 12.28, 0.00	0.00, 4.87, 10.91, 16.60
10	**A** [W] → **E** [REST W] → **H** [REST W] → **D**	1.62, 7.32, 13.36, 0.00	0.00, 5.95, 12.36, 17.68
13	**A** [W] → **G** [REST W] → **H** [REST W] → **D**	2.94, 8.27, 13.90, 0.00	0.00, 7.27, 12.59, 18.22

Table 8: Segment of Table 18 showing convoys traversing **G→H** in mode T and convoys traversing **H→D** in mode W sorted on departure times

The headway time for mode W is 0.5 h. Using Equation (23), the length of the road convoys l_u is 2.850 km. The time it takes for the last vehicle to leave the node is $\frac{l_u}{v_{arc}} = 0.04$ h. This implies that the difference between the departure times on road arcs should be greater than or equal to 0.54 h, which holds.

5.4 Train prioritisation for certain convoys

The train prioritisation is tested, with u' possessing the value 6, meaning the amount of train convoys is at least 6. Furthermore, the value for f is set to 1, meaning that the train convoys are allowed to travel on one road arc. In this case, transshipment is not part of the optimal solution due to the time it takes. In Appendix D, the run can be seen, and it can be seen that the first six convoys are not using two or more road arcs.

5.5 Resting constraints

The resting constraints are tested as well, in order to know they are functioning properly. There are two main goals for the resting constraints. Firstly, a convoy cannot continuously drive for over a hours. In all cases, a is set to 8. Secondly, when a convoy is resting, it needs to rest for at least

b hours, which is set to 1. In Appendices B and D, graphs for the continuous driving times C^{arr} and C^{dep} are shown. As shown in these graphs, the continuous driving time does not exceed the value of a, which is in every case equal to 8. Every dot represents a node in the network at which that particular convoy is situated at that moment. The C value is reset to zero if a rest occurs, also marked with a vertical dotted line.

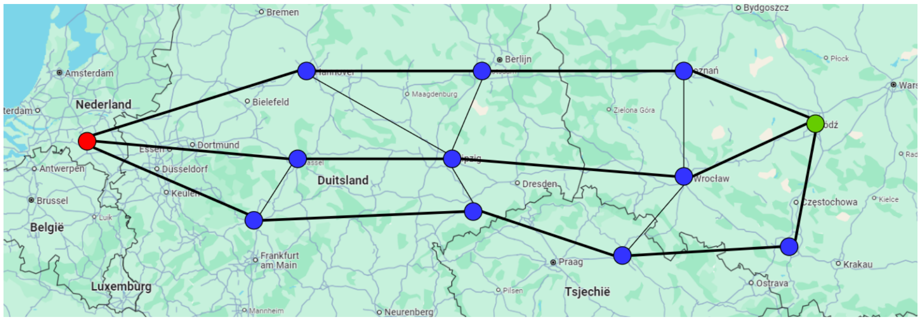
5.6 Validation

In order to validate the implementation, the model is subjected to a real-world scenario. There are four main types of validation, being conceptual model validation, already mentioned in Section 5.1, where the model with all its assumptions is deemed to possess sufficient detail. Secondly, data validation, ensuring the data used is accurate. Thirdly, white box validation, which determines whether the sub-processes within the computer model represent the real world elements in a proper way. Finally, black box validation, which assesses the output of the model to represent the real world scenario with sufficient accuracy [19].
In this case, the conceptual model serves to translate the real world into a mathematical model, consisting of sets, decision variables and constraints. First, a study is done on how movements are coordinated and executed. Then, several parts within the execution of the movement are identified, and translated into requirements and assumptions. This is carefully discussed with experienced employees in the work field.

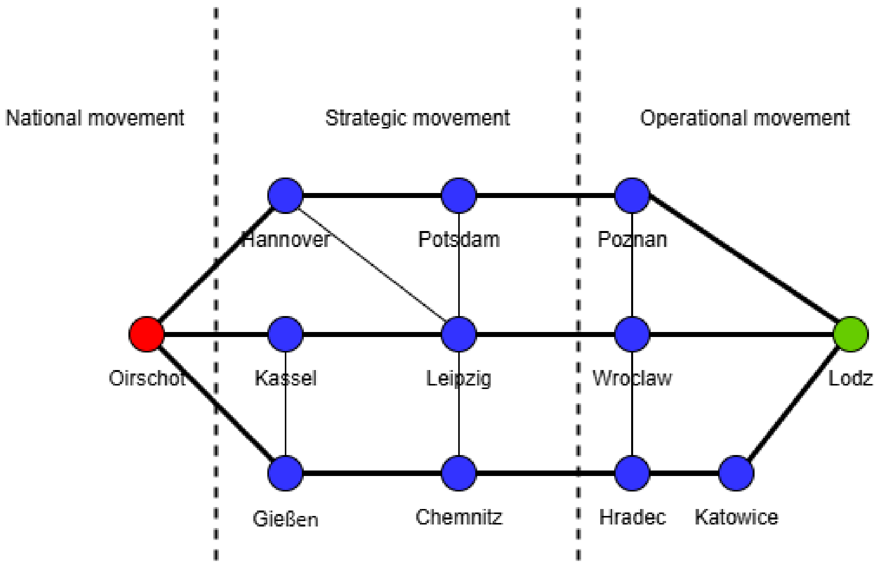
For validation purposes, two real-world scenarios are sketched. The first scenario demands a Staging Area to be in Lodz, Poland, to which the brigade is travelling. The Point of Embarkation is in Oirschot, the Netherlands which is home to the 13 Light Brigade (13 lightbrig). Three Main Supply Routes are defined, to enhance the smoothness of the operation, and they are outlined below:

MSR 1: Oirschot - Hannover - Potsdam - Poznan - Lodz
MSR 2: Oirschot - Kassel - Leipzig - Wroclaw - Lodz
MSR 3: Oirschot - Gießen - Chemnitz - Hradec - Katowice - Lodz

This results in a transport network with nodes and arcs, seen in Figure 7:



(a) Network on the map



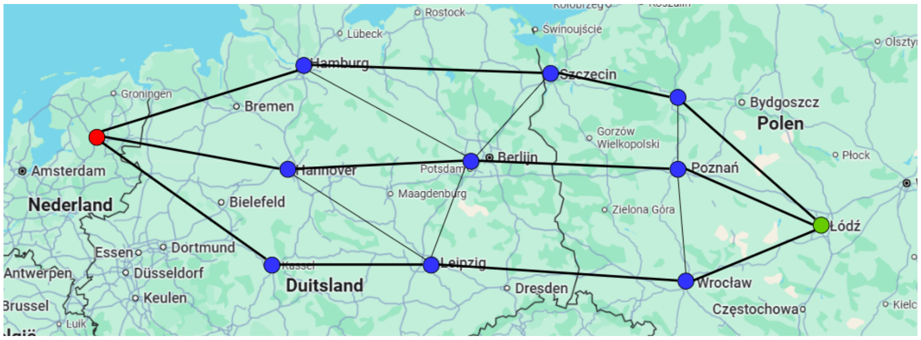
(b) Network in schematic form

Figure 7: Transport network for 13 lightbrig

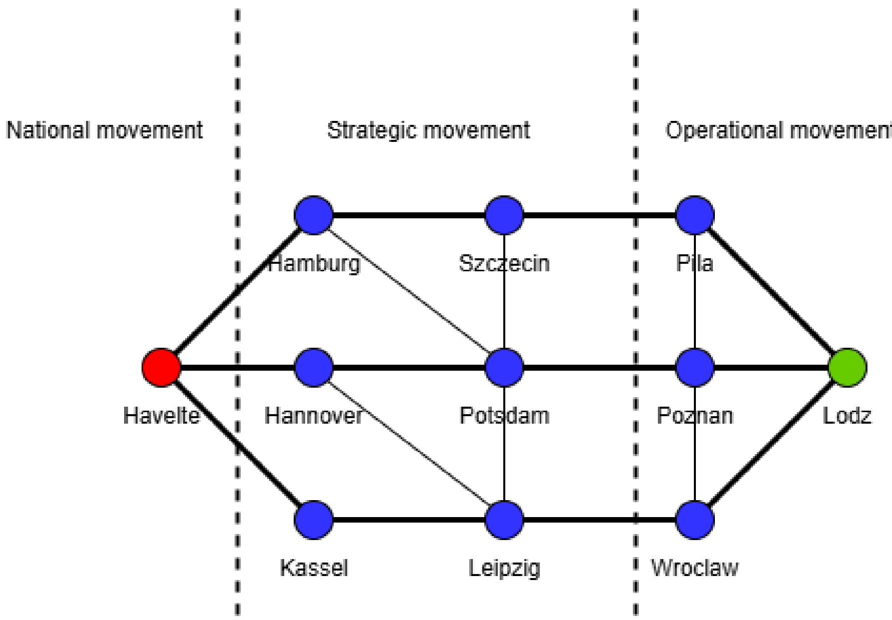
As illustrated, the nodes are arranged in layers. This is done deliberately in order to be able to retreat or advance in a proper way. For the second real world application, the Staging Area is again, in Lodz, Poland. The POE in this case is Havelte, where the 43 Mechanised Brigade (43 mechbrig) is stationed. The following transport network is depicted:

MSR 1: Havelte - Hamburg - Szczecin - Pila - Lodz
MSR 2: Havelte - Hannover - Potsdam - Poznan - Lodz
MSR 3: Havelte - Kassel - Leipzig - Wroclaw - Lodz

Resulting in a transport network as seen in Figure 8



(a) Network on the map



(b) Network in schematic form

Figure 8: Transport network for 43 mechbrig

For both validation cases, only road transport is considered, due to the limited comparative material. The input variables can be seen in Table 9. The arc lengths are obtained via Google Maps, where only highway or carriageway type roads are selected in a manner that ensures the convoys do not travel along the same roads. With the exception of a limited number of vertical arcs, all arcs are one-way arcs, implying that they can only be traversed in the manner in which they have been written. This approach is implemented with the aim of reducing computational time. Appendix K shows the lengths of the arcs, accompanied by the fact that the arcs are one- or two-way traversable. In Figure 9 and Table 10, the outputs can be seen for the 13 lightbrig case. An elaboration on the convoy paths can be seen in Appendix E.

Notation	**Description**	**Value**
M	Big M for travel time	30
M_t	Big M for transshipment	15
M_{hw}	Big M for headway time	30
M_C	Big M for C value	15
M_R	Big M for Rests	15
v^{road}	Vehicle velocity in road mode in km/h	70
a	Maximum continuous driving time on road in h	8
b	Minimum rest time in h	1
h	Headway time in h	0.5
n^v	Total vehicle amount to deploy	1000
u	Amount of convoys	10
l^v	Average vehicle length in m	7
d^i	Inter vehicle distance in m	50
k	Maximum amount of convoys on one arc	4
MIPFocus	MIPFocus parameter	1

Table 9: Input variables for real-world scenarios

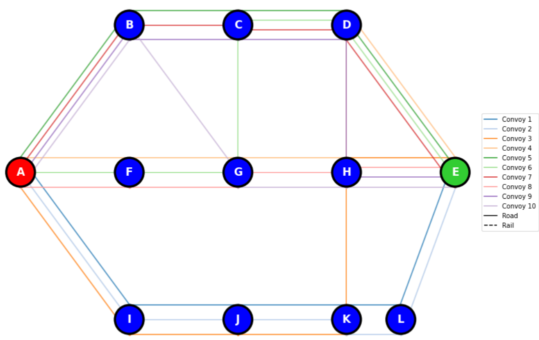


Figure 9: Convoy visualisation for validation 13 lightbrig case

Indicator	**Value**
Runtime	94.43 s
Best objective	24.65
Best bound	24.65
Gap	0.00%
Cumulative arrival time	226.13
Shortest possible convoy path	18.85

Table 10: Overall performance for validation 13 lightbrig case

Similarly, the output for the 43 mechbrig can be seen in Figure 10 and Table 11. The elaborated information regarding the convoy paths can be seen in Appendix E.

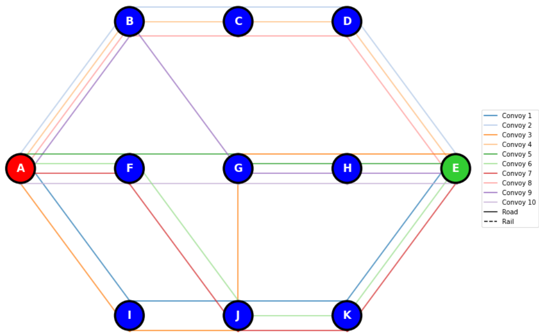


Figure 10: Convoy visualisation for validation 43 mechbrig case

Indicator	Value
Runtime	126.77 s
Best objective	21.49
Best bound	21.49
Gap	0.00%
Cumulative arrival time	207.35
Shortest possible convoy path	17.73

Table 11: Overall performance for validation 43 mechbrig case

The data used is obtained from NATO and RNLA documents, as well as interviews from employees with deployment experience.
The concept of white-box validation is centred on the sub-processes within the model. In the context of large-scale conflicts, the RNLA has only conducted exercises in recent years. The movements undertaken for exercise purposes are of an administrative nature, with a significant degree of movement occurring only during periods of low traffic volume. Consequently, it is challenging to generate comparative material for the purpose of validation. A Route Time Table (RTT) has been made available for the purpose of validation; however, it cannot be shared in the appendices due to security reasons. An RTT is defined as a planned route that is allocated to a convoy for execution. In this RTT, the starting point is Lager Planken in Germany, and the end point varies for the convoys, but encompasses the Johannes Postkazerne in Havelte and the Generaal Majoor de Ruyter van Steveninckkazerne in Oirschot. Along with this RRT and interviews from experienced employees in this field, the model is validated.

The location of Lager Planken is in the neighbourhood of Hannover, which is a node in the transport network of both scenarios. The RTT describes a movement from Lager Planken, via the Scharnhorstkaserne in Hannover, to various end points in the Netherlands. In this movement, a long rest is planned at the Scharnhorstkaserne with the duration of one hour. A short rest with the duration of 20 minutes is executed 6 hours after deployment. The convoy paths can be seen in Table 12. In this table, the short rest is not added to the table as a node, as the short rests are not scoped in the research.

Convoy	Path	Departures	Arrivals	Distance
13 lightbrig	Lager Planken - Scharnhorstkaserne - GenMaj de Ruyter van Steveninckkazerne	00:00, 03:10, 00:00	00:00, 02:08, 08:50	512 km
43 mechbrig	Lager Planken - Scharnhorstkaserne - Johannes Postkazerne	00:00, 03:10, 00:00	00:00, 02:08, 08:45	502 km

Table 12: Real values for convoy path validation

The values presented by Table 12 are for convoys of maximum 9 vehicles. Furthermore, the rest executed is an administrative rest with the duration of one hour. The rests scoped in this research consist of the minimum rest time for a long rest, including the time to drive to the rest place from the highway and vice versa. The nodes in this movement are of interest, as the places Hannover, Oirschot and Havelte are present in the sketched real-world scenarios. If the movement is reversed, and the Scharnhorstkaserne is considered as the end point, disregarding the arc Scharnhorstkaserne - Lager Planken, the movement acts as the first arc for both scenarios, being either Oirschot - Hannover or Havelte - Hannover. When calculating the average velocity of the convoy while subtracting the short rest from the travel time, it is observed that the convoy is driving with a velocity of approximately 70 km/h, and therefore has similar duration compared to the duration in the model. Furthermore, since the convoy in the RTT consists of 9 vehicles, the length of the convoy is disregarded, as it is negligible. In the model, the convoy length is implemented.

The principle of black box validation is the exclusive focus on the outputs of the model. The fundamental premise in this context is that if the model is operated under identical conditions (inputs) as in the real world, the model's output will possess sufficient similarity. However, it should be noted that there is currently a lack of available deployment data for the purpose of output validation. Consequently, experienced experts from the RNLA with regards to deployments have been consulted and asked for their opinion about the output data, which deem both scenarios are sufficiently accurate and therefore the model is validated for road transport.

5.7 Section overview

The model is verified for every aspect, and deemed to correctly translate the mathematical model into the computer. Furthermore, the model is validated, based on an RTT which represents part of the movement executed by the convoys. Additionally, the model is validated by employees from the RNLA experienced with movements. Based on these validation methods, the model is considered useful for the intended purpose.

Evaluation 6

6.1 Introduction

Upon completion of the model's construction, verification and validation, the subsequent task is to describe the experimental plan. In order to formulate the experimental plan, it is first necessary to clarify the first two terms, being scenarios and configurations. A scenario is defined as the description of one (possible) situation (including actions, events, etc.) that exists or could exist (in the past, at present, or in the future). A configuration is defined as a set of data that is used to establish the framework for an experiment [20]. In this thesis, the term 'scenario' is employed to denote the input network, i.e. the placements of the nodes and arcs, as well as the brigade type, affecting the vehicle types. Secondly, the configuration is defined as the set of data, including velocities, headway and transshipment times, the number of convoys and the number of vehicles.

This section will describe two scenarios. These scenarios will differ from one another by the brigade the problem will be solved for. The brigades are situated in different places in the Netherlands, resulting in different transport networks. Furthermore, due to the differences in specialisations of these brigades, there is a difference in the vehicle types as well, influencing the amount of convoys that are preferred to go by train as much as possible. For both scenarios, benchmarks are established. These benchmarks encompass the makespan of the deployment when only using road modality, and are thus sketched in Section 5.6. Secondly, both scenarios are subject to a number of configurations. These configurations will be explained in the experimental plan. For each configuration, several experiments are run for different parameter values. The results are presented in an organised table, which enables an overview of the outcomes. Following this, a comparison of the outcomes is made, from which conclusions can be drawn.

6.2 Experimental plan

In order to give a value judgement regarding the different outcomes of the model, two Key Performance Indicators (KPIs) have been established, along with measurements. The KPIs are a good indicator from which different experiments can be compared with one another. The measurements are utilised in order to obtain a better understanding on why the KPIs differ. These KPIs consist of:

- Makespan
- Route efficiency

The makespan is the most important KPI, as it is the variable which is minimised. The efficiency of the route is calculated by comparing the fastest possible route with the actual routes taken by the convoys. The fastest possible route with one convoy in the 13 lightbrig case is equal to 18.85 hours. This number is calculated by running the model with one convoy, and adjusting the convoy length to the convoy length that is applicable for $n^v = 1000$, and $u = 10$, disregarding Equation (23). It is interesting to notice that the fastest possible route is not depicted in Table 20. The actual convoy routes are between 6.2% and 30.7% slower than the fastest route for one convoy. Running a second optimisation in order to minimise the cumulative arrival time is possible and will possibly lower the

arrival time of convoys other than the last convoy. This optimisation however is time intensive and provides relatively few additional information, and is therefore excluded. Therefore, only the last arriving convoy is considered and thus the route efficiency is equal to $\frac{18.85}{24.65} = 76.5\%$. Similarly, for the 43 mechbrig case, the shortest possible path is 17.73 hours, and the actual convoy routes are between 11.4% and 21.2% slower than the fastest route for one convoy, and the route efficiency is equal to 82.5%.
The measurements are stated below:

- Amount of train convoys
- Amount of rests
- Average arrival time
- Average travel time

The amount of train convoys is a noteworthy indicator, as it provides insight into the relative comparison between the train and road networks. The amount of rests are also interesting to picture, as rests are necessary, but need to be kept at a minimum in order to complete a deployment fast. The average arrival time is a viable measurement, as it provides insight into the arrival times of the convoys following the movement. Lastly, the average travel time per convoy is an interesting measurement, especially when compared with the average arrival time.

As briefly mentioned before, the measurements consist of variables that have not been optimised. Therefore, these values can facilitate the comprehension of the reasons behind the specific value of the KPI.

6.2.1 Scenario 1

The 13 Light Brigade has been ordered to immediately go to a staging area in Lodz, Poland. The brigade is stationed in Oirschot, the Netherlands, and characterised by the armoured wheeled vehicles, which have the capacity for worldwide deployment. Therefore, the amount of convoys which are preferred to go by train as much as possible is not existent. The transport network is depicted in Section 5.6. The movement until the nodes of Poznan, Wroclaw and Brno is considered strategic movement. From these nodes onwards, the movement is considered to be operational. Therefore, the train arcs Poznan-Lodz, Poznan-Wroclaw, Wroclaw-Lodz, Wroclaw-Brno, Wroclaw-Katowice, Hradec-Katowice and Katowice-Lodz are not used.

6.2.2 Scenario 2

The 43 Mechanised Brigade has also obtained the orders to immediately go to a staging area in Lodz, Poland. This brigade is stationed in Havelte, the Netherlands. The core of 43 mechbrig is constituted by armoured (caterpillar) vehicles. Consequently, there are some convoys that prefer to be transferred via rail. This transport network is visible in Section 5.6. From interviews conducted with Simon Bijzitter, approximately 13% of the total vehicle fleet is preferred to be transferred by train. The operational movement starts at the nodes of Pila, Poznan and Wroclaw, meaning the train arcs Pila-Lodz, Pila-Poznan, Poznan-Lodz, Poznan, Wroclaw and Wroclaw-Lodz are not used.

It is important to note here that the train arcs, as stated in the modelling assumptions, are equipped with the same lengths as the road arcs. The scenarios should be of interest in two ways.

Firstly, the scenarios should contain different characteristics, in order to ensure the generic value of the model. Characteristics, in this case, consist of a difference in network, and in vehicle type. As previously mentioned, 13 lightbrig is not equipped with heavy or caterpillar vehicles, making it not dependent on train transport. Besides that, the place where the brigade is stationed is different compared to 43 mechbrig. In order to compare the two scenarios with each other, the same end point is chosen. This way, the variation of parameters, or configurations, can be compared objectively. Additionally, the RNLA is highly interested in deployments to this area in Europe, as there is an immediate threat present here. With both of the brigades being involved in the scenarios, this is a realistic scenario.

6.2.3 Configurations

The benchmark experiments consist of road only deployment. Therefore, the first configuration should encompass the multimodal case. In this configuration, the velocity of the train convoys is set to 80 km/h, and the amount of convoys that have preference for train transportation is set to 2 for the 43 mechbrig, adhering to the 13% of the total vehicle fleet. Transshipment nodes are present at the nodes at which the train arcs cease to be available.

Secondly, due to technological advancements that are achieved in the civil transportation domain [21], the possibility for platooning is a realistic innovation for military transports for strategic and operational movements [22]. This allows the convoys to maintain a constant velocity more conveniently. Additionally, the inter-vehicle distance can be reduced, thereby decreasing the convoy length. In civil applications, platooned vehicles can reduce the headway distance up to 0.3 seconds, substantially less than the 1 second a European driver normally allocates in busy traffic [21]. Therefore the first experiment will solve the optimisation for road velocity v^{road} of 80 km/h and inter vehicle distance d^{iv} of 30 m, and the second experiment will solve for v^{road}= 90 km/h, and d^{iv}= 30 m. The value for d^{iv} is chosen this way because a reduction in the inter vehicle distance improves the makespan, however, the military convoy does not cease to be a target for disruption. Therefore, the inter vehicle distance is not as much reduced compared to the potential in civil applications.

The third configuration presents a case for all road convoys to reduce speed for traffic reasons. The underlying premise of this analysis is that the convoys initiate the deployment after the evening traffic. As convoys approach their destination, traffic levels are expected to rise, resulting in a decline in velocity. Consequently, from the nodes Potsdam, Leipzig and Chemnitz in scenario 1, and nodes Szczecin, Potsdam and Leipzig in scenario 2, road convoys are limited to a maximum speed of 50 km/h in the first experiment, and 60 km/h in the second experiment.

In the fourth configuration, the deployment of different amounts of convoys and brigade sizes is considered. When changing the amount of convoys, the maximum amount of allowed convoys on one arc k needs modification as well. The first experiments encompasses values of 1000 and 6 for n and u, respectively. This results in a road convoy length of 9.5 km, which is in the range of 5-10 km. The second experiment solves the optimisation for n= 2000 and $u = 10$. The k value will be equal to $k = \frac{u}{3}$, rounded up to whole numbers. This way, the robustness of the deployment will be maximised, as the end node is reachable by three road arcs only.

Lastly, the trade off between the robustness and the makespan is examined. This is tested by varying the maximum amount of convoys on one arc k. When allowing more convoys to traverse the same arcs, the deployment will be executed faster. However, the deployment would lose robustness, making it a higher priority target for enemies.

An overview of the configurations, along with the concrete parameter changes are stated in Table 13.

	Scenario 1	**Scenario 2**
Applied in every configuration		
Velocity for train convoys v^{train} in km/h	80	80
Headway time for train convoys h_t in hours	2	2
Amount of train preferred convoys u'	0	2
Maximum amount of road arcs for convoy u'	0	1
	exp 1, exp 2	**exp 1, exp 2**
Config 1: Multi modal		
Train arcs included		
Config 2: Platooning innovation		
Velocity for road convoys v^{road} in km/h	80, 90	80, 90
Inter-vehicle distance d^{iv} in m	30, 30	30, 30
Config 3: Road velocity decrease		
Velocity for road convoys from third nodes onwards$v^{roadthird}$ in km/h	50, 60	50, 60
Config 4: Different brigade and convoy sizes		
Amount of vehicles n^v	1000, 2000	1000, 2000
Amount of convoys u	6, 10	6, 10
Amount of train preferred convoys u'	0, 0	1, 2
Config 5: Robustness examination		
Amount of convoys on one arc k	10, 5	10, 5

Table 13: Configurations overview

6.3 Results

The result for the benchmark of both scenarios is stated in Section 5.6. An overview of the various configuration results are given in Table 14. For extra information, Appendices F to J can be consulted, where experiment 1 is elaborated for every scenario and configuration.

KPI / Measurement	Scenario 1		Scenario 2	
Benchmark				
Makespan	24.65		21.49	
Shortest possible convoy path	18.85		17.73	
Route efficiency	76.5%		82.5%	
Amount of train convoys	0		0	
Amount of rests	26		24	
Average arrival time	22.61		20.73	
Average travel time	21.92		19.98	
Config 1: Multi modal				
Makespan	24.06		20.71	
Shortest possible convoy path	17.95		16.96	
Route efficiency	74.6%		81.9%	
Amount of train convoys	5		4	
Amount of rests	16		14	
Average arrival time	22.75		20.00	
Average travel time	22.15		19.43	
	Sc. 1 exp 1	**Sc. 1 exp 2**	**Sc. 2 exp 1**	**Sc. 2 exp 2**
Config 2: Platooning innovation	$v^{road} = 80, 90$; $d^{iv} = 30, 30$			
Makespan	20.85	18.81	18.37	17.47
Shortest possible convoy path	15.85	14.02	14.66	13.14
Route efficiency	76.0%	74.5%	76.3%	75.2%
Amount of train convoys	2	0	2	2
Amount of rests	16	16	12	15
Average arrival time	19.99	18.11	17.64	16.75
Average travel time	19.60	17.11	16.88	16.37
Config 3: Road velocity decrease	$v^{roadthird} = 50, 60$			
Makespan	28.07	26.36	23.64	22.08
Shortest possible convoy path	19.20	18.47	18.21	17.48
Route efficiency	68.4%	70.1%	77.0%	79.2%
Amount of train convoys	8	7	8	6
Amount of rests	10	14	10	12
Average arrival time	26.34	24.68	22.35	20.95
Average travel time	23.75	23.40	21.29	20.23
Config 4: Different brigade and convoy sizes	$n = 1000, 2000$; $u = 6, 10$			
Makespan	24.28	24.34	20.34	21.11
Shortest possible convoy path	18.02	18.06	17.04	17.07
Route efficiency	74.2%	74.2%	83.8%	80.9%
Amount of train convoys	5	4	4	4
Amount of rests	3	16	6	14
Average arrival time	23.11	23.22	19.97	20.17
Average travel time	22.43	22.52	19.63	19.46
Config 5: Robustness examination	$k = 10, 5$			
Makespan	21.25	21.83	20.63	20.63
Most amount of convoys on one arc	6	5	6	5
Route efficiency	84.5%	82.2%	82.2%	82.2%
Amount of train convoys	2	3	3	3
Amount of rests	19	18	15	15
Average arrival time	19.82	20.40	19.39	19.61
Average travel time	19.16	19.88	18.86	19.08

Table 14: KPI and performance results per configuration

From the outcomes seen in Table 14, several conclusions can be drawn. Firstly, despite the multimodal case achieving a lower value than the benchmark, it is important to note that the makespan is no more than 2.4% faster than the benchmark for scenario 1. For scenario 2, this figure is 3.6%. This is an absolute difference of 35 minutes and 47 minutes, respectively, which is not significant compared to the total makespan. Implementing multimodality brings extra challenges and it therefore should be considered whether this decrease in makespan is worth it. In Table 15a, the differences per configuration can be seen relative to the benchmark. The differences per configuration relative to the first configuration are shown in Table 15b.

The innovation regarding platooning is highly interesting, making the obligatory train transport for heavy caterpillar vehicles a bottleneck at higher road velocities, as seen in the second experiment in the 43 mechbrig scenario. Therefore, the decision could be made to transport these vehicles on a flatbed truck, in order to get them to the destination. Generally, the vehicle platooning configuration decreases the makespan with 11.3% to 21.8% compared to a normal double modal deployment, thus inducing a significant impact.

Thirdly, the reduction of road velocity due to network congestion is having an impact on the makespan. For scenario 1, the makespan for experiment 1 increases with 13.9% compared to the benchmark value and for scenario 2 this is equal to 10.0%, whereas the shortest possible convoy path is 1.9% and 2.7% slower, respectively. When compared to the first configuration, i.e. the multimodal case, this increase in makespan (Sc.1: +16.7%, +9.6%, Sc.2: +14.2%, +6.6%) is higher than the relative velocity decrease (Sc.1: -14.0%, -6.6%, Sc.2: -12.6%, -6.4%), partly due to the extra needed rests.

When convoy amounts and sizes are changed, the results barely change (-1.9% to +1.9%). This is due to the great distances that are travelled. For shorter deployments, such as strategic-only, changing the amount of convoys or its sizes will have a greater influence on the results, as the constant factors such as headway times, resting times, and transshipment times are going to have a greater relative influence. It is interesting to notice that all experiments result in an increase in makespan, except for the first experiment of scenario 2. In this particular scenario, reducing the amount of convoys is beneficial for the makespan.

The robustness of both scenarios is examined. As stated in Table 14, when allowing more than four convoys on one arc, the makespan improves, as expected. However, the difference between scenario 1 and 2 in this instance is relatively high. For scenario 1, increasing k induces a makespan decrease of 11.7%, relative to configuration 1. For scenario 2, this is only 0.4%.

The previous finding provides additional information for the comparison of the two networks, as differences in transport networks are found as well. It is clear that the makespan value for scenario 1 is higher than the value for scenario 2, as the averages of the MSRs are lower for scenario 2 (1187 km) than for scenario 1 (1259 km). An important note to make here is that configuration 2 is disregarded, as scenario 2 is constrained by the train convoys in this case, as previously mentioned. Scenario 2 performs consequently better regarding route efficiencies. This can be attributed to the quantity of diagonal arcs present within the network, compared to the graph in scenario 1.

KPI / Measurement	Scenario 1		Scenario 2	
Config. 1 Multi modal				
Δ Makespan	-2.4%		-3.6%	
Δ Shortest possible convoy path	-4.8%		-4.3%	
Δ Average arrival time	+0.6%		-3.5%	
Δ Average travel time	+1.0%		-2.8%	
	exp 1	**exp 2**	**exp 1**	**exp 2**
Config 2: Platooning innovation $v^{road} = 80, 90$ (+14.3%, +28.6%) ; $d^{iv} = 30, 30$ (-40%)				
Δ Makespan	-15.4%	-23.7%	-14.5%	-18.7%
Δ Shortest possible convoy path	-15.9%	-25.6%	-17.3%	-25.9%
Δ Average arrival time	-11.6%	-19.9%	-14.9%	-19.2%
Δ Average travel time	-10.6%	-21.9%	-15.5%	-18.1%
Config 3: Road velocity decrease $v^{roadthird} = 50, 60$ (-28.6%, -14.3%)				
Δ Makespan	+13.9%	+6.9%	+10.0%	+2.7%
Δ Shortest possible convoy path	+1.9%	-2.0%	+2.7%	-1.4%
Δ Average arrival time	+16.5%	+12.6%	+7.8%	+1.1%
Δ Average travel time	+8.3%	+6.8%	+6.6%	+1.3%
Config 4: Different brigade and convoy sizes $n = 1000, 2000$ (0%, +100%); $u = 6, 10$ (-40%, 0%)				
Δ Makespan	-1.5%	-1.3%	-5.4%	-1.8%
Δ Shortest possible convoy path	-4.4%	-4.2%	-3.9%	-3.7%
Δ Average arrival time	+2.2%	+2.7%	-3.7%	-2.7%
Δ Average travel time	+2.3%	+2.7%	-1.8%	-2.6%
Config 5: Robustness examination $k = 10, 5$				
Δ Makespan	-13.8%	-11.4%	-4.0%	-4.0%
Δ Average arrival time	-12.3%	-9.8%	-6.5%	-5.4%
Δ Average travel time	-12.6%	-9.3%	-5.6%	-4.5%

(a) Difference in KPI/ measurement per configuration relative to benchmark

KPI / Measurement	Scenario 1		Scenario 2	
	exp 1	**exp 2**	**exp 1**	**exp 2**
Config 2: Platooning innovation $v^{road} = 80, 90$ (+14.3%, +28.6%) ; $d^{iv} = 30, 30$ (-40%)				
Δ Makespan	-13.3%	-21.8%	-11.3%	-15.6%
Δ Shortest possible convoy path	-11.7%	-21.9%	-13.6%	-22.5%
Δ Average arrival time	-12.1%	-20.3%	-11.8%	-16.3%
Δ Average travel time	-11.5%	-22.8%	-13.1%	-15.7%
Config 3: Road velocity decrease $v^{roadthird} = 50, 60$ (-28.6%, -14.3%)				
Δ Makespan	+16.7%	+9.6%	+14.2%	+6.6%
Δ Shortest possible convoy path	+7.0%	+2.9%	+7.4%	+3.1%
Δ Average arrival time	+15.8%	+8.5%	+11.8%	+4.8%
Δ Average travel time	+7.2%	+5.6%	+9.6%	+4.1%
Config 4: Different brigade and convoy sizes $n = 1000, 2000$ (0%, +100%); $u = 6, 10$ (-40%, 0%)				
Δ Makespan	+0.9%	+1.2%	-1.9%	+1.9%
Δ Shortest possible convoy path	+0.4%	+0.6%	+0.5%	+0.6%
Δ Average arrival time	+1.6%	+2.1%	-0.2%	+0.9%
Δ Average travel time	+1.3%	+1.7%	+0.5%	+0.2%
Config 5: Robustness examination $k = 10, 5$				
Δ Makespan	-11.7%	-9.3%	-0.4%	-0.4%
Δ Average arrival time	-12.9%	-10.3%	-3.1%	-2.0%
Δ Average travel time	-13.5%	-10.2%	-2.9%	-1.8%

(b) Difference in KPI/ measurement per configuration relative to Configuration 1

Table 15: KPI/ measurements differences for every configuration

6.4 Section overview

The two scenarios defined in Section 5.6 are subjected to a number of configurations, with some of them being equipped with a more futuristic trend, and some of them experimenting with current issues. These experiments have been valued by a number of KPIs and measurements. The KPIs are used to compare the differences, and the measurements are used to provide an insight in the differences between the KPI values in every experiment. The results are shown in Table 14, and the differences relative to the benchmark value and configuration 1 per configuration are stated in Table 15. The deployment makespan varies from 18 to 28 hours, depending on the network and specific experiment. Furthermore, the multimodal configuration does not improve the makespan by a large margin (-2.4%, -3.6%). When the road convoy velocities are increased to 80 and later 90 km/h, and inter vehicle distances are decreased to 30 m due to the implementation of truck platooning, the makespan decreases by a substantial number (-11% to -21%). When the road velocities drop from halfway the deployment to 50 or 60 km/h, the makespan increases with 6% to 16%. Varying the amount of convoys and fleet size does not induce a great difference, with maximum absolute changes of -1.9% and +1.9%. Finally, allowing more convoys to traverse one arc and therefore allowing the deployment to be less robust, the 13 lightbrig scenario decreases with around 10%, whereas the 43 mechbrig scenario decreases with 0.7%. With the acquisition of the results, conclusions can be drawn, which is done in Section 7.

Conclusion 7

This section presents the conclusion of the research. This is done by answering every sub question separately before answering the main research question.

Subquestion 1: *In what way is the current transport system for vehicle movement built up?*

The answer to this question has two parts, the deployment chain and the convoy movement. Within the deployment chain, it is important to make a distinction between the types of movement. These consist of strategic, operational and tactical movement. Strategic movement is the type of movement which is the furthest away from the front line. Therefore, the level of threats is the lowest. A Point of Embarkation (POE) is present in this domain, where vehicles are embarking on train, road, sea or air transport. Going further into the chain, there is operational movement and finally, tactical movement. Within operational movement the threats are still relatively low, but contact with the enemy is not impossible. A Point of Disembarkation (POD) is present, where the vehicles disembark and continue their journey by road, to a Concentration Area (CA) or Staging Area (SA). From there on, tactical movement starts. Within the tactical domain, enemy contact is anticipated, and therefore a greater network of smaller roads is used. With regard to convoy movement, the convoys travel in groups, called convoy packs. These packs can measure up to 10 km in length, consisting of up to 90 vehicles. Within these packs, vehicles have a distance between them, a so-called inter vehicle distance. A headway time is maintained for the convoy packs, in order to prevent collisions. Furthermore, the convoys need to have rests every 6 hours, providing a guideline for the model.

Subquestion 2: *What is found in literature around these Convoy Movement Problems and the identified challenges?*

In existing literature, a general basis has been established around these CMPs. The main aspects of this problem are cited from **Mokhtar et al, (2020)**, encompassing collision prevention with headway times and waiting on nodes. Decision variables on what arcs are used and whether two convoys traverse the same arc are commonly used. Furthermore, the literature diverges in the application it is meant for. The multimodal aspect is found in the paper written by **Akgün and Tansel, (2007)**, introducing 'mode free arcs'. A mathematical formulation for the implementation of rests in a truck routing problem is found in the paper authored by **Mayerle et al, (2020)** where a continuous driving time variable is implemented.

Subquestion 3: *What steps need to be taken for developing a model to simulate the brigade vehicle deployment problem?*

The development of the model is subject to the requirements that are set, along with the assumptions made. This can be seen from the previous research question, as there are numerous of varieties in the models around the CMP. For this thesis, the requirements are focused around implementing multimodality in transport modes, respecting headway time for both transport modes and resting times for road transport. Furthermore, robustness is implemented by having a maximum amount of convoys on one arc. A distinction is made regarding the highway suitability for certain vehicles, resulting in the 'preferred train convoys', being convoys that must go by train until the POD. Additionally, the model is made for the strategic and operational movement domain. The movement starts at a POE, and near the end is a POD, a point where transshipment is possible, as the end node, being a SA or CA, is only accessible by road modality. The model is established in such a way, that the parameters can be changed in order to experiment with certain configurations. The model is verified in order to ensure every modelling aspect is working properly. Furthermore, the model is validated with a run that concludes only road transport. A Route Time Table is made available from which the important point could be extracted and evaluated. Additionally, the model is validated with the broad deployment knowledge of two RNLA employees.

Subquestion 4: *How does the model perform under different scenarios and configurations?*
Based on the results in Section 6.3, the execution of train movements should not be motivated by makespan oriented reasons, as the decrease in makespan is negligible. Instead, this should mainly be motivated by reasons including vehicle suitability, robustness, and other externalities such as road congestion. The innovation of truck platooning, also in the military convoy operations is highly promising, decreasing the makespan between 11-21%, and reducing train convoys. When the road velocity towards the end decreases due to road congestion, the makespan increases, partially due to the need for extra rest moments. The deployment is not significantly influenced by the quantity of convoys or the size of brigades. An increase of 100% in vehicle amount only increases the makespan up to 2%. This suggests that it would be more logical to deploy all vehicles in one deployment, rather than executing two smaller deployments. However, larger deployments will automatically be a more important target for enemies. Finally, when not maintaining the criterion for maximum deployment robustness, a significant improvement (11.7%) in the makespan is reached for scenario 1. This is not the case for scenario 2, as it only shows a marginal improvement (0.4%). This provides insights into the quality of the network for these scenarios, encompassing the fact that scenario 2 possesses a network that is more robust compared to scenario 1.

Main research question: *How can a brigade effectively be transferred to an area of conflict in case of a major conflict and what parameters are of influence?*
The deployment of a brigade is subject to certain aspects of the deployment. These aspects include vehicle amounts, the locations of the POE and SA/CA and the corresponding transport network. Based on these aspects, the deployment is modelled for a POE the Netherlands and a SA/CA in Lodz, Poland, and conclusions are drawn. The main findings conclude that the core of the deployment is road transport, due to the wide options and availability, accompanied by the fact that the deployment is ended in road transport mode. The deployment can be affected by differentiating several parameter values. Truck platooning is an interesting implementation for future deployments, as it has been demonstrated to reduce the makespan by 11% or 21% for road velocities of 80 or 90 km/h, respectively, and decreases the amount of rest periods. When the deployment experiences a reduction in velocity to 50 or 60 km/h halfway through the deployment, the makespan increases by approximately 15% or 7%, respectively. The makespan is not influenced a lot by changing the amount of convoys to 6 (+0.9% for 13 lightbrig, -1.9% for 43 mechbrig) or doubling the vehicle fleet (+1.2% for 13 lightbrig, +1.9% for 43 mechbrig). Finally, when the robustness constraint neglected (k is set to 10), the makespan is decreased by 11.7% in scenario 1 and 0.4% in scenario 2. This shows that the first scenario possesses a less robust network than the second scenario.

8 Discussion and recommendations

This thesis serves as a handle to obtain a comprehensive understanding on the brigade vehicle deployment problem. Some remarks are be made on the limitations of the research, resulting in improvements for further research, and recommendations regarding the conclusions made in Section 7.

8.1 Discussion

A distinction is made in two different vehicle types, being wheeled vehicles and heavy/caterpillar vehicles. These vehicle types influence the model, as the preferred way of transportation for the heavy/caterpillar vehicles is by train. In reality, the RNLA possesses numerous of different vehicles, making it a valuable study to elaborate on the vehicle types.

The objective function of the model minimises the makespan. This is the primary goal. As already mentioned in Section 6.2, there are factors within the deployment that are worth looking at to minimise as well. These factors include the average travel time. In this thesis, this is excluded due to the fact that this is highly time intensive.

Train convoys are modelled in a more simple way than road convoys. Trains are not subject to obligatory rests, and are expected to be able to traverse the next arc instantly. However, in reality, the space on the railroads is most of the time full or highly occupied. In instances where a deployment does not necessitate a high degree of urgency, the train convoys can be relocated to a side track and await the passage of other rail traffic that has priority. This will likely change when a conflict of a considerable scale will take place. Nevertheless, regardless of the conflict's size, civil traffic will have to continue in order to keep the nation's economy going. This automatically induces that the convoys experience some form of nuisance from civil traffic. For train convoys, this is more of a problem at administrative level, as the rail schedule needs adjustments. The manner in which the train convoys are thereby constrained is not scoped in the research.

In scenario 2, the 43 mechbrig is transported to the SA/CA in Poland. This brigade is equipped with a number of vehicles which are not suitable for road transport. The rail modality provides an alternative for these vehicles, as they do not have to be transported by road. However, as briefly mentioned in Section 6, it could be argued that they should be transported by heavy equipment transport systems, which are capable of transporting these vehicles by road. This would reduce dependence on rail transport but increase the need for these transport systems. Therefore, this transportation option is only considered at the end of the deployment.

It is anticipated that, in the event of a major conflict, there will be an increase in the number of deployments on a NATO-wide scale. It is therefore interesting to look at cases with a substantially higher amount of convoys and vehicles, for example 10,000 vehicles spread over 100 convoys. The model is incapable of handling these figures, as the computational time becomes excessively high. In order to achieve the desired outcome, it is necessary to employ superior equipment or to modify the model in order to suit the intended purpose. Additionally, the responsible commanders should give full consideration to the potential consequences of becoming a prominent target.

The validation of the model relies on data which is comparable with the purpose of the model.

Due to the difficulty of obtaining reliable assumptions and parameter values, certain values and assumptions need stronger investigation. These consist of velocities, vehicle amounts and deployment systematics. The values employed in the model are derived from the documentation and from RNLA employees, but they may be outdated or inaccurate due to the scale of the deployment.

8.2 Recommendations and future research

The scenarios and configurations have evolved from conversations made with experienced RNLA employees. In this research, the focus was put on the variety in configurations, delivering additional knowledge on this specific deployment, one that is of high interest in this era. However, the model is suitable for other deployments as well. Elaborating on that, other deployments can be experimented with, in order to obtain information on different transport networks consisting of different SAs and POEs. Also, the model can be tested in different networks, on aspects such as robustness. This will eventually result in the generation of an optimal network, allowing the transport network to be extended with the water transport mode, a mode which is disregarded in this thesis, due to the limited amount of arcs within the network. Adding to that, air transport could be looked at as well. When doing so, the relevance of this mode in accordance with the first core task of the RNLA should be investigated before, as the transport volume is deemed to be too low for the deployment for a major conflict.

Furthermore, the robustness per transport graph can be examined by transforming variable k into a stochastic variable. This will provide insights in the possibilities regarding certain routes that can be taken in order to reach the destination, and the optimal solution for the objective function with it. Additionally, a study can be performed regarding network optimisation. In this study, the placement of nodes and arcs can be executed in a way that continuous driving time is maximised, limiting the amount of rest moments. Thereby, the robustness of the network can be optimised.

It is recommended that vehicles be transported via rail when the suitability of the vehicles or roads for transport is considered to be incompatible. It has been demonstrated that, in comparison to road convoys, train convoys do not offer a significant increase in deployment efficiency. Furthermore, there is less certainty that sufficient space will be available on the rail network, and that there will be administrative commitment to permit all trains to operate. Consequently, if vehicles are suitable for road transport, it is recommended that they are transported via road. This is also attributable to the fact that rail transport is terminated at the start of the operational movement. As previously stated, the caterpillar vehicles can be transported via road; however, this is only considered for the final stage of the deployment. The selection of rail transport for military convoys should be made with consideration for the vehicle's suitability and robustness, as well as external factors such as road and rail congestion.

As concluded in the previous section, the platooning configuration is improving the makespan with a significant margin. Therefore, it is worthwhile to conduct further research of implementing platooning in the deployments. A plan could be executed where first the national movement is equipped with platooning technology, and then this can be elaborated stepwise. The nuisance of civil traffic should be examined more thoroughly, as platooning brings extra safety/liability risks.

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Scientific research paper A

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A quantitative brigade vehicle deployment optimisation on a multimodal transport network

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Abstract

This paper investigates the vehicle deployment of a military brigade and models it in a Multi-Integer Linear Programme (MILP), with the objective to minimise the makespan of the deployment, e.g. the arrival time of the last convoy. The model is suited for deployments that use a double modal network, being road and rail transport. Two scenarios are established, distinguishable by their transport networks and vehicle types, and they are subjected to configurations in which parameters are varied. The research is conducted in cooperation with the Royal Netherlands Army (RNLA), and serves as a handle to obtain understanding on deployments when varying certain parameters. Observations are made regarding the different experiments that are conducted, comprising of multimodality, vehicle velocities, convoy and fleet sizes, and deployment robustness. This thesis further highlights other challenges within this field, and possible further research.

Key words: Convoy Movement Problem, Brigade vehicle deployment problem, Multi-Integer Linear Programme, Military logistics

1 Introduction

Following a relatively stable in the aftermath of the cold war, a new era of tensions has emerged. In this past era, the core tasks the Royal Netherlands Army (RNLA) was mainly equipped with, had to do with providing safety and security in other countries, or providing emergency assistance during nature disasters. The last core task, keeping own territory and allied territory safe, was not in the picture due to the relatively low tensions [1]. Due to the increasing threat from Russia, the RNLA must put a great focus on this first core task again and increase defence budget.

A part of the first core task is the deployment of a great amount of vehicles in a certain deployment area. A brigade should be able to get to a certain conflict location within a foreseeable time from the moment it gets the orders. An immense operation, particularly when considering the size of this unit. A brigade includes up to 1000 vehicles, a mix of wheeled vehicles, caterpillar vehicles and flatrack vehicles. The conflict areas are situated at the eastern borders of Europe. The areas of conflict are situated throughout the eastern regions of Europe, since the threat is coming from Russia. Given the considerable geographical distances involved, there is a great need to ensure that this is well planned, especially in times of major conflict on the European continent. The mode of transport of the vehicles can be via road in the form of convoys on highways, or via railroad, loaded on trains. Additionally, the transportation of the vehicles can be facilitated by water transport, specifically by (inland) barges. However, this is not a probable occurrence due to the geographical positioning of the sea and inland waterways relative to the Netherlands and eastern Europe. In the case of a major conflict at NATO's eastern borders, all allies need to respond and send their troops. Due to the considerable distances that need to be travelled, the vehicles are obliged to stop while in-transit for purposes such as resting and re-fuelling. In military terms, vehicle movement along the route can be divided into three categories: strategic, operational and tactical. These categories differ from each other with respect to important variables such as vehicle speed, length of convoys and transportation capacities. In essence, as the front line gets closer, vehicle speed, convoy lengths and transportation capacities decrease [2]. The magnitude of this undertaking, added to the number of vehicles that need to be transported makes it a highly complex problem.

Within literature, the Convoy Movement Problem arises, which is highly applicable to military deployments. A base line is concluded in the existing literature, however numerous of distinctions can be made within this problem. The main goal is to develop a quantitative answer to the question how a brigade is transported to a conflict area, as soon as possible, using multiple transport modalities. A primary challenge in this regard is the coordination of vehicles to ensure their timely and effective deployment. Consequently, this research exclusively focuses on the vehicles themselves, disregarding factors such as their loading methods or intended purposes. The length of a vehicle is an important factor in this research, as vehicles with a shorter length produces shorter convoys. The amount of vehicles of certain lengths within the brigade are chosen for this research in a representative way, ensuring all types of vehicles are represented realistically. The movement types that are focused on are of strategic and operational nature.

This paper is built up as follows: Section 2 describes the deployments of the RNLA, in Section 3, the current literature around the Convoy Movement Problem (CMP) is studied. Section 4 gives an insight in the model's development, including requirements and assumptions. In Section 5, the model is evaluated based on certain scenarios and configurations. The paper ends with a conclusion and discussion in Section 6

2 Transport system

The transport system consists of two main parts; the deployment chain and the convoy movement. The deployment chain encompasses the total system of movements from the starting point to the end point. It provides a clear overview on the total deployment. The deployment can be categorised into four different phases, national, strategic, operational, and tactical movement. The national movement is a movement under national responsibility. The movement would be starting at the Homebase (HB) and ending at the Point of Embarkation (POE), where the strategic movement will start. Or, for redeployment, the starting point would be the Point of Disembarkation (POD) and ending point the HB. The HB obtains supplies from depots and suppliers. For the Netherlands, this national movement can be seen as a rearrangement of personnel and equipment before or after a major deployment is taking place. Therefore, this movement type is not in scope of this research.

Strategic movement consists of movements from designated POEs to PODs. This is mainly done with the utilisation of highways, allowing vehicles to drive with a velocity of up to 80 km/h. Within this type, normal traffic rules apply, as there is no risk of contact with the enemy. The length of the strategic movement is approximately $\frac{2}{3}^{\text{th}}$ of the total deployment route length. Subsequent to this phase, the operation will be overseen by an international coordinating organ. The aforementioned organ will be responsible for communicating the timeframes in which transport is both permitted and necessary. The organ in question may be affiliated with NATO, the UN, the EU, or an alternative international body, depending on the specific operational context.

Operational movement is defined as the movement of personnel and equipment into a phase line objective. In this phase, the probability of contact with the enemy is low, although this is not impossible. Consequently, the maximum permissible vehicle velocity is set at 50 km/h. Within the operational movement, Staging Areas (SA) and Concentration Areas (CA) are positioned to ensure the optimal preparation of convoys for battle-ready deployment. From the CA onwards, a multinational commander will be responsible. In some occasions, the SA and CA coincide. The operational movement is estimated to account for approximately $\frac{1}{4}^{\text{th}}$ of the total deployment route length.

Lastly, tactical movement is the movement of personnel and equipment within their Area of Operation (AOR). Due to the movement within the AOR, the probability of contact with the enemy is anticipated. It is therefore evident that, in order to reduce the visibility of the enemy, a network of smaller roads is necessary to use to reach the final objective. This approach further reduces the maximum vehicle velocity to 20 km/h.

The deployment chain can be seen in Figure 1.

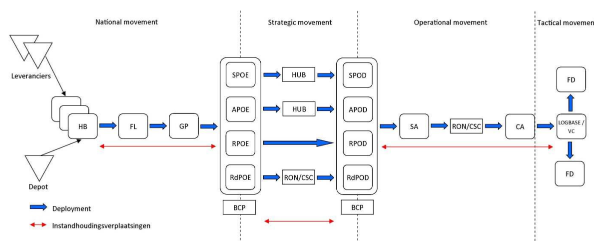


Figure 1: Deployment chain [2]

The movements depicted above are executed in convoy formation. Convoys are not necessarily constrained to any kind of form. Due to continuous threats when executing movements, the convoys are divided into smaller 'convoy packs' of approximately 5 to 10 km in length. In accordance with Simon Bijzitter, deputy head of movements at the 43^{th} mechanised brigade, the average vehicle length is up to 7 meters, and vehicles within the convoy are expected to keep a 50 meters inter vehicle distance. A convoy pack of 5 km would accommodate approximately 80 to 90 vehicles. Given that the deployment is expected to encompass 1000 vehicles in total, it is estimated that the number of convoy packs required will fall within the range of 5 and 12. A headway time of half an hour is maintained, meaning that when the last vehicle of the convoy pack is leaving, the next convoy pack is obliged to wait for half an hour in order to be able to traverse the same arc. This interval is crucial in ensuring sufficient space between the convoy packs, providing enough safety and flexibility. In the context of transporting convoys over rails, it is possible to transport the convoy packs as a whole. At present, the train carriages have a capacity to transport half a convoy pack. However, in the event of a conflict, the regulations permit the RNLA to increase the carriage capacity to a whole convoy pack. Loading a whole convoy pack on a train is estimated to take 6 hours, whereas unloading a convoy pack is estimated to take 3 hours, both durations can be influenced by weather conditions.

Rests are planned throughout the deployment. This is necessary to not only to prevent the personnel from getting exhausted, but they can also be utilised for commanding by the commander. There are two types of rests, short rests, which last up to 10 minutes, and long rests, which last at least 30 minutes. The location and duration of the long rests will depend on the strategic goal of the rest. During administrative movements, the long rests will occur approximately every six hours. This resting frequency will be used as a guideline in the model [2].

Road transport possesses an impressive degree of transport capability, owed to the variety of vehicles and their loading capacities. Road transport is characterised by its speed and robustness, given the extensive road network available in order to reach the end destination. Rail transport is extensively utilised by military forces in Europe, due to the fact that the network is regarded as being of a high standard. The velocity of the trains vary between 60 and 120 km/h, assuming normal conditions. In environments characterised by a relatively dense network, rail transport systems exhibit a high degree of flexibility. In contrast to road transport, additional transportation is required to reach the destination. Furthermore, the utilisation of transshipment locations and additional transshipment time is necessary. Any type of cargo within the designated volume and weight parameters can be transported due to the enormous variety in rail vehicles. Lastly, the utilisation of rail transport reduces the emission of carbon dioxide relative to road transport [2].

In this paper, the transport network where the deployment is taking place is a multimodal network, consisting of transport mode road and transport mode rail. A generic transport network graph is established in Figure 2, showing the starting node and the end node connected by three Main Supply Routes (MSR) drawn in bold. In order to establish a connection between the MSRs, vertical and diagonal arcs are drawn on nodes in between the starting node and end node. The operation is mainly focused in the strategic/operational domain, with the starting node being at the edge of the national movement, at a POE, and the end node at a CA. The whole network can be used by all modalities, meaning that the arcs drawn are both rail and road arcs. In Section 5, the transport network is adapted to a real-world scenario.

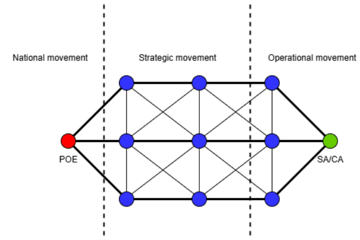


Figure 2: Generic outline of the network

3 Literature review

The literature review aims to gather knowledge on certain deployment aspects, next to the basic CMP knowledge. Firstly, a similar amount of convoy packs that are obliged to prevent collisions and to maintain headway time are researched. These will be referred to as convoys in the remainder of this paper. Secondly, the starting points and destinations of the convoys are looked into, as one starting point and one destination is required. Thirdly, the way previous papers have implemented multimodality in a similar problem is researched. Lastly, rests and pauses in these long distance travels are looked at.

Mokhtar et al, (2020) presented a Generalised CMP (GCMP), a theoretical framework that has since been widely adopted in the field. The Linear Convoy Movement Problem-Node (LCMP-Node) model utilises a nodal approach in order to ensure crossing of convoys is not occurring. It has been demonstrated to accommodate all common variants, thus establishing a comprehensive foundation for addressing the CMP. A mixed-integer linear programme (MILP) is established with several constraints, including general CMP constraints that ensure no-crossing or overtaking, headway time, as well as convoy-specific velocity, timeframes and waiting on specific nodes. The LMCP-Node mathematical formulation is compared with three current formulations and tested. It is important to note that the model does not incorporate disruptions; however, it is possible to manually manipulate the nodes and arcs in order to induce disruptions and observe the subsequent rerouting of the deployment. Furthermore, the convoy length is not specified, and the amount of convoys are modelled up to 15 convoys. It can be concluded from these numbers that Mokhtar et al. utilise a smaller inter-vehicle distance than RNLA. In the context of the research, multimodality is not a factor that has been taken into consideration, since the only mode of transportation utilised is road transport. Moreover, it is important to note that the starting points and destinations of the convoys can be either unique or shared by multiple convoys. The LCMP-Node mathematical formulation is outperforming existing methods found in papers from **Ram Kumar et al, (2009)** [3,4], especially with denser networks and increasing amounts of convoys [5]. The core elements of the LCMP-Node model are described by numerous equations, consisting of an objective function that minimises the sum of arrival times of convoy u at destination d^u. Furthermore, the equations consist of constraints, regulating flow through the network and headway time. The model implements a no-halting policy.

From this point, the literature varies considerably, depending on the specific implementation. A relevant example van be observed with the no-halting policy stated by Mokhtar et al.

In the paper written by **Akgün and Tansel, (2007)**, an approach for implementing multimodality within convoy movement is sketched. The paper begins with a similar well-known basis of mathematical formulation of the CMP. After that, a number of nodes N_{TR} are modelled as transfer points, resulting in a limited number of nodes where a switch from transport mode can take place. At these nodes, the transshipment time is modelled using so called 'mode free arcs' (i, i') and (i', i). The transshipment time is modelled as the travel time at these nodes [6].

Mayerle et al, (2020) presented a mathematical formulation of the Vehicle Routing and Truck Driver Scheduling Problem with Intermediate Stops (VRTD-SPIS). This is done in order to give advice to policy makers to help define policy around long-distance transport with intermediate stops. An optimisation model is written, consisting of a graph with nodes and arcs. The goal of the optimisation is to minimise the total costs, while adhering to all regulatory restrictions. Several types of rests are being researched, including maximum continuous driving time, maximum daily driving time, minimum over-night rests. The continuous driving time h_n^1 is subject to a maximum value L_{drv}, which is determined by law. The essence of the theory is that the value for h_n^1 cannot exceed L_{drv}. After a rest, the continuous driving time is set to zero, and will count up again [7].

4 Modelling

Following the literature review, the model is built. First, the goal of the model is defined. *The model should calculate the route for every convoy to take while minimising the total makespan of the deployment.* In order to achieve this, a transport network is used, with different modalities. The requirements are stated here:

- Convoys may not cross each other or overtake each other.
- A headway time is maintained between convoys when traversing the same arc.
- When traversing by road modality, rests should be implemented.
- Switching transport modes is possible on certain transshipment nodes, with the costs of transshipment time.

The model is equipped with the general CMP constraints established by **Mokhtar et al, (2020)**, added with the 'mode free arcs' implemented by **Akgün and Tansel, (2007)**. Furthermore, two variables regarding continuous driving time upon arrival and departure C^{arr} and C^{dep} are established based on the paper written by **Mayerle et al, (2020)**.

The sets and parameters are shown in Table 1, and the decision variables are shown in Table 2.

Notation	**Description**
N	Set of n nodes i, j
A	Set of arcs (i, j, m)
U	Set of u convoys
U'	Subset of u' train convoys $U' \subseteq U$
P	Set of transport modes
O	Set of transshipments
W	Set of transshipment nodes $W \subseteq N$
v_{ijm}	Convoy velocity on arc $(i, j, m) \in A$
h_m	Headway time for mode $m \in P$
τ_t	Transshipment time $t \in O$
o	Origin of the convoys $u \in N$
e	Destination of the convoys $\in N$
f	Max amount of road arcs for convoys u'
k	Max amount of convoys on one arc
a	Max continuous driving time on road
b	Min rest time on road
l_{ijm}	Length of arc (i, j, m)
l_{um}	Length of convoy u in mode m
n^v	Amount of vehicles in the fleet
n^c	Amount of convoys
$d^i_{m_1}$	Inter vehicle distance within a road convoy
l^v	Average vehicle length

Table 1: Sets and parameters

Decision variables	**Description**	
X_{ijmu}	Binary value which determines if convoy u traverses arc (i, j, m)	$u \in U$, $(i, j, m) \in A$
Y_{ijmuv}	Binary value which determines if convoy u traverses arc (i, j, m) sooner than convoy v	$u, v \in U$, $(i, j, m) \in A$
V_{iu}	Binary value which determines if convoy u visits node i	$i \in N$, $u \in U$
Z_{itu}	Binary value which determines if convoy u is performing a transshipment t on node i	$i \in N$, $t \in O, u \in U$
R_{iu}	Binary value which determines if convoy u rests on node i	$i \in N$, $u \in U$
L_{imu}	Arrival time of convoy u in mode m on node i	$i \in N$, $u \in U$, $m \in P$
D_{imu}	Departure time of convoy u in mode m on node i	$i \in N$, $u \in U$, $m \in P$
C^{arr}_{iu}	Continuous road driving time upon arrival at node i by convoy u	$i \in N$, $u \in U$
C^{dep}_{iu}	Continuous road driving time upon departure from node i by convoy u	$i \in N$, $u \in U$
T	Arrival time of the last convoy at e	

Table 2: Decision variables

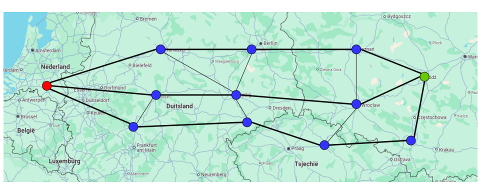
The objective function is stated in Equation (1):

$$min\ T \tag{1}$$

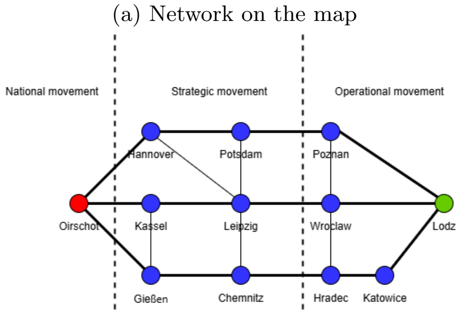
The constraints involved are such that they ensure the conservation of flow, headway time and transshipment time when transport modes are changed. Furthermore, it is only permissible for these transshipments to take place at specific transshipment nodes. In addition, rest constraints for road transport are employed, with a continuous resting time variable utilised. The robustness of the system is ensured by parameter k, which employs a maximum number of convoys on a single arc. Train transport prioritisation is enforced for certain convoys, using a subset U'. The model is verified for all these specific modelling tasks, and verified for a road-only case with data from the RNLA and experienced employees.

5 Evaluation

Upon completion of the model, the model needs evaluation, and thus the experimental plan is established. The experimental plan consists of two scenarios, scenario 1 states that the 13 Light Brigade (13 lightbrig) needs to be deployed to Lodz, Poland. The POE in this scenario is located in Oirschot, the Netherlands, as the brigade is stationed there. This brigade is characterised by the armoured wheeled vehicles, which have the capacity for worldwide deployment. Therefore, the amount of convoys which are preferred to go by train as much as possible is not existent. The transport network is depicted in Figure 3. The movement until the nodes of Poznan, Wroclaw and Brno is considered strategic movement. From these nodes onwards, the movement is considered to be operational. Therefore, the train arcs Poznan-Lodz, Poznan-Wroclaw, Wroclaw-Lodz, Wroclaw-Brno, Wroclaw-Katowice, Hradec-Katowice and Katowice-Lodz are not used.



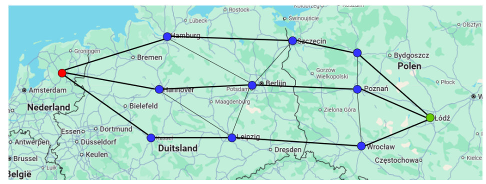
(a) Network on the map



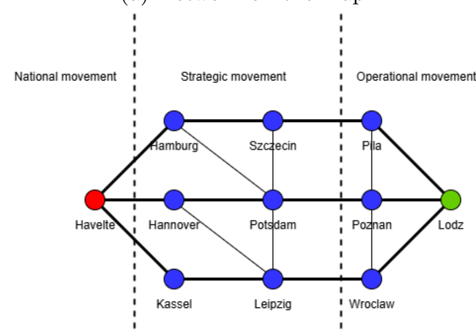
(b) Network in schematic form

Figure 3: Transport network for 13 lightbrig

Scenario 2 describes a deployment for the 43 Mechanised Brigade (43 mechbrig) to Lodz, Poland. This brigade is stationed in Havelte, the Netherlands. The core of 43 mechbrig is constituted by armoured (caterpillar) vehicles. Consequently, there are some convoys that prefer to be transferred via rail. This transport network is visible in Figure 4. Based on interviews conducted with RNLA employees, approximately 13% of the total vehicle fleet is preferred to be transferred by train. The operational movement starts at the nodes of Pila, Poznan and Wroclaw, meaning the train arcs Pila-Lodz, Pila-Poznan, Poznan-Lodz, Poznan, Wroclaw and Wroclaw-Lodz are not used.



(a) Network on the map



(b) Network in schematic form

Figure 4: Transport network for 43 mechbrig

A benchmark value is established, which is the road-only situation. Furthermore, five configurations are created, in which the deployment is analysed. In the first configuration, the train arcs are added. The second configuration provides a future scenario of truck platooning in military convoy movement, increasing the vehicle velocity and decreasing the inter vehicle distance. In the third configuration, from the nodes Potsdam, Leipzig and Chemnitz in scenario 1, and nodes Szczecin, Potsdam and Leipzig in scenario 2, road convoys will reduce velocity, anticipating on traffic congestion when approaching the Staging Area. The fourth configuration investigates the case when different amounts of vehicles and convoys are being deployed. Lastly, the fifth configuration investigates the trade off between robustness and makespan, by varying the maximum amount of convoys on one arc k. Configuration 2 to 5 are executed in two experiments per scenario, in order to properly vary the parameters involved.

From the outcomes of the experiments, several conclusions can be drawn. Firstly, despite the multimodal case achieving a lower value than the benchmark, it is important to note that the makespan is no more than 2.4% faster than the benchmark for scenario 1. For scenario 2, this figure is 3.6%. This is an absolute difference of 35 minutes and 47 minutes, respectively, which is not significant.

The innovation regarding platooning is highly interesting, making the train transport a bottleneck at higher road velocities. Therefore, the decision could be made to transport these vehicles on a flatbed truck, in order to get them to the destination. Generally, the vehicle platooning configuration decreases the makespan by at least 15%, thus inducing a significant impact. The difference in makespan relative to configuration 1 can be seen in Table 3.

Thirdly, the reduction of road velocity due to network congestion is having an impact on the makespan. The makespan for experiment 1 increases with 13.9% compared to the benchmark value for scenario 1 and 10.0% for scenario 2, whereas the shortest possible convoy path is 1.9% and 2.7% slower, respectively. When compared to the first configuration, i.e. the multimodal case, this increase in makespan (Sc.1: +16.7%, +9.6%, Sc.2: +14.2%, +6.6%) is higher than the relative velocity decrease (Sc.1: -14.0%, -6.6%, Sc.2: -12.6%, -6.4%), partly due to the extra needed rests.

When convoy amounts and sizes are changed, the results barely change. When compared to configuration 1, the differences are within ± 2%. This is due to the great distances that are travelled. For shorter deployments, such as strategic-only, changing the amount of convoys or its sizes will have a greater influence on the results, as the constant factors such as headway times, resting times, and transshipment times are going to have a greater relative influence.

The robustness of both scenarios is examined. When allowing more than four convoys on one arc, the makespan improves, as expected. However, the difference between scenario 1 and 2 in this instance is relatively high. For scenario 1, increasing k induces a makespan decrease of 11.7%, relative to configuration 1. For scenario 2, this is only 0.4%.

	Scenario 1		**Scenario 2**	
	exp 1	**exp 2**	**exp 1**	**exp 2**
Config 2	-13.3%	-21.8%	-11.3%	-15.6%
Config 3	+16.7%	+9.6%	+14.2%	+6.6%
Config 4	+0.9%	+1.2%	-1.9%	+1.9%
Config 5	-11.7%	-9.3%	-0.4%	-0.4%

Table 3: Difference in makespan compared to configuration 1

The previous finding provides additional information for the comparison of the two networks, as differences in transport networks are found as well. It is clear that the makespan value for scenario 1 is higher than the value for scenario 2, as the averages of the MSRs are lower for scenario 2 (1187 km) than for scenario 1 (1259 km). An important note to make here is that configuration 2 is disregarded, as scenario 2 is constrained by the train convoys in this case, as previously mentioned. Scenario 2 performs consequently better regarding route efficiencies. This can be attributed to the quantity of diagonal arcs present within the network, compared to the graph in scenario 1.

6 Conclusion and discussion

Based on the previously discussed results, the execution of train movements should not be motivated by makespan oriented reasons, as the decrease in makespan is negligible. Instead, this should mainly be motivated by reasons including vehicle suitability, robustness, and other externalities such as road congestion. The innovation of truck platooning, also in the military convoy operations is highly promising, decreasing the makespan between 11-21%, and reducing train convoys. When the road velocity towards the end decreases due to road congestion, the makespan increases, partially due to the need for extra rest moments. The deployment is not significantly influenced by the quantity of convoys or the size of brigades. An increase of 100% in vehicle amount only increases the makespan up to 2%. This suggests that it would be more logical to deploy all vehicles in one deployment, rather than executing two smaller deployments. However, larger deployments will automatically be a more important target for enemies. Finally, when not holding the criterion for maximum deployment robustness, a significant improvement (11.7%) in the makespan is reached for scenario 1. This is not the case for scenario 2, as it only shows a marginal improvement (0.4%). This provides insight into the quality of the network for these scenarios.

The deployment of a brigade is subject to certain aspects of the deployment. These aspects include vehicle amounts, the locations of the POE and SA/CA and the corresponding transport network. Based on these aspects, the deployment is modelled for a POE the Netherlands and a SA/CA in Lodz, Poland, and conclusions are drawn. The main findings conclude that the core of the deployment is road transport, due to the wide options and availability, accompanied by the fact that the deployment is ended in road transport mode. The deployment can be affected by differentiating in several parameter values. Truck platooning is an interesting implementation for future deployments, as it has been demonstrated to reduce the makespan and decreases the requirement for rest periods.

The validation of the model relies on data which is comparable with the purpose of the model. Due to the difficulty of obtaining reliable assumptions and parameter values, certain values and assumptions need stronger investigation. These consist of velocities, vehicle fleets and arc permissions. The values employed in the model are derived from the documentation and from RNLA employees, but they may be outdated or inaccurate due to the scale of the deployment.

The model utilised can be elaborated, eliminating several assumptions. If done correctly, additional goals can be reached with the model. For example, the maximum amount of convoys traversing on an arc k can be implemented as a stochastic variable, focussing on robustness in relation to makespan of the deployment. Furthermore, the assessment of this problem around 10,000 vehicles and 100 convoys is a highly interesting configuration, as multiple NATO brigades should traverse a similar route. It is thereby as important for the responsible commanders to give full consideration to the potential consequences of becoming a prominent target.

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Testrun B

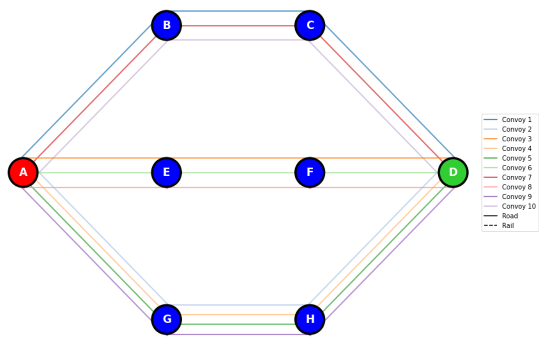

Figure 11: Convoy visualisation testrun

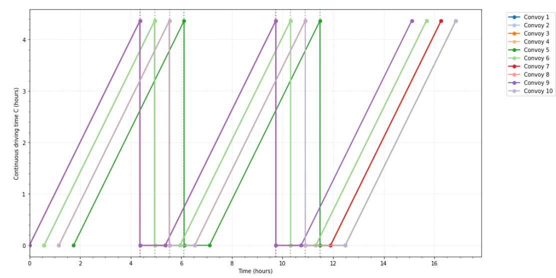

Figure 12: Continuous driving time testrun

Convoy	**Path [mode]**	**Departure (h)**	**Arrival (h)**
1	**A** [W] → **B** [REST W] [W] → **C** [REST W] [W] → **D**	0.58, 5.95, 11.32, 0.00	0.00, 4.95, 10.32, 15.68
2	**A** [W] → **G** [REST W] [W] → **H** [REST W] [W] → **D**	1.16, 6.53, 11.90, 0.00	0.00, 5.53, 10.90, 16.26
3	**A** [W] → **E** [REST W] [W] → **F** [REST W] [W] → **D**	1.16, 6.53, 11.90, 0.00	0.00, 5.53, 10.90, 16.26
4	**A** [W] → **G** [REST W] [W] → **H** [REST W] [W] → **D**	0.58, 5.95, 11.32, 0.00	0.00, 4.95, 10.32, 15.68
5	**A** [W] → **G** [REST W] [W] → **H** [REST W] [W] → **D**	1.74, 7.11, 12.48, 0.00	0.00, 6.11, 11.48, 16.85
6	**A** [W] → **E** [REST W] [W] → **F** [REST W] [W] → **D**	0.58, 5.95, 11.32, 0.00	0.00, 4.95, 10.32, 15.68
7	**A** [W] → **B** [REST W] [W] → **C** [REST W] [W] → **D**	0.00, 5.37, 11.90, 0.00	0.00, 4.37, 9.73, 16.26
8	**A** [W] → **E** [REST W] [W] → **F** [REST W] [W] → **D**	0.00, 5.37, 10.73, 0.00	0.00, 4.37, 9.73, 15.10
9	**A** [W] → **G** [REST W] [W] → **H** [REST W] [W] → **D**	0.00, 5.37, 10.73, 0.00	0.00, 4.37, 9.73, 15.10
10	**A** [W] → **B** [REST W] [W] → **C** [REST W] [W] → **D**	1.16, 6.53, 12.48, 0.00	0.00, 5.53, 10.90, 16.85

Table 16: Convoy paths for testrun

Headway and transshipment verification

C

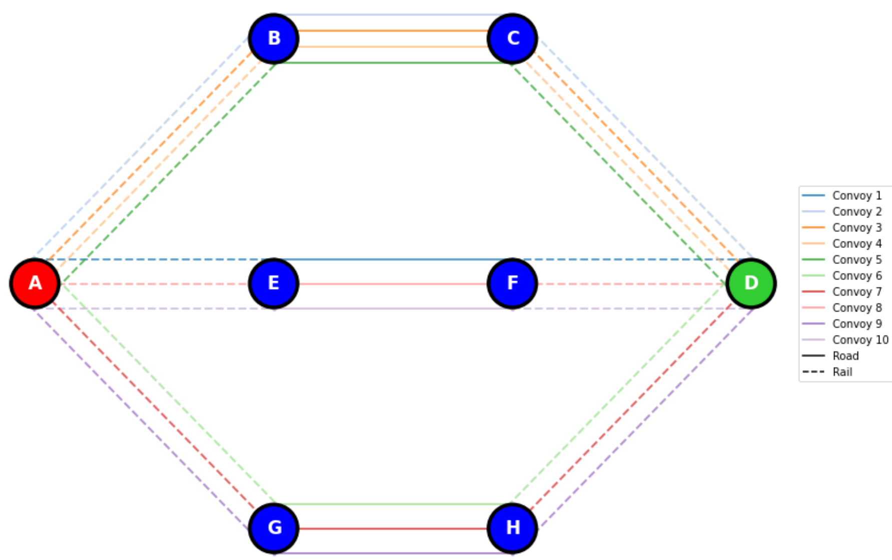

Figure 13: Convoy visualisation for headway and transshipment verification

Convoy	Path [mode]	Departure Times (h)	Arrival Times (h)
1	**A** [T] → **E** [T→W] → **F** [W→T] → **D**	4.02, 10.78, 21.14, 0.00	0.00, 7.78, 15.14, 24.90
2	**A** [T] → **B** [T→W] → **C** [W→T] → **D**	6.03, 12.79, 23.15, 0.00	0.00, 9.79, 17.15, 26.91
3	**A** [T] → **B** [T→W] → **C** [W→T] → **D**	4.02, 10.78, 21.14, 0.00	0.00, 7.78, 15.14, 24.90
4	**A** [T] → **B** [T→W] → **C** [W→T] → **D**	2.01, 8.77, 19.13, 0.00	0.00, 5.77, 13.13, 22.89
5	**A** [T] → **B** [T→W] → **C** [W→T] → **D**	0.00, 6.76, 17.13, 0.00	0.00, 3.76, 11.13, 20.88
6	**A** [T] → **G** [T→W] → **H** [W→T] → **D**	4.02, 10.78, 21.14, 0.00	0.00, 7.78, 15.14, 24.90
7	**A** [T] → **G** [T→W] → **H** [W→T] → **D**	2.01, 8.77, 19.13, 0.00	0.00, 5.77, 13.13, 22.89
8	**A** [T] → **E** [T→W] → **F** [W→T] → **D**	2.01, 8.77, 19.13, 0.00	0.00, 5.77, 13.13, 22.89
9	**A** [T] → **G** [T→W] → **H** [W→T] → **D**	0.00, 6.76, 17.13, 0.00	0.00, 3.76, 11.13, 20.88
10	**A** [T] → **E** [T→W] → **F** [W→T] → **D**	0.00, 6.76, 17.13, 0.00	0.00, 3.76, 11.13, 20.88

Table 17: Convoy paths for headway and transshipment verification

C.1 Headway and transshipment verification for 20 convoys

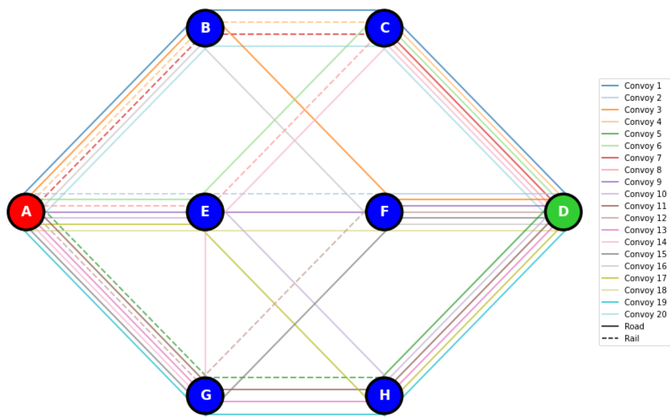

Figure 14: Convoy visualisation for headway and transshipment verification 20 convoys

Convoy	Path [mode]	Departure (h)	Arrival (h)
1	**A** [W] → **B** [REST W] → **C** [REST W] → **D**	1.08, 6.41, 11.73, 0.00	0.00, 5.41, 10.73, 16.06
2	**A** [T] → **E** [T] → **F** [T→W] → **D**	2.00, 6.60, 13.36, 0.00	0.00, 5.76, 10.36, 17.68
3	**A** [W] → **B** [REST W] → **F** [REST W] → **D**	0.00, 5.33, 11.73, 0.00	0.00, 4.33, 10.37, 16.06
4	**A** [T] → **B** [T] → **C** [T→W] → **D**	0.00, 3.75, 10.51, 0.00	0.00, 3.75, 7.51, 14.84
5	**A** [T] → **G** [T] → **H** [T→W] → **D**	2.00, 5.76, 12.82, 0.00	0.00, 5.76, 9.51, 17.14
6	**A** [W] → **E** [REST W] → **C** [REST W] → **D**	1.08, 6.41, 12.82, 0.00	0.00, 5.41, 11.45, 17.14
7	**A** [T] → **B** [T] → **C** [T→W] → **D**	2.00, 5.76, 13.36, 0.00	0.00, 5.76, 9.51, 17.68
8	**A** [T] → **E** [T] → **C** [T→W] → **D**	0.00, 3.75, 11.13, 0.00	0.00, 3.75, 8.13, 15.46
9	**A** [W] → **E** [REST W] → **F** [REST W] → **D**	2.16, 7.49, 12.82, 0.00	0.00, 6.49, 11.82, 17.14
10	**A** [W] → **E** [REST W] → **H** [REST W] → **D**	1.62, 7.32, 13.36, 0.00	0.00, 5.95, 12.36, 17.68
11	**A** [W] → **G** [REST W] → **H** [REST W] → **D**	0.54, 5.87, 11.19, 0.00	0.00, 4.87, 10.19, 15.52
12	**A** [T] → **G** [T] → **F** [T→W] → **D**	0.00, 3.75, 11.19, 0.00	0.00, 3.75, 8.13, 15.52
13	**A** [W] → **G** [REST W] → **H** [REST W] → **D**	2.94, 8.27, 13.90, 0.00	0.00, 7.27, 12.59, 18.22
14	**A** [W] → **G** [REST W] → **E** [W] → **C** [REST W] → **D**	0.00, 5.67, 7.86, 13.90, 0.00	0.00, 4.33, 7.86, 12.90, 18.22
15	**A** [W] → **G** [REST W] → **F** [REST W] → **D**	1.62, 7.86, 13.90, 0.00	0.00, 5.95, 12.90, 18.22
16	**A** [W] → **B** [REST W] → **F** [REST W] → **D**	0.54, 5.87, 12.28, 0.00	0.00, 4.87, 10.91, 16.60
17	**A** [W] → **E** [REST W] → **H** [REST W] → **D**	0.54, 5.87, 12.28, 0.00	0.00, 4.87, 10.91, 16.60
18	**A** [W] → **E** [REST W] → **F** [REST W] → **D**	0.00, 5.33, 10.65, 0.00	0.00, 4.33, 9.65, 14.98
19	**A** [W] → **G** [REST W] → **H** [REST W] → **D**	1.08, 6.41, 11.73, 0.00	0.00, 5.41, 10.73, 16.06
20	**A** [W] → **B** [REST W] → **C** [REST W] → **D**	1.62, 6.95, 12.28, 0.00	0.00, 5.95, 11.28, 16.60

Table 18: Convoy paths for headway and transshipment verification 20 convoys

D
Train prioritisation

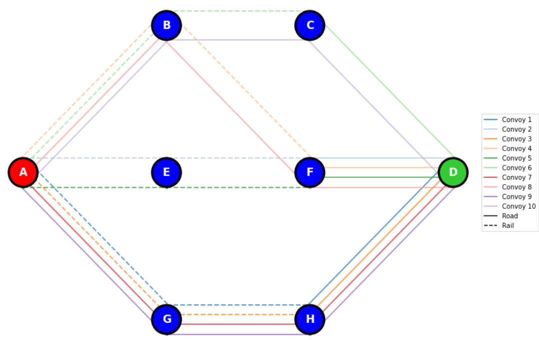

Figure 15: Convoy visualisation for train prioritisation verification

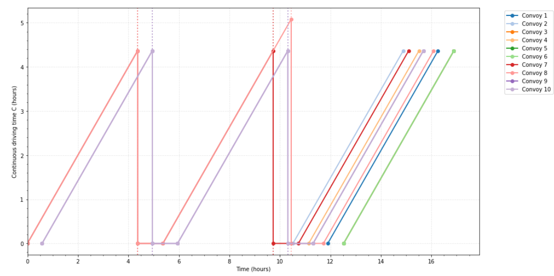

Figure 16: Continuous driving time on road for train prioritisation verification

Convoy	Path [mode]	Departure (h)	Arrival (h)
1	**A** [T] → **G** [T] → **H** [T→W] → **D**	0.00, 3.76, 11.90, 0.00	0.00, 3.76, 7.52, 16.26
2	**A** [T] → **E** [T] → **F** [T→W] → **D**	0.00, 3.76, 10.52, 0.00	0.00, 3.76, 7.52, 14.88
3	**A** [T] → **G** [T] → **H** [T→W] → **D**	2.01, 5.77, 12.53, 0.00	0.00, 5.77, 9.53, 16.89
4	**A** [T] → **B** [T] → **F** [T→W] → **D**	0.00, 3.76, 11.14, 0.00	0.00, 3.76, 8.14, 15.51
5	**A** [T] → **E** [T] → **F** [T→W] → **D**	2.01, 5.77, 12.53, 0.00	0.00, 5.77, 9.53, 16.89
6	**A** [T] → **B** [T] → **C** [T→W] → **D**	2.01, 5.77, 12.53, 0.00	0.00, 5.77, 9.53, 16.89
7	**A** [W] → **G** [REST W] → **H** [REST W] → **D**	0.00, 5.37, 10.73, 0.00	0.00, 4.37, 9.73, 15.10
8	**A** [W] → **B** [REST W] → **F** [REST W] → **D**	0.00, 5.37, 11.72, 0.00	0.00, 4.37, 10.45, 16.09
9	**A** [W] → **G** [REST W] → **H** [REST W] → **D**	0.58, 5.95, 11.32, 0.00	0.00, 4.95, 10.32, 15.68
10	**A** [W] → **B** [REST W] → **C** [REST W] → **D**	0.58, 5.95, 11.32, 0.00	0.00, 4.95, 10.32, 15.68

Table 19: Convoy paths for train prioritisation verification

Validation convoy paths E

E.1 Validation 13 lightbrig

Convoy	Path [mode]	Departure (h)	Arrival (h)
1	**A** [W] → **I** [REST W] → **J** [REST W] → **K** [REST W] → **L** [W] → **E**	0.58, 6.35, 12.33, 17.31, 21.66, 0.00	0.00, 5.35, 11.33, 16.31, 21.66, 24.65
2	**A** [W] → **I** [REST W] → **J** [REST W] → **K** [REST W] → **L** [W] → **E**	0.00, 5.77, 11.75, 16.73, 21.08, 0.00	0.00, 4.77, 10.75, 15.73, 21.08, 24.06
3	**A** [W] → **I** [REST W] → **J** [REST W] → **K** [W] → **H** [REST W] → **E**	1.16, 6.93, 12.91, 16.89, 20.62, 0.00	0.00, 5.93, 11.91, 16.89, 19.62, 23.77
4	**A** [W] → **F** [REST W] → **G** [REST W] → **H** [REST W] → **D** [W] → **E**	0.00, 5.80, 10.49, 16.93, 19.63, 0.00	0.00, 4.80, 9.49, 15.93, 19.63, 22.75
5	**A** [W] → **B** [REST W] → **C** [REST W] → **D** [W] → **E**	1.74, 8.54, 14.60, 18.73, 0.00	0.00, 7.54, 12.35, 18.73, 21.85
6	**A** [W] → **F** [REST W] → **G** [W] → **C** [REST W] → **D** [W] → **E**	1.16, 6.96, 10.65, 14.02, 18.15, 0.00	0.00, 5.96, 10.65, 13.02, 18.15, 21.27
7	**A** [W] → **B** [REST W] → **C** [W] → **D** [REST W] → **E**	0.00, 6.80, 10.61, 15.73, 0.00	0.00, 5.80, 10.61, 14.73, 18.85
8	**A** [W] → **F** [REST W] → **G** [REST W] → **H** [REST W] → **E**	0.58, 6.38, 12.83, 21.20, 0.00	0.00, 5.38, 10.07, 18.26, 24.35
9	**A** [W] → **B** [REST W] → **C** [W] → **D** [REST W] → **H** [W] → **E**	1.16, 7.96, 11.77, 16.89, 19.59, 0.00	0.00, 6.96, 11.77, 15.89, 19.59, 22.74
10	**A** [W] → **B** [REST W] → **G** [REST W] → **H** [REST W] → **E**	0.58, 7.38, 12.24, 18.68, 0.00	0.00, 6.38, 11.24, 17.68, 21.84

Table 20: Convoy paths for validation 13 lightbrig

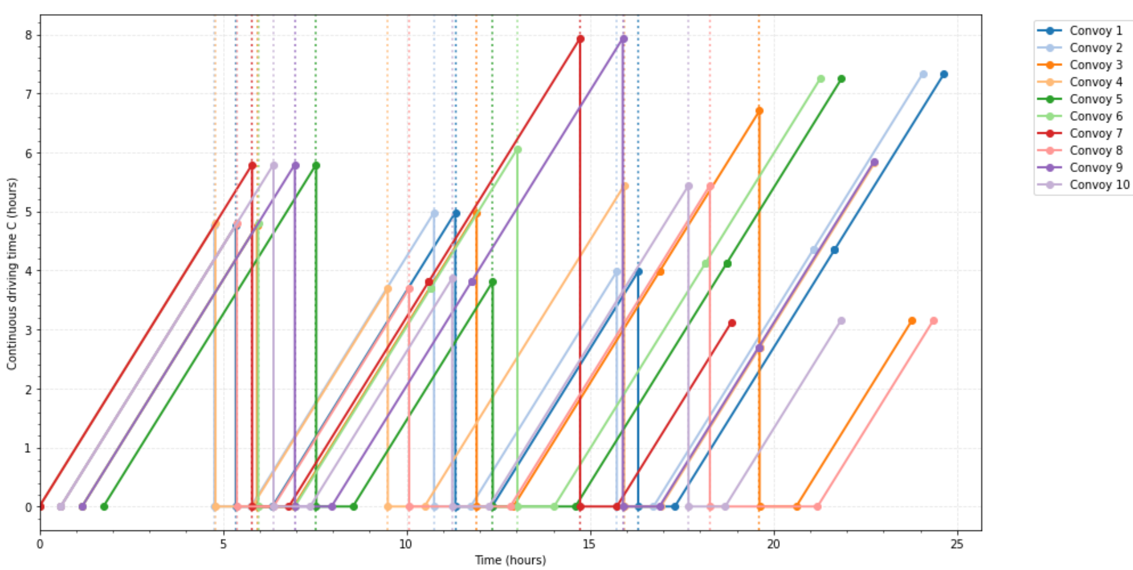

Figure 17: C values for validation run 13 lightbrig

E.2 Validation 43 mechbrig

Convoy	Path [mode]	Departure (h)	Arrival (h)
1	**A** [W] → **I** [REST W] → **J** [REST W] → **K** [REST W] → **E**	0.58, 7.21, 11.90, 18.34, 0.00	0.00, 6.21, 10.90, 17.34, 21.49
2	**A** [W] → **B** [REST W] → **C** [REST W] → **D** [W] → **E**	0.00, 6.10, 13.03, 15.60, 0.00	0.00, 5.10, 12.03, 15.60, 20.20
3	**A** [W] → **I** [REST W] → **J** [W] → **G** [REST W] → **H** [W] → **E**	0.00, 6.62, 10.32, 13.69, 18.37, 0.00	0.00, 5.62, 10.32, 12.69, 17.81, 21.49
4	**A** [W] → **B** [REST W] → **C** [REST W] → **D** [W] → **E**	1.16, 7.26, 14.20, 16.76, 0.00	0.00, 6.26, 13.20, 16.76, 21.36
5	**A** [W] → **F** [REST W] → **G** [REST W] → **H** [REST W] → **E**	1.74, 7.41, 12.22, 17.79, 0.00	0.00, 6.41, 11.22, 16.35, 20.91
6	**A** [W] → **F** [REST W] → **J** [REST W] → **K** [REST W] → **E**	0.58, 6.25, 11.12, 17.76, 0.00	0.00, 5.25, 10.12, 16.55, 20.91
7	**A** [W] → **F** [REST W] → **J** [REST W] → **K** [REST W] → **E**	0.00, 5.67, 10.53, 17.18, 0.00	0.00, 4.67, 9.53, 15.97, 20.33
8	**A** [W] → **B** [REST W] → **C** [REST W] → **D** [W] → **E**	0.58, 6.68, 13.62, 16.18, 0.00	0.00, 5.68, 12.62, 16.18, 20.78
9	**A** [W] → **B** [REST W] → **G** [REST W] → **H** [W] → **E**	1.74, 7.84, 12.98, 17.10, 0.00	0.00, 6.84, 11.98, 17.10, 20.23
10	**A** [W] → **F** [REST W] → **G** [W] → **H** [REST W] → **E**	1.16, 6.83, 10.64, 16.52, 0.00	0.00, 5.83, 10.64, 14.76, 19.65

Table 21: Convoy paths for validation 43 mechbrig

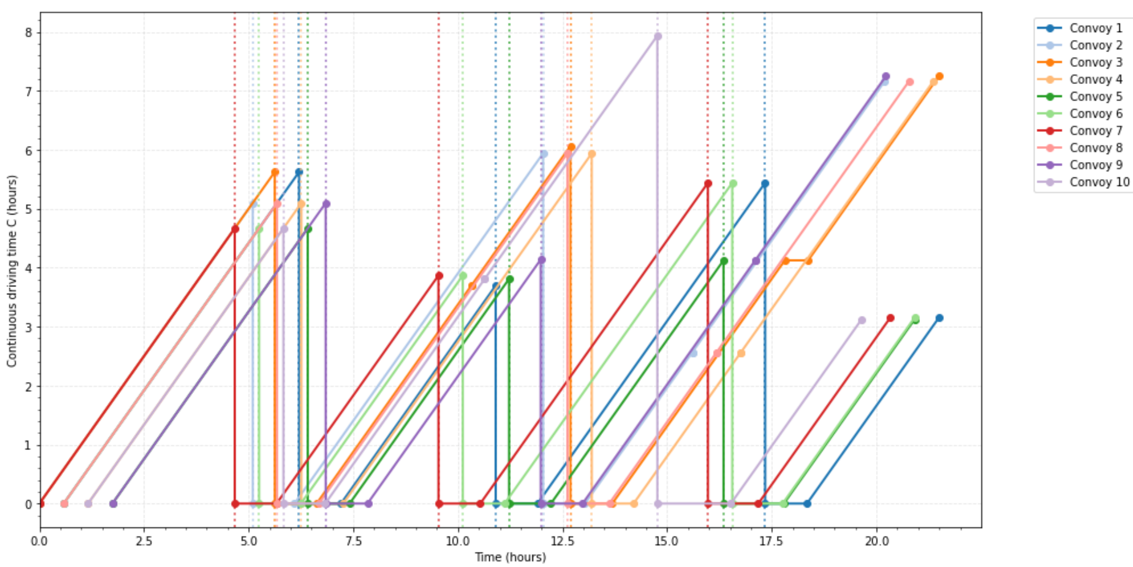

Figure 18: C values for validation 43 mechbrig

Configuration 1 F

F.1 Scenario 1

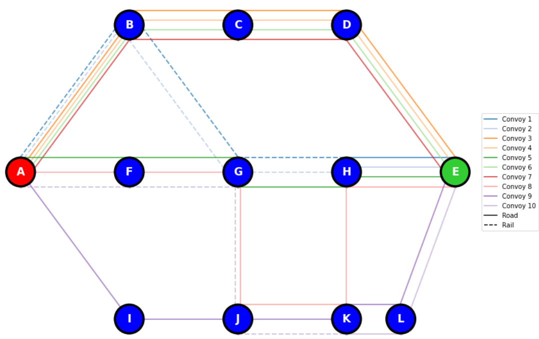

Figure 19: Convoy visualisation for configuration 1 for 13 lightbrig

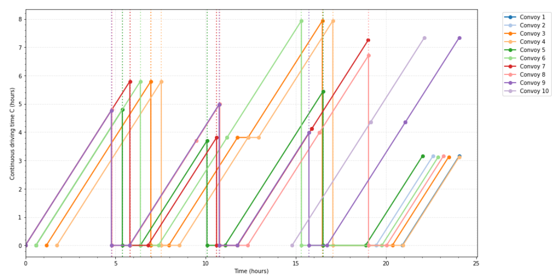

Figure 20: Convoy visualisation for configuration 1 for 13 lightbrig

Convoy	Path [mode]	Departure (h)	Arrival (h)
1	**A** [T] → **B** [T] → **G** [T] → **H** [T→W] → **E**	0.00, 5.01, 8.33, 20.91, 0.00	0.00, 5.01, 8.33, 13.03, 24.06
2	**A** [T] → **B** [T] → **G** [T] → **H** [T→W] → **E**	2.01, 7.02, 10.34, 19.45, 0.00	0.00, 7.02, 10.34, 15.04, 22.61
3	**A** [W] → **B** [REST W] → **C** [W] → **D** [REST W] → **E**	1.16, 7.96, 12.35, 20.36, 0.00	0.00, 6.96, 11.77, 16.47, 23.48
4	**A** [W] → **B** [REST W] → **C** [W] → **D** [REST W] → **E**	1.74, 8.54, 12.93, 20.94, 0.00	0.00, 7.54, 12.35, 17.06, 24.06
5	**A** [W] → **F** [REST W] → **G** [REST W] → **H** [REST W] → **E**	0.58, 6.38, 11.07, 18.87, 0.00	0.00, 5.38, 10.07, 16.51, 22.03
6	**A** [W] → **B** [REST W] → **C** [W] → **D** [REST W] → **E**	0.58, 7.38, 11.19, 19.78, 0.00	0.00, 6.38, 11.19, 15.31, 22.90
7	**A** [W] → **B** [REST W] → **C** [REST W] → **D** [W] → **E**	0.00, 6.80, 11.77, 15.89, 0.00	0.00, 5.80, 10.61, 15.89, 19.02
8	**A** [W] → **F** [REST W] → **G** [W] → **J** [REST W] → **K** [W] → **H** [REST W] → **E**	0.00, 5.80, 9.49, 12.33, 16.31, 20.04, 0.00	0.00, 4.80, 9.49, 10.79, 16.31, 19.04, 23.19
9	**A** [W] → **I** [REST W] → **J** [REST W] → **K** [REST W] → **L** [W] → **E**	0.00, 5.77, 11.75, 16.73, 21.08, 0.00	0.00, 4.77, 10.75, 15.73, 21.08, 24.06
10	**A** [T] → **F** [T] → **G** [T] → **J** [T] → **K** [T→W] → **L** [W] → **E**	0.00, 4.13, 7.31, 8.38, 14.80, 19.15, 0.00	0.00, 4.13, 7.31, 8.38, 11.80, 19.15, 22.13

Table 22: Convoy paths for configuration 1 for 13 lightbrig

F.2 Scenario 2

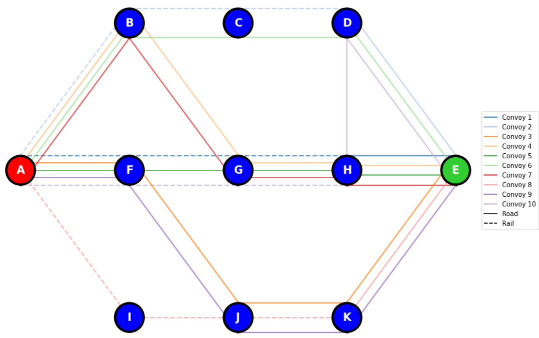

Figure 21: Convoy visualisation for configuration 1 for 43 mechbrig

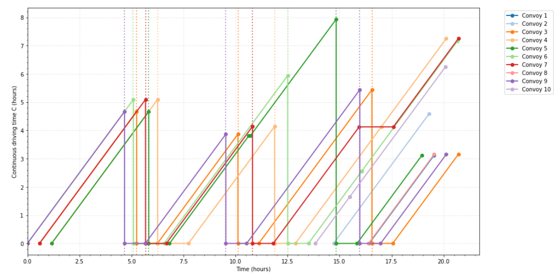

Figure 22: Continuous driving time on road for configuration 1 for 43 mechbrig

Convoy	Path [mode]	Departure (h)	Arrival (h)
1	**A** [T] → **F** [T] → **G** [T] → **H** [T→W] → **H** [W] → **E**	2.01, 6.03, 9.30, 16.42, 16.42, 0.00	0.00, 6.03, 9.30, 12.85, 15.85, 19.54
2	**A** [T] → **B** [T] → **C** [T] → **D** [T→W] → **D** [W] → **E**	0.00, 4.40, 9.53, 14.71, 14.71, 0.00	0.00, 4.40, 9.53, 11.71, 14.71, 19.31
3	**A** [W] → **F** [REST W] → **J** [REST W] → **K** [REST W] → **E**	0.58, 6.25, 11.12, 17.55, 0.00	0.00, 5.25, 10.12, 16.55, 20.71
4	**A** [W] → **B** [REST W] → **G** [REST W] → **H** [W] → **E**	1.16, 7.74, 12.88, 17.00, 0.00	0.00, 6.26, 11.88, 17.00, 20.13
5	**A** [W] → **F** [REST W] → **G** [W] → **H** [REST W] → **E**	1.16, 6.83, 10.71, 15.84, 0.00	0.00, 5.83, 10.64, 14.84, 18.96
6	**A** [W] → **B** [REST W] → **C** [REST W] → **D** [W] → **E**	0.00, 6.57, 13.51, 16.07, 0.00	0.00, 5.10, 12.51, 16.07, 20.67
7	**A** [W] → **B** [REST W] → **G** [REST W] → **H** [W] → **E**	0.58, 6.68, 11.82, 17.58, 0.00	0.00, 5.68, 10.82, 15.94, 20.71
8	**A** [T] → **I** [T] → **J** [T] → **K** [T→W] → **K** [W] → **E**	0.00, 4.86, 8.03, 16.39, 16.39, 0.00	0.00, 4.86, 8.03, 12.73, 15.73, 19.54
9	**A** [W] → **F** [REST W] → **J** [REST W] → **K** [REST W] → **E**	0.00, 5.67, 10.53, 16.97, 0.00	0.00, 4.67, 9.53, 15.97, 20.13
10	**A** [T] → **F** [REST T] → **G** [REST T] → **H** [T→W] → **H** [W] → **D** [W] → **E**	0.00, 4.02, 7.29, 13.84, 13.84, 15.49, 0.00	0.00, 4.02, 7.29, 10.84, 13.84, 15.49, 20.09

Table 23: Convoy paths for configuration 1 for 43 mechbrig

Configuration 2 G

G.1 Scenario 1

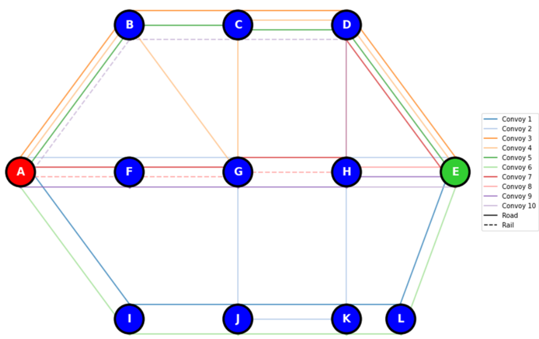

Figure 23: Convoy visualisation for configuration 2 for 13 lightbrig

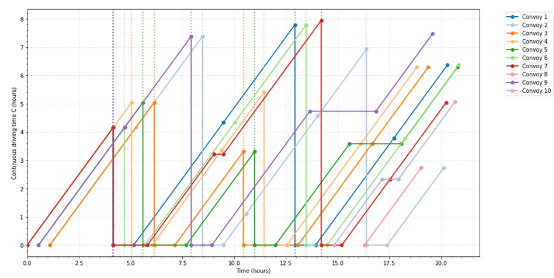

Figure 24: Continuous driving time on road for configuration 2 for 13 lightbrig

Convoy	Path [mode]	Departure (h)	Arrival (h)
1	**A** [W] → **I** [REST W] → **J** [W] → **K** [REST W] → **L** [W] → **E**	0.00, 5.15, 9.48, 13.94, 17.72, 0.00	0.00, 4.15, 9.48, 12.94, 17.72, 20.31
2	**A** [W] → **F** [W] → **G** [REST W] → **J** [W] → **K** [W] → **H** [REST W] → **E**	1.09, 5.26, 9.47, 10.58, 14.04, 17.40, 0.00	0.00, 5.26, 8.47, 10.58, 14.04, 16.40, 20.13
3	**A** [W] → **B** [REST W] → **C** [REST W] → **D** [W] → **E**	1.09, 7.14, 13.09, 16.67, 0.00	0.00, 6.14, 10.45, 16.67, 19.38
4	**A** [W] → **B** [REST W] → **G** [W] → **C** [REST W] → **D** [W] → **E**	0.00, 6.05, 9.41, 12.54, 16.12, 0.00	0.00, 5.05, 9.41, 11.45, 16.12, 18.83
5	**A** [W] → **B** [REST W] → **C** [REST W] → **D** [W] → **E**	0.55, 7.69, 11.99, 18.09, 0.00	0.00, 5.59, 10.99, 15.58, 20.80
6	**A** [W] → **I** [REST W] → **J** [W] → **K** [REST W] → **L** [W] → **E**	0.55, 5.69, 10.03, 14.49, 18.27, 0.00	0.00, 4.69, 10.03, 13.49, 18.27, 20.85
7	**A** [W] → **F** [REST W] → **G** [W] → **H** [REST W] → **D** [W] → **E**	0.00, 5.81, 9.47, 15.21, 17.54, 0.00	0.00, 4.17, 9.02, 14.21, 17.54, 20.25
8	**A** [T] → **F** [T] → **G** [T] → **H** [T→W] → **E**	0.00, 4.13, 7.31, 16.31, 0.00	0.00, 4.13, 7.31, 12.00, 19.04
9	**A** [W] → **F** [W] → **G** [REST W] → **H** [W] → **E**	0.55, 4.72, 8.93, 16.85, 0.00	0.00, 4.72, 7.93, 13.66, 19.59
10	**A** [T] → **B** [T] → **C** [T] → **D** [T→W] → **H** [W] → **E**	0.00, 5.01, 8.28, 14.83, 17.95, 0.00	0.00, 5.01, 8.28, 11.83, 17.16, 20.68

Table 24: Convoy paths for configuration 2 for 13 lightbrig

G.2 Scenario 2

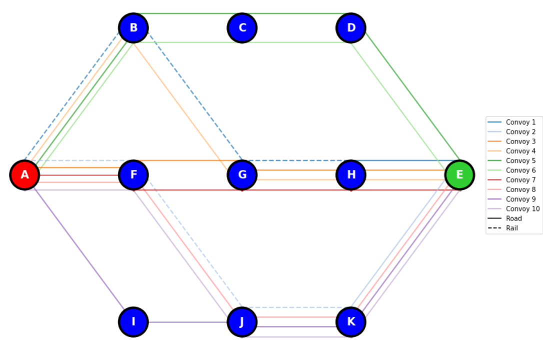

Figure 25: Convoy visualisation for configuration 2 for 43 mechbrig

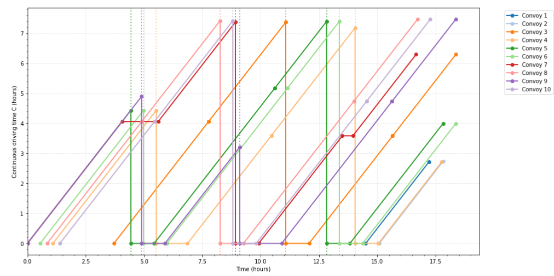

Figure 26: Continuous driving time on road for configuration 2 for 43 mechbrig

Convoy	Path [mode]	Departure (h)	Arrival (h)
1	**A** [T] → **B** [T] → **G** [T] → **H** [T→W] → **E**	0.00, 4.40, 7.96, 14.50, 0.00	0.00, 4.40, 7.96, 11.50, 17.21
2	**A** [T] → **F** [T] → **J** [T] → **K** [T→W] → **E**	0.00, 4.02, 7.39, 15.09, 0.00	0.00, 4.02, 7.34, 12.09, 17.82
3	**A** [W] → **F** [W] → **G** [REST W] → **H** [W] → **E**	3.71, 7.77, 12.08, 15.66, 0.00	0.00, 7.77, 11.08, 15.66, 18.37
4	**A** [W] → **B** [REST W] → **G** [W] → **H** [REST W] → **E**	1.09, 6.87, 10.46, 15.05, 0.00	0.00, 5.53, 10.46, 14.05, 17.76
5	**A** [W] → **B** [REST W] → **C** [W] → **D** [REST W] → **E**	0.00, 5.43, 10.61, 13.83, 0.00	0.00, 4.43, 10.61, 12.83, 17.82
6	**A** [W] → **B** [REST W] → **C** [W] → **D** [REST W] → **E**	0.55, 5.98, 11.15, 14.37, 0.00	0.00, 4.98, 11.15, 13.37, 18.37
7	**A** [W] → **F** [W] → **G** [REST W] → **H** [W] → **E**	0.00, 5.61, 9.92, 13.96, 0.00	0.00, 4.06, 8.92, 13.50, 16.66
8	**A** [W] → **F** [W] → **J** [REST W] → **K** [W] → **E**	0.85, 4.90, 9.26, 14.00, 0.00	0.00, 4.90, 8.26, 14.00, 16.73
9	**A** [W] → **I** [REST W] → **J** [REST W] → **K** [W] → **E**	0.00, 5.90, 10.90, 15.64, 0.00	0.00, 4.90, 9.11, 15.64, 18.37
10	**A** [W] → **F** [W] → **J** [REST W] → **K** [W] → **E**	1.39, 5.45, 9.81, 14.54, 0.00	0.00, 5.45, 8.81, 14.54, 17.28

Table 25: Convoy paths for configuration 2 for 43 mechbrig

Configuration 3

H

H.1 Scenario 1

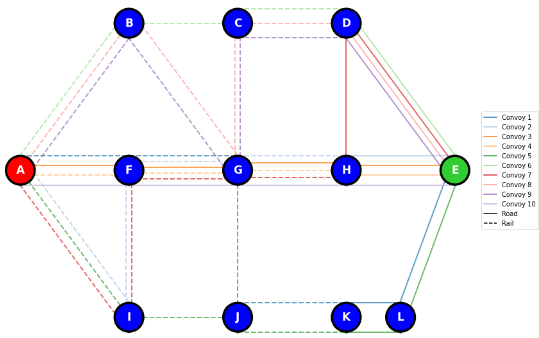

Figure 27: Convoy visualisation for configuration 3 for 13 lightbrig

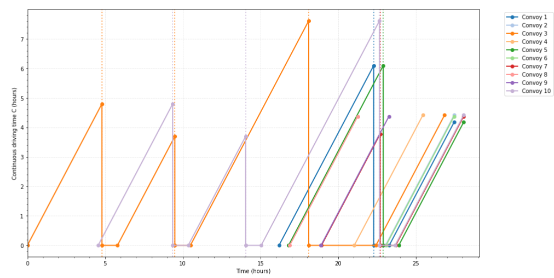

Figure 28: Continuous driving time on road for configuration 3 for 13 lightbrig

Convoy	Path [mode]	Departure (h)	Arrival (h)
1	**A** [T] → **F** [T] → **G** [T] → **J** [T] → **K** [T→W] → **L** [REST W] → **E**	0.00, 4.13, 7.31, 8.38, 16.19, 23.29, 0.00	0.00, 4.13, 7.31, 8.38, 11.80, 22.29, 27.46
2	**A** [T] → **I** [T] → **F** [T] → **G** [T] → **H** [T→W] → **E**	6.38, 10.49, 12.08, 15.35, 23.05, 0.00	0.00, 10.49, 12.08, 15.25, 20.05, 27.46
3	**A** [W] → **F** [REST W] → **G** [REST W] → **H** [REST W] → **E**	0.00, 5.80, 10.49, 22.43, 0.00	0.00, 4.80, 9.49, 18.11, 26.85
4	**A** [T] → **F** [T] → **G** [T] → **H** [T→W] → **E**	2.01, 10.07, 13.34, 21.04, 0.00	0.00, 6.14, 13.24, 18.04, 25.45
5	**A** [T] → **I** [T] → **J** [T] → **K** [T→W] → **L** [REST W] → **E**	0.36, 4.47, 10.39, 16.81, 23.90, 0.00	0.00, 4.47, 8.76, 13.81, 22.90, 28.07
6	**A** [T] → **B** [T] → **C** [T] → **D** [T→W] → **E**	8.26, 13.27, 16.54, 23.09, 0.00	0.00, 13.27, 16.54, 20.09, 27.46
7	**A** [T] → **I** [T] → **F** [T] → **G** [T] → **H** [T→W] → **D** [REST W] → **E**	2.37, 6.48, 8.06, 11.23, 18.93, 23.70, 0.00	0.00, 6.48, 8.06, 11.23, 15.93, 22.70, 28.07
8	**A** [T] → **B** [T] → **G** [T] → **C** [T] → **D** [T→W] → **E**	0.00, 5.01, 8.33, 10.34, 16.89, 0.00	0.00, 5.01, 8.33, 10.34, 13.89, 21.26
9	**A** [T] → **B** [T] → **G** [T] → **C** [T] → **D** [T→W] → **E**	2.01, 7.02, 10.34, 12.35, 18.89, 0.00	0.00, 7.02, 10.34, 12.35, 15.89, 23.27
10	**A** [W] → **F** [REST W] → **G** [REST W] → **H** [REST W] → **E**	4.55, 10.35, 15.05, 23.66, 0.00	0.00, 9.35, 14.05, 22.66, 28.07

Table 26: Convoy paths for configuration 3 for 13 lightbrig

H.2 Scenario 2

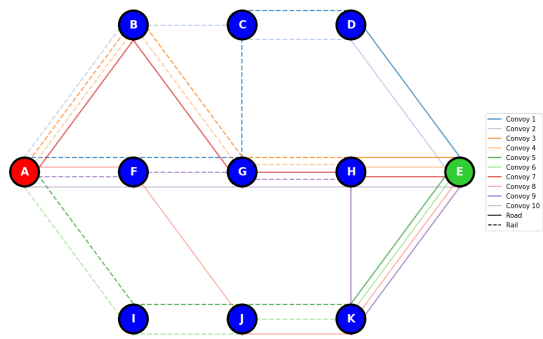

Figure 29: Convoy visualisation for configuration 3 for 43 mechbrig

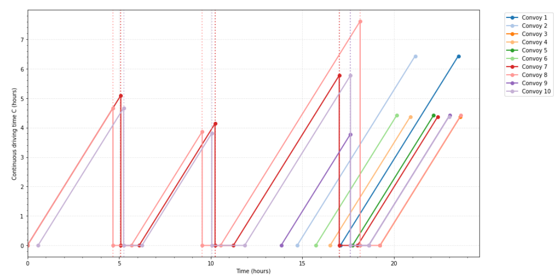

Figure 30: Continuous driving time on road for configuration 3 for 43 mechbrig

Convoy	Path [mode]	Departure (h)	Arrival (h)
1	**A** [T] → **F** [T] → **G** [T] → **C** [T] → **D** [T→W] → **E**	2.01, 6.03, 9.30, 11.89, 17.07, 0.00	0.00, 6.03, 9.30, 11.89, 14.07, 23.50
2	**A** [T] → **B** [T] → **C** [T] → **D** [T→W] → **E**	0.00, 4.40, 9.53, 14.71, 0.00	0.00, 4.40, 9.53, 11.71, 21.15
3	**A** [T] → **B** [T] → **G** [T] → **H** [T→W] → **E**	4.02, 8.41, 11.97, 19.24, 0.00	0.00, 8.41, 11.97, 15.52, 23.61
4	**A** [T] → **B** [T] → **G** [T] → **H** [T→W] → **E**	2.01, 6.41, 9.96, 16.51, 0.00	0.00, 6.41, 9.96, 13.51, 20.88
5	**A** [T] → **I** [T] → **J** [T] → **K** [T→W] → **E**	2.01, 6.87, 10.04, 17.74, 0.00	0.00, 6.87, 10.04, 14.74, 22.15
6	**A** [T] → **I** [T] → **J** [T] → **K** [T→W] → **E**	0.00, 4.86, 8.03, 15.73, 0.00	0.00, 4.86, 8.03, 12.73, 20.14
7	**A** [W] → **B** [REST W] → **G** [REST W] → **H** [REST W] → **E**	0.00, 6.10, 11.23, 18.01, 0.00	0.00, 5.10, 10.23, 17.01, 22.38
8	**A** [W] → **F** [REST W] → **J** [REST W] → **K** [REST W] → **E**	0.00, 5.67, 10.53, 19.23, 0.00	0.00, 4.67, 9.53, 18.15, 23.64
9	**A** [T] → **F** [T] → **G** [T] → **H** [T→W] → **K** [REST W] → **E**	0.00, 4.02, 7.29, 13.84, 18.61, 0.00	0.00, 4.02, 7.29, 10.84, 17.61, 23.03
10	**A** [W] → **F** [REST W] → **G** [REST W] → **H** [REST W] → **E**	0.58, 6.25, 11.85, 18.62, 0.00	0.00, 5.25, 10.06, 17.62, 23.00

Table 27: Convoy paths for configuration 3 for 43 mechbrig

Configuration 4 I

I.1 Scenario 1

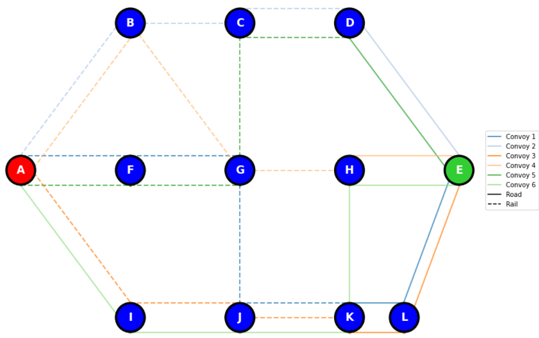

Figure 31: Convoy visualisation for configuration 4 for 13 lightbrig

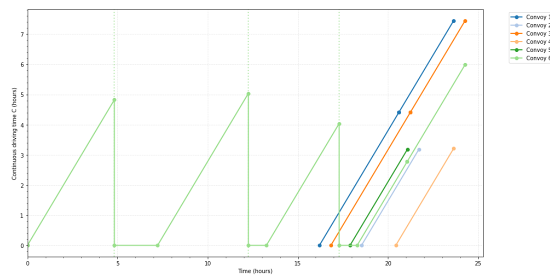

Figure 32: Continuous driving time on road for configuration 4 for 13 lightbrig

Convoy	Path [mode]	Departure (h)	Arrival (h)
1	**A** [T] → **F** [T] → **G** [T] → **J** [T] → **K** [T→W] → **L** [W] → **E**	0.00, 4.14, 7.32, 8.39, 16.20, 20.61, 0.00	0.00, 4.14, 7.32, 8.39, 11.82, 20.61, 23.64
2	**A** [T] → **B** [T] → **C** [T] → **D** [T→W] → **E**	0.00, 5.01, 8.29, 18.53, 0.00	0.00, 5.01, 8.29, 11.84, 21.71
3	**A** [T] → **I** [T] → **J** [T] → **K** [T→W] → **L** [W] → **E**	0.00, 6.11, 10.41, 16.84, 21.24, 0.00	0.00, 4.11, 10.41, 13.84, 21.24, 24.28
4	**A** [T] → **B** [T] → **G** [T] → **H** [T→W] → **E**	2.01, 9.41, 12.73, 20.44, 0.00	0.00, 7.03, 12.73, 17.44, 23.64
5	**A** [T] → **F** [T] → **G** [T] → **C** [T] → **D** [T→W] → **E**	2.01, 6.15, 9.33, 11.35, 17.90, 0.00	0.00, 6.15, 9.33, 11.35, 14.90, 21.08
6	**A** [W] → **I** [REST W] → **J** [REST W] → **K** [REST W] → **H** [W] → **E**	0.00, 7.22, 13.26, 18.29, 21.07, 0.00	0.00, 4.82, 12.26, 17.29, 21.07, 24.28

Table 28: Convoy paths for configuration 4 for 13 lightbrig

I.2 Scenario 2

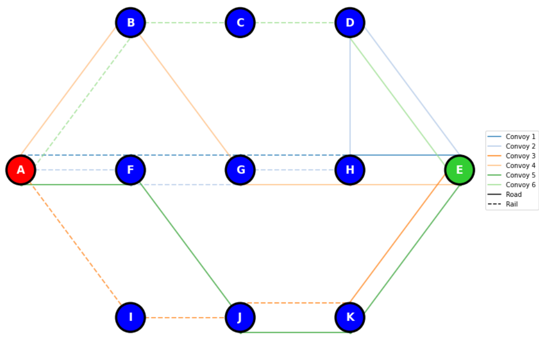

Figure 33: Convoy visualisation for configuration 4 for 43 mechbrig

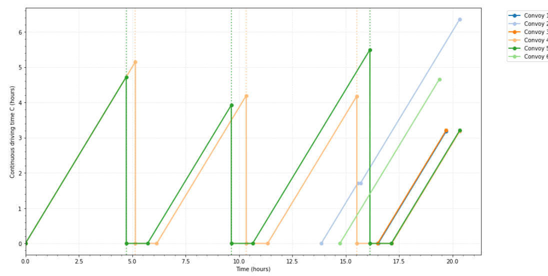

Figure 34: Continuous driving time on road for configuration 4 for 43 mechbrig

Convoy	Path [mode]	Departure (h)	Arrival (h)
1	**A** [T] → **F** [T] → **G** [T] → **H** [T→W] → **E**	2.01, 6.04, 9.98, 16.53, 0.00	0.00, 6.04, 9.32, 13.53, 19.71
2	**A** [T] → **F** [T] → **G** [T] → **H** [T→W] → **D** [W] → **E**	0.00, 4.03, 7.30, 13.86, 15.69, 0.00	0.00, 4.03, 7.30, 10.86, 15.56, 20.34
3	**A** [T] → **I** [T] → **J** [T] → **K** [T→W] → **E**	0.00, 4.86, 8.04, 16.50, 0.00	0.00, 4.86, 8.04, 12.74, 19.71
4	**A** [W] → **B** [REST W] → **G** [REST W] → **H** [REST W] → **E**	0.00, 6.15, 11.34, 17.16, 0.00	0.00, 5.15, 10.34, 15.52, 20.34
5	**A** [W] → **F** [REST W] → **J** [REST W] → **K** [REST W] → **E**	0.00, 5.72, 10.64, 17.14, 0.00	0.00, 4.72, 9.64, 16.14, 20.34
6	**A** [T] → **B** [T] → **C** [T] → **D** [T→W] → **E**	0.00, 4.40, 9.54, 14.73, 0.00	0.00, 4.40, 9.54, 11.73, 19.38

Table 29: Convoy paths for configuration 4 for 43 mechbrig

Configuration 5 — J

J.1 Scenario 1

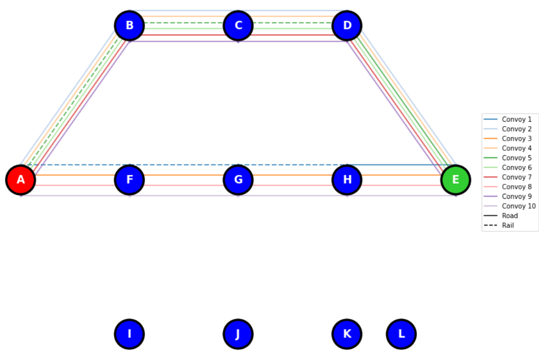

Figure 35: Convoy visualisation for configuration 5 for 13 lightbrig

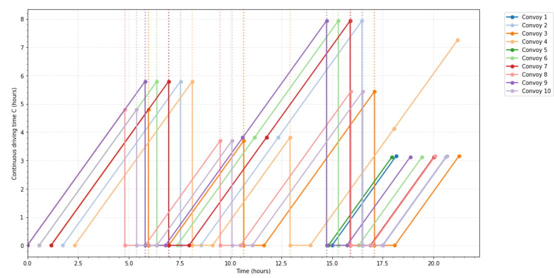

Figure 36: Continuous driving time on road for configuration 5 for 13 lightbrig

Convoy	Path [mode]	Departure (h)	Arrival (h)
1	**A** [T] → **F** [T] → **G** [T] → **H** [T→W] → **E**	0.00, 4.13, 7.31, 15.00, 0.00	0.00, 4.13, 7.31, 12.00, 18.15
2	**A** [W] → **B** [REST W] → **C** [W] → **D** [REST W] → **E**	1.74, 8.54, 12.35, 17.47, 0.00	0.00, 7.54, 12.35, 16.47, 20.60
3	**A** [W] → **F** [REST W] → **G** [REST W] → **H** [REST W] → **E**	1.16, 6.96, 11.65, 18.09, 0.00	0.00, 5.96, 10.65, 17.09, 21.25
4	**A** [W] → **B** [REST W] → **C** [REST W] → **D** [W] → **E**	2.33, 9.12, 13.93, 18.06, 0.00	0.00, 8.12, 12.93, 18.06, 21.18
5	**A** [T] → **B** [T] → **C** [T] → **D** [T→W] → **E**	0.00, 5.01, 8.28, 14.83, 0.00	0.00, 5.01, 8.28, 11.83, 17.95
6	**A** [W] → **B** [REST W] → **C** [W] → **D** [REST W] → **E**	0.58, 7.38, 11.19, 16.31, 0.00	0.00, 6.38, 11.19, 15.31, 19.44
7	**A** [W] → **B** [REST W] → **C** [W] → **D** [REST W] → **E**	1.16, 7.96, 11.77, 16.89, 0.00	0.00, 6.96, 11.77, 15.89, 20.02
8	**A** [W] → **F** [REST W] → **G** [REST W] → **H** [REST W] → **E**	0.00, 5.80, 10.49, 16.93, 0.00	0.00, 4.80, 9.49, 15.93, 20.08
9	**A** [W] → **B** [REST W] → **C** [W] → **D** [REST W] → **E**	0.00, 6.80, 10.61, 15.73, 0.00	0.00, 5.80, 10.61, 14.73, 18.85
10	**A** [W] → **F** [REST W] → **G** [REST W] → **H** [REST W] → **E**	0.58, 6.38, 11.07, 17.51, 0.00	0.00, 5.38, 10.07, 16.51, 20.66

Table 30: Convoy paths for configuration 5 for 13 lightbrig

J.2 Scenario 2

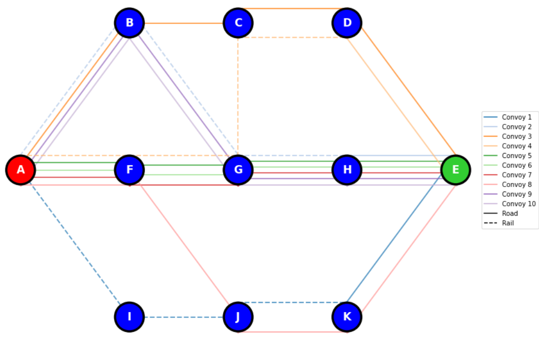

Figure 37: Convoy visualisation for configuration 5 for 43 mechbrig

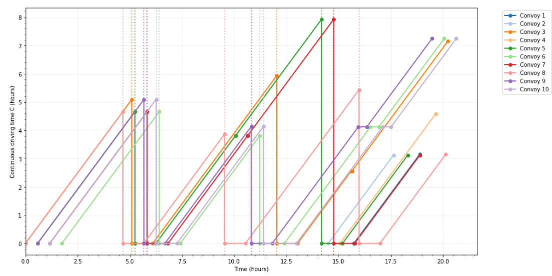

Figure 38: Continuous driving time on road for configuration 5 for 43 mechbrig

Convoy	Path [mode]	Departure (h)	Arrival (h)
1	**A** [T] → **I** [T] → **J** [T] → **K** [T→W] → **E**	0.00, 4.86, 8.03, 15.73, 0.00	0.00, 4.86, 8.03, 12.73, 18.88
2	**A** [T] → **B** [T] → **G** [T] → **H** [T→W] → **E**	0.00, 4.40, 7.96, 14.50, 0.00	0.00, 4.40, 7.96, 11.50, 17.63
3	**A** [W] → **B** [REST W] → **C** [REST W] → **D** [W] → **E**	0.00, 6.10, 13.03, 15.64, 0.00	0.00, 5.10, 12.03, 15.60, 20.24
4	**A** [T] → **F** [T] → **G** [T] → **C** [T] → **D** [T→W] → **E**	0.00, 4.02, 7.29, 9.88, 15.06, 0.00	0.00, 4.02, 7.29, 9.88, 12.06, 19.66
5	**A** [W] → **F** [REST W] → **G** [W] → **H** [REST W] → **E**	0.58, 6.25, 10.06, 15.18, 0.00	0.00, 5.25, 10.06, 14.18, 18.31
6	**A** [W] → **F** [REST W] → **G** [REST W] → **H** [W] → **E**	1.74, 7.41, 12.40, 16.93, 0.00	0.00, 6.41, 11.22, 16.52, 20.05
7	**A** [W] → **F** [REST W] → **G** [W] → **H** [REST W] → **E**	1.16, 6.83, 10.64, 15.76, 0.00	0.00, 5.83, 10.64, 14.76, 18.89
8	**A** [W] → **F** [REST W] → **J** [REST W] → **K** [REST W] → **E**	0.00, 5.67, 10.53, 16.97, 0.00	0.00, 4.67, 9.53, 15.97, 20.13
9	**A** [W] → **B** [REST W] → **G** [REST W] → **H** [W] → **E**	0.58, 6.68, 11.82, 16.35, 0.00	0.00, 5.68, 10.82, 15.94, 19.47
10	**A** [W] → **B** [REST W] → **G** [REST W] → **H** [W] → **E**	1.16, 7.26, 12.98, 17.51, 0.00	0.00, 6.26, 11.40, 17.10, 20.63

Table 31: Convoy paths for configuration 5 for 43 mechbrig

Arc lengths K

K.1 Scenario 1 (13 lightbrig)

	Arc	Distance (km)
MSR 1:	Oirschot–Hannover	400
	Hannover–Potsdam	261
	Potsdam–Poznan	283
	Poznan–Lodz	213, total: 1157
MSR 2:	Oirschot–Kassel	330
	Kassel–Leipzig	253
	Leipzig–Wroclaw	375
	Wroclaw–Lodz	215, total: 1173
MSR 3:	Oirschot–Gießen	328
	Gießen–Chemnitz	343
	Chemnitz–Hradec	273
	Hradec–Katowice	299
	Katowice–Lodz	203, total: 1446
One way vertical arcs:	Gießen–Kassel	126
	Leipzig–Potsdam	160
	Leipzig–Chemnitz	85
	Hradec–Wroclaw	185
Two way vertical arcs:	Hannover–Kassel	166
	Poznan–Wroclaw	183
Diagonal arcs:	Hannover–Leipzig	265

Table 32: Overview of all arc lengths for scenario 1

K.2 Scenario 2 (43 mechbrig)

	Arc	**Distance (km)**
MSR 1:	Havelte–Hamburg	351
	Hamburg–Szczecin	410
	Szczecin–Pila	174
	Pila–Lodz	316, total: 1251
MSR 2:	Havelte–Hannover	321
	Hannover–Potsdam	261
	Potsdam–Poznan	283
	Poznan–Lodz	213, total: 1078
MSR 3:	Havelte–Kassel	388
	Kassel–Leipzig	253
	Leipzig–Wroclaw	375
	Wroclaw–Lodz	215, total: 1231
One way vertical arcs:	Potsdam–Szczecin	206
	Leipzig–Potsdam	160
Two way vertical arcs:	Pila–Poznan	110
	Poznan–Wroclaw	183
Diagonal arcs:	Hamburg–Potsdam	284
	Hannover–Leipzig	265

Table 33: Overview of all arc lengths for scenario 2