MSC THESIS

The efficiency of ground forces following Network Centric Warfare characteristics in the urban region of The Hague: An ABM study in GAMA

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ABSTRACT

Principles of Network Centric Warfare (NCW) have proven to be more effective than the application of Platform Centric Warfare (PCW) principles in warfare. Network Centric Warfare creates its advantage by gaining a technological, structural and organisational advantage. Because warfare is known to be a complex system, it is difficult to predict the future status of the battlespace. Therefore, it is relevant to investigate the concept of NCW to be well prepared when it is put to practice. Essential for simulating this concept of warfare is the acquisition of knowledge through experience by practicing the NCW principles in real-life scenarios. Agent Based Modelling (ABM) is one of the ways to simulate these real-life scenario, which will be the analysis method in this research. Both PCW and NCW are programmed in the ABM software GAMA to create empirical data about the differences between the PCW and NCW doctrine. These differences are grounded by literature and expert advice to create the behavioural rule set for every agent and scenario. The empirical data is acquired from 6 different scenarios that are written as outputs from the simulations. The indicators for mission success in this research are: (1) mission duration and (2)casualty rate per simulation. The results of the analysis is that scenario 6: Combination is the most favourable in terms of mission success, whereas scenario 4: Group-size is the least favourable. There is room for extra and more efficient coding for further research. However, this research serves as a basis to possible further research that focus more on impact of the destruction of roads or line of sight for example.

ABBREVIATIONS

Command and control	C2
System of systems	SoS
Network Centric Warfare	NCW
Platform Centric Warfare	PCW
Situation Awareness	SA
Self-synchronization	SS
Agent-Based Modelling	ABM
Line of Sight	LoS
Complex Adaptive Systems	CAS
High-Value Target	HVT

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1 INTRODUCTION

1.1 Context

In the past decades, there has been a ‘revolution in military affairs’ in military tactics (Bousquet, 2017; Phister et al., 2004; Yang, 2004). This ‘revolution in military affairs’ means the need of armies to improve with the help of technology or change of doctrine (Burmaoglu & Sarıtas, 2017; Dillon, 2002). This revolution meant an increased role of networked military units, by sharing information, understanding and knowledge of the battlespace (Yang, 2004). Considering the military as an interdependent system that operates in a constantly changing environment has become more important as well (Dillon, 2002)**.** Sharing knowledge between war fighters and creating situation awareness in the battlespace is meant to gain advantage over the enemy (Gherman, 2010). Relying on the added value of networked war fighters to achieve intelligence advantage is in line with the principle of Network-Centric Warfare, or NCW (Moon et al., 2010). This new way of thinking is to be considered as revolutionizing as the new mass conscription laws during the Napoleonic era in the end of the 18th century (Alberts et al., 2000a; Wesensten et al., 2005a).

Figure 1: The idea of PCW where three aircrafts form a formation (Anand et al., 2011, p. 899)

Formerly, orders were based on the concepts of the traditional principle of Platform Centric Warfare (PCW). This concept embodies doctrines based on large formations of ground, air or naval units performing a mission (Figure 1) (Dillon, 2002)**.** These formations used tactics and performed missions scaled to the extent of the technological capabilities of those times (Anand et al., 2011). Doctrines of PCW are more focused on the power of the weapon (platform) and the resulting damage to the enemy unit from this weapon (Anand, 2011; Dillon, 2002). In addition to this viewpoint is the hierarchical status of information flow from the command centre to the units (Alberts et al., 2003). Typical for the PCW approach is that any communication for tactics is originating from high command via direct communication and hierarchical flow of command (Lee et al., 2018). The result is a relatively large force of army, naval or land units that follow initially and robust orders from before the initiation of the mission (Anand et al., 2011).

However, the Network-Centric Warfare concept is based on linking nodes in a network with the use of electronics. These electronics empower the military with e.g. reconnaissance, tactics, computing, scenario prediction (Anand et al., 2011) and the increased use of communication technologies (Kang et al., 2015). Armies that are calibrated by PCW principles have less advantages from these linked nodes due to their technological and network capabilities (Gherman, 2010).

One example of NCW warfare in practice is the 'Operation Iraqi Freedom' or OIF from 2003 till 2011. In this operation, information advantage was created by sharing information on all levels of command. This resulted in a shared knowledge environment in which operations from friendly and enemy forces were collected and shared efficiently (Hill et al., 2004).

Another example of the collaboration between sensors and jets is an operation in which jets were taking out Surface-to-air missile (SAM). If jets would simply patrol to spot them, SAM sites operators would go into hiding because they say the jets coming. This leads to virtually no successful missions. However, if jets were linked with sensors, such as radar, sonar and drones, jets could react faster and inflict more focused damage to SAM sites before hostile operators could react (Alberts et al., 2000a; Pushkar, 1998).

Concludingly, there is a change of doctrine in the past years that focuses more on connections between different types of war fighters and the importance of information sharing. This concept has been put into practice in the mentioned cases, but more experience can to be gained on this relatively new way of warfare. Especially the urban areas are prone to the uncertainties that are paired with warfare (Riper, 1997).

1.2 Relevance and research question

As the viewpoints of military affairs are evolving (Bousquet, 2017; Phister et al., 2004; Yang, 2004), it is important to understand the nature of this new way of thinking. This evolved way of thinking is known as the Network Centric Warfare principle. One of the principles on which the NCW doctrine is built is the situation awareness of the engaged forces (Endsley & Jones, 1997; Oxenham et al., 2006; Salmon et al., 2017).

Misunderstanding whether an army unit is friendly or hostile, can lead to preventing undesirable situations, as discussed by Salmon et al. (2017). This literature discusses a scenario in which a friendly tank unknowingly targets another friendly tank unit, thinking it was hostile. This resulted in casualties which could have been avoided if the engaging tank was more aware of its surroundings. This example might be extreme, but it shows the results of inadequate 'situation awareness' in already dangerous battlespaces.

Especially urban areas can be a challenge for the operational efficiency of war fighters. Junctions, vertical and horizontal dimensions of cities and the changing environment due to collapsing buildings are important instigators of this increased challenge (Riper, 1997b). In addition to these challenges is the nature of urban operations, which are based on attrition and close combat conflicts. These intense forms of fighting result in losses in military and civilian personnel alike. These ways do no longer fit in the mind-set that is set in the modern ways of warfare (Riper, 1997b) in which avoiding casualties is set as a priority. Not only are the PCW doctrines no longer in line with our ideals, they have proven to be less effective than NCW in battlespace (Bolia & Nelson, 2007; Ceruti, 2001; Dillon, 2002; Guha, 2022; Lee et al., 2018; Porche et al., 2007; Porter, 2004; Pushkar, 1998; Yang, 2004). Because the NCW doctrine will replace the PCW doctrine, it is important to create an understanding of Network Centric Warfare.

Warfare in general is known to be influenced by characteristics of *complexity*. One of the characteristics of *complexity* is its unpredictability. (Kang et al., 2018; Marshall, 1999; Moffat, 2010; Yang et al., 2008) and uncertainty of future statuses of actors in the system (Holland, 1997, 2014a; Mitchell, 2009). This uncertainty is seen as a problem when planning an operation (Wesensten et al., 2005b). To tackle this uncertainty, it could be advantageous to get an understanding of complexity in relation to warfare.

One of the ways to gain more insights about this complexity (thus the uncertainty of warfare) is to perform ABM simulations. (Macal & North, 2010; Porche et al., 2007; Thompson & Morris-King, 2018; Vaněk et al., 2013). This method is frequently used and trustworthy way to explore behavioural movements (Batty & Jiang, 1999; Connors et al., 2016; Crino, 2001; Hill et al., 2004; Seo et al., 2014; Thompson & Morris-King, 2018). ABM's enable the programmer to write sets of rules for individual agents, by which they behave and adapt to a changing complex environment (Holland, 1997). By programming agents according to NCW and PCW principles, it will become clear how these two approaches differ in efficiency. Indicators such as mission duration and casualty rate play an important factor in determining the efficiency of a mission.

ABM simulation for scenarios creates unique outcomes, which are not easily applicable to other fields of research (Balci, 1994a). Because the nature of ABM is so unique, already existing empirical data is difficult to use as validation for new research (Klügl, 2008). The environmental research area however, is becoming more and more prominent in the future. Because the world is urbanizing and more and more people will live in cities in the future, it is important to get an idea of how ground forces operate in urban environments when following NCW principles (Riper, 1997b). Especially urban operations are difficult to analyse, as urban warfare is more complex than rural warfare (Crino, 2001). Gaining ideas of how NCW ground forces operate in urban areas is therefore important now but will be even more important in the future.

The nature of complex systems like warfare (Johnson, 2021; Moffat, 2010), the unique nature and the applicability of ABM's (Balci, 1994b; Klügl, 2008; Macal & North, 2010) and the urbanisation of the world (Crino, 2001; Riper, 1997b) leads to the following research question:

To what extent can the efficiency of NCW and PCW managed ground forces be measured with 2D simulation, and what behavioural ruleset fits NCW and PCW principles?

1.3 Sub-questions and research approach

The research question is divided by four sub-questions that will each discuss different aspects of the research question. These sub questions are as follows:

1. What are the main differences between NCW and PCW principles?
2. How can NCW an PCW principles be translated into programming language and which characteristics should be implemented?
3. How applicable is the GAMA software with simulating a complex system such as NCW and PCW.
4. What outputs are to be selected from the simulation to analyse possible patterns and relations between scenarios?

The first sub-question can be answered by reviewing literature that covers these aspects. Literature about the processes of NCW and PCW have been read to understand the processes behind Network Centric Warfare and how it differs from the Platform Centric Warfare variant. Further details of these processes are discussed in chapter 2.

Then, sub-question 2 will focus on the methods and operationalization choices that are to be made to correctly link literary statements with the behaviour of the agents in the simulation. This behaviour is transformed into lines of code that are written in the language GAML in the software GAMA (Grignard et al., 2013; Taillandier et al., 2019). More information about GAMA is provided in section 3.3. Sub-question 2 also entails the experimentation of different sets of rules to discover patterns. The experimentation phase makes sure that the model is validated towards reality. Further details about the operationalisation and methodology are discussed in chapter 3.

Sub-question 3 will be built upon the experiences that were gained during the research. This research will focus on the applicability of GAMA software for complex systems that occur in the battlespace. This sub-question will be answered by checking whether GAMA can simulate the necessary aspects that are important for a realistic battlespace.

Literature and expert advice have been used to answer sub-question 4. These indicators will be extracted from the output from analysis and quantitative analysis is performed to prove relations between scenarios. The results from this analysis will help answer the main research question in terms of validity of the research.

1.4 Research Scope

As this research only focuses on the movement of NCW and PCW agents in urban areas, battlespace efficiency in rural areas is excluded from the research. This choice has been made because a wider scope would lead to more complicated relations within the model, which are already extensive as it is. If rural areas are to be implemented, then agents should have different rule sets for rural and urban. Environments differ significantly between rural and urban battlespaces. Therefore, agents should behave differently as well. To prevent a scope in which the research environment is too big, it is decided to only research urban regions.

The research has been conducted from halfway September 2022 to the end of May 2023. This limited time requires a well-defined scope to ascertain focus during the research. Actors that were not within scope are discussed in the Discussion in more detail.

Concludingly, this research serves as a concept of how complexity in warfare situations can be simulated. The applicability of the software GAMA has been taken into account for simulating NCW principles in an ABM environment. The results from these simulations should serve as an introduction of applying the GAMA software to NCW concepts with this particular software. These results could then be used in further research as a basis to start from.

1.5 Reading guide

At first, literature resolving around *complexity*, NCW and ABM is discussed in chapter 2. The operationalization of the agents' attributes will be based on the literary statements in this chapter.

The methodology, including the operationalization, is described in chapter 3. Aspects as agent attributes, environment- and scenario setting and operationalization are discussed in this chapter as well.

Then, chapter 4 will be discussing the results, which are followed by the discussion in chapter 5 and a conclusion in chapter 6. The literature references and appendices are at the end of this thesis as the final chapters.

2 THEORETICAL FRAMEWORK

As the complexity theory is linked to NCW principles, it shall be discussed at the beginning of this chapter (Johnson, 2021; Marshall, 1999; Moffat, 2010). This elaboration includes the theories of *emergence*, *network-thinking*, and *adaptation* within systems. Because NCW principles are principles of complexity, understanding these aspects is vital for understanding the problem at hand.

Then, the complexity theory is applied to the NCW principle. This entails the literary discussion of command and control (C2) situation awareness (SA) self-synchronization and speed of command. Complexity in warfare is reoccurring in these concepts of warfare, which is why these are discussed in the NCW theorization.

After discussing the theory of complexity and the role of complexity in NCW, the measures to practice and simulate it are discussed with theory about Agent-Based Modelling (ABM). ABM is a valid method to measure complex systems in warfare (Borgonovo et al., 2022; Ceruti, 2001; Cil & Mala, 2010; Connors et al., 2016; Grignard et al., 2013; Hill et al., 2004; Lee et al., 2018; Macal & North, 2010; Vaněk et al., 2013; Yang et al., 2008), so it is important for the research to address the theory behind ABM. The opportunities and limitations of ABM simulation and NCW combined are discussed as well, exploring the abilities of ABM with NCW programmed agents.

Finally, some relevant literature about NCW and ABM modelling is discussed at the end of this chapter. The way the theoretical framework is built up in shown in a schema in figure 2 to create an overview of the structure of this thesis.

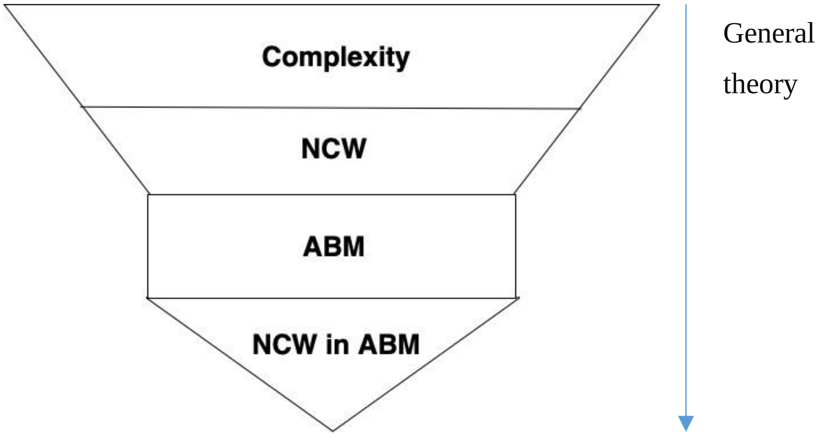


Figure 2: Conceptual framework of the literary framework

2.1 Complexity

First, let's discuss the meaning of the word *complexity*. Work from Mitchell and Holland is frequently cited by literature used in this research. Therefore, literature from these two authors will be the base of the major statements of complexity. As this term is widely discussed by scholars (Bailey, 2004; Bolia & Nelson, 2007; Dillon, 2002; Holland, 1997, 2014a; Johnson, 2021; Kang et al., 2018; Mitchell, 2009; Moffat, 2010; Pushkar, 1998; Yang, 2004; Yang et al., 2008), there is no clear theory of complexity. So, some general statements will be quoted to gain a general understanding of the concept complexity.

Literature by Holland (1997, 2014) describes complexity as nodes that interact within a system with each other and with the environment to react on gained information. Another explanation of complexity theory is the theorization of complex systems by Mitchell (2009): "… [complex systems] seek to explain how large numbers of relatively simple entities organize themselves, without the benefit of any central controller, into a collective whole that creates patterns, uses information, and, in some cases evolves and learns".

Moffat (2010) describes it as: "Complexity is associated with the intricate intertwining or inter-connectivity of elements within a system and between a system and its environment". This basically means that entities in a system communicate with each other and that these entities gain information from these interactions. These theories have in common that entities in systems communicate with and learn from each other.

Although complex systems vary in detail, they generally overlap in terms of the following three properties (Mitchell, 2009):

1. **Complex collective behaviour**: the collective actions of individual entities cause the system to gain complexity. These entities follow simple rules, without direct control from a controller. However, the individual actions from entities cause a complex collective behaviour when seen as a whole. An example of a complex collective behaviour is the collaboration of army ants in the amazon rainforest (Holland, 2014a), as seen in figure 3 (next page).

Figure 3: Army ants showing complex collective behaviour

2. **Signalling and information processing**: Entities in a system operate with and send out signals retrieved from both internal as external structures. An internal structure is the set of rules that an entity follows and external structures are interactions between agents and with the environment.
3. **Adaptation:** Entities adapt to their environment when circumstances change. This ability to adapt increases survivability by learning and processing information. This is partly achieved by gaining situation awareness, which will be discussed later in section 2.2.5.

2.1.1 Network thinking

Network thinking focuses on the relationships that entities have with each other instead of the individual characteristics of each entity (Mitchell, 2009). Essentially, a network is a group of 'nodes' that are connected with links. Although systems may have the same number of entities, the system that shares more information between the entities is more complex due to this interaction. In real life, the distance of these networks can vary, as some nodes do not have the same connections as others. An example of network thinking is the idea that two random people in the world are only 6 connections parted from each other. For instance, the reader of this thesis can get into contact with the president of the United States. And this connection is possible with only 6 links (Holland, 2014a).

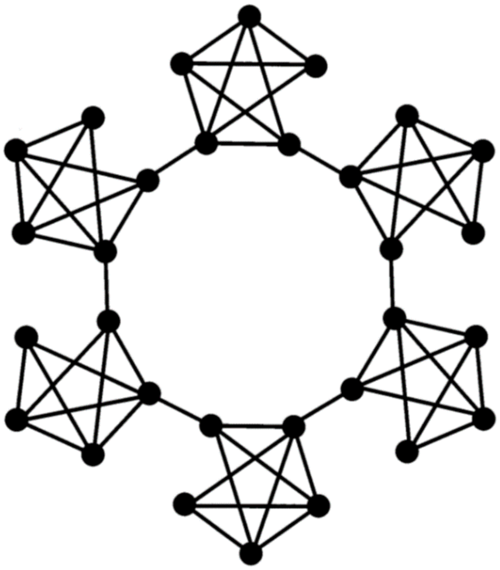


Figure 4: Small-world principle (source: ResULTS Project. < https://upland-resilience.org/small-world-networks-theoretical-framework-for-the-results-project/>)

2.1.2 Small-world principle

Nodes with the same characteristics and high likelihood are clustered together because their intensity of mutual information sharing is higher than with nodes outside of this cluster(Holland, 2014b). This saves energy and is more sustainable than if all nodes relate to each other. Examples of a network that has a small-world property is the brain, in which likewise neurons are connected with each other in clustered groups. Adding few long-distance between hubs in the clusters ensures that each neuron is, someway, connected to each other (Mitchell, 2009). A simplified visualization is shown in figure 4. Here it shows that hubs are connected to each other by only a few nodes, which are in their turn connected to a cluster of nodes with similar nature. This method of networking has proven to be preserving energy, as most communication between nodes occurs between closely related nodes. This network thinking is related to Boyd's OODA loop (Boyd, 2020; Revay et al., 2017), which will be discussed in section 2.2.8.

Before mentioned programmed properties of agents leads to adapted behaviour (Kang et al., 2018). This evolved behaviour or property of agents is the result of something called *emergence.*

2.1.3 Emergence

The emergence of properties in a system and *complex adaptive systems* (Section 2.1.4) are closely related. First, it is important to discuss the principle of *emergence.* Emergence is identified as the principle that the whole is more than just a sum of the parts (Holland, 2014a). It is the result of entities that operate in complex systems (Mitchell, 2009).

An example of emergence is the relation of the molecule H2O and multiple H2O particles. One particle of H2O (part) is not considered as ‘wet’ and does not contain this property by itself. However, the collection of multiple H2O particles (whole) is considered as ‘wet’, even though the single particle (part) did not contain the property of ‘wetness’ on its own. This new property emerged by summing the parts into a whole (Holland, 2014a). Another example of emergent properties and behaviour is the bridge of army ants shown in figure 3. Ants are not capable of forming these bridges themselves, but can create bridges between leaves by interaction. The emergent behaviour, in this example, is the building of a bridge by a group of ants.

As a war fighter, one must adapt to changing environments due to unexpected emerging properties in the network. However, these war fighters have been instructed with orders from command that are based on information before the start of the operation. These agents are consequently expected to adapt to this change. High levels of adaptation in complex system is to be referred as a *complex adaptive system*, or *CAS*. These CAS are systems in which environments can adjust to emergent properties as the system develops (Moffat, 2010). The fact that the system can adjust on its own accord means that agents in these systems must be able to do this as well.

2.1.4 Complex Adaptive Systems (CAS)

Considering emergence and adaptation in modelling overlaps with the field of *CAS* (Holland, 1997; Johnson, 2021; Kang et al., 2018; Mitchell, 2009; Yang et al., 2008), because emergence is the result of adaptation in the CAS. CAS cover elements that are open to alterations by adaption to input by external influence. This type of system is generated by the intrinsic rule set of its agents. This means that CAS are formed by interactions between the agents and their behaviour. However, these rules allow the agent to alter their behaviour, by adapting to external input. For example, car drivers may determine that their initial way home is not the best solution anymore, due to increasing traffic. Because the car driver interacts with its environment, it alters its behaviour. Therefore, the structure and the environment of CAS are determined by the rule set of the agents and its resulting behaviour (Holland, 2014a). Another example of CAS, with more interaction, is the import and export market. Here, sellers alter their prices and buyers determine their willingness to buy, according to market fluctuations. In this scenario, the buyers and the sellers are the agents and the trade market is the environment. (Holland, 2014a).

Agents in a CAS model do not act with full knowledge of how their actions influence future states of the environment (Holland, 2014a). However, high levels of cognitive development and situation awareness of the agents increases this level of knowledge of agents in CAS. This means, that agents with NCW principles can adapt to changes in the environment by themselves and still act according to the goal of the mission. This ability is useful for an agent, as environments in CAS are rapidly changing during simulation (Johnson, 2021). Conducting warfare with NCW principles in mind is therefore less differentiating in the physical domain but more on in the cognitive domain of warfare (Moffat, 2010). More elaboration of the domains of warfare are discussed in section 2.2.4.

2.2 NCW and Complexity

Applying the complexity theory to warfare is broadly discussed in military science (Alberts et al., 2002; Bolia & Nelson, 2007; Ceruti, 2001; Guha, 2022; Kang et al., 2018; Moffat, 2010; Pushkar, 1998; Wesensten et al., 2005; Yang et al., 2008). In a complex system, agents behave according to a set of rules, which are predetermined (Castle & Crooks, 2006). However, these agents are intelligent, for they can adapt to changes in their environment. Their adaptable behaviour will then lead to an undetermined number of futures. These different futures are caused by all the possible interactions that agents can have in complex systems. This means that all the different possible interactions that agents can have will lead to many possible futures states of this agent (Moffat, 2010). As all future states are influenced by the interactions and actions of agents in the present, it is difficult to predict the exact state of the agent in the future.

The ways of waging ware are known to be controlled by uncertainty, due to this unpredictable nature of warfare (Cil & Mala, 2010). As NCW is a relatively new concept, it is important to assess the differences between NCW and the traditional ways of warfare. The implementation of complexity in warfare essentially means that it is riddled with chaos, emergent behaviour, and networks between agents (Alberts et al., 2000a).

2.2.1 NCW

NCW focuses on the connection between sensors, engagement systems and the people in charge of decisions to create a reactive organization. The technological developments in the information age enables war fighters to be connected with friendly war-fighters in the battlefield to increase their battle efficiency (Alberts et al., 2000a). The use of NCW in battlespace increases the speed of command, situation awareness and increases effective information distribution between entities (Yang, 2004). Connecting units in battlespace within a network and pursuing cognitive awareness of war fighters is important for effective NCW practice (Alberts et al., 2000a).

NCW is an approach in the school of warfare that transforms information superiority to combat strength by creating a communication network between well-informed warfare entities in the battlespace (Oxenham et al., 2006). Theory from the complex systems and the understanding of NCW has led to the following six key aspects (Yang, 2004).

1. **Nonlinear interaction**: The results from interaction between nodes can be surprising and unpredictable. The communication between agents might not be as expected, so unexpected interaction can be the result of interaction between agents.

2. **Decentralised control**: Agents can teach themselves new sets of rules, which are caused by decentralised emergent behaviour. This means that agents learn and evolve from each other due to interactions that are not necessarily commanded.
3. **Self-organisation**: Entities can organise themselves without control or advice from external actors in the environment.
4. **Disorderly interactions:** The order of interactions does not always follow the same order, as timing of interactions are unpredictable.
5. **Adaptation**: Interaction with the environment and other nodes can cause a node to adapt to a more favourable position.
6. **Collectivist dynamics**: Interaction between nodes influences the system, which enables continuous feedback loops of past and current feedback. This influences all states of the elements in the system.

2.2.2 Differences NCW and PCW doctrines

One of the concepts that is part of the way of thinking within NCW is the perceptive of ‘system of systems’ (SoS). A ‘system’ is here defined as separate actors that work and communicate together to achieve a common goal. An example is a formation of fighter jets (figure 1) or ground formations. Then, the SoS means that these systems collectively work together to achieve a goal that they cannot attain on their own (Kang et al., 2015). An example of the collaboration with SoS is shown in figure 5, in which the ‘shooter’ communicates with the commander and receives information from sensors about the location of the target.

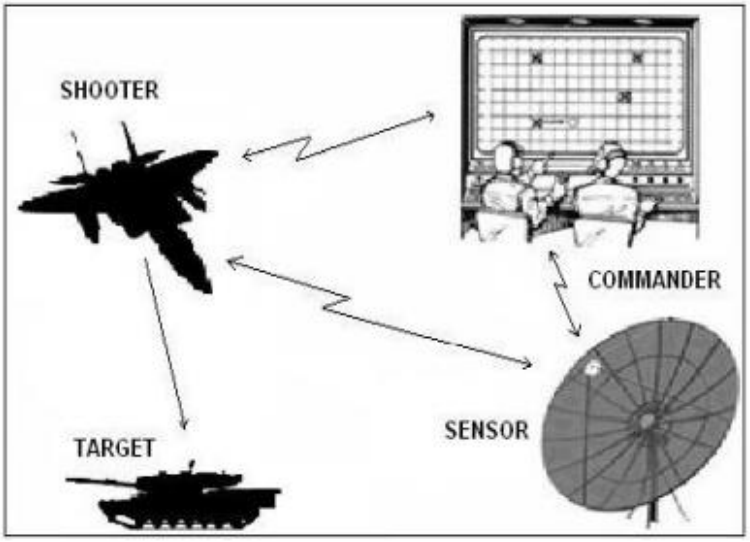


Figure 5: Communication within NCW (Anand et al., 2011, p. 899)

Figure 6 is a result from a naval exercise performed via both PCW and NCW concepts to test the effectiveness of both doctrines (Anand, 2011). PCW principles of warfare are based on the power of a weapon and the damage it does, following doctrines of overwhelming the opponent with firepower (Anand, 2011). The US navy exercised with both NCW and PCW principles, resulting in figure 6. The amount of time necessary to destroy targets is visibly lower for the NCW doctrine compared to the traditional PCW doctrine.

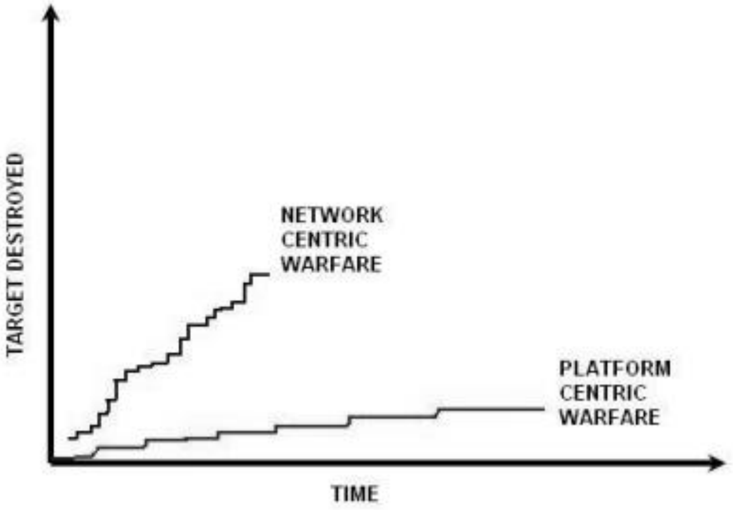


Figure 6: The comparison between PCW and NCW in terms of time/damage efficiency (Anand et al., 2011, p. 899)

2.2.3 Command and Control (C2)

The concept of command and control (later referenced as C2) is the responsibility of a commanding force to organize, direct, coordinate, and control military forces, as well as monitoring the use of resources and taking care of employment. Next to this, C2 takes care of the health as well as the morale, welfare, and discipline of the troops (Alberts et al., 2003). The information in the battlespace network is influenced by the C2 system as well. In C2, the information is created, improved, and then shared to the right person (Yang, 2004). So C2 does not only spread the information, but also monitors the destination of the information. One of the other responsibilities of C2 systems is the preparation of the mission. This includes organizing the administration for a mission, motivating and training the involved individuals and setting up the structures to collect and share information and the organizations that enable communication between agents and organizations (Alberts et al., 2003).

The initial idea of command and control is focused on a top-down hierarchical which is also leading in PCW principles (Alberts et al., 2003). This means that the C2 mechanic is centralized. However, this viewpoint differs heavily from the NCW principle, in which large scale operations are best operated from bottom-up (Pushkar, 1998). NCW principles in perspective to the role of C2 in warfare is shown in the following six statements (Revay et al., 2017):

- Situation awareness (section 2.2.5.) has a central role in C2 systems of the Information Age

- Old hierarchical top-down oriented structures make place for a network in which nodes communicate with fellow war fighters with the same rank.
- Each node in the C2 system is flexible and aims for self-synchronization (section 2.2.6.).
- C2 systems will vary between being centralized and a decentralized approach. The levels of control from the C2 system will thus vary in the information age.
- C2 systems will be iterative in their decision making, as boundaries between operation phases fade.
- Cooperation between knowledgeable nodes is encouraged.

2.2.4 Domains of C2

The span of C2 spreads over four domains: physical, information, cognitive and social:

1. The *physical* domain of C2 is about sensors, platforms, facilities and systems in the battlespace (Alberts et al., 2003). This is where the navy, army or air force operate in terms of strikes, protection and battle movements. Effectivity of operations in the physical domain is measured by survivability and lethality (Yang, 2004).
2. The *information* domain entails the collection, posting, displaying, processing and storing the information from the battlespace (Alberts et al., 2003). The goal of the information domain in NCW principles is to maintain the information advantage over the enemy. This is reached by sharing, accessing and protecting this gained information (Yang, 2004).
3. The third domain is the *cognitive* domain. This domain is all about retrieving knowledge from the information. This domain takes care of what the information states and the meaning of it. Ways of understanding and interpretation are considered when assessing the information, as well as the nature of the information (Alberts et al., 2003). Situation awareness and self-synchronization are two of the many aspects that are created in this domain (Yang, 2004).
4. The fourth domain of C2 is the *social* domain, in which individuals and organizations communicate with each other to establish mutual understanding (Alberts et al., 2003). Improved intelligence can be the result of these communications.

2.2.5 Situation awareness

Situation awareness is the ability of an entity to assess the current state of a situation and reflect it on the initial plans and the possible effect it has on those plans. Then, the entity can react on the changed situation in such a way that its behaviour is still in line with the initial plans. This concept is considered as a central aspect of military command and control systems in the information age (Revay et al., 2017; Salmon et al., 2017).

The degree of situation awareness of NCW oriented troops determines the ability to self-organize and collaborate within a military organization (Yang, 2004). Other important aspects are the use of sensors, self-synchronization, and the understanding among troops of the intent of the operation (Yang, 2004). Entities can gain situation awareness by scanning the environment and integrate this newly gained information with previously gained information (Endsley & Jones, 1997). This newly created knowledge is then used to predict future development of situations and then the entity can react (Salmon et al., 2017). This is all on its own accord, by correctly self-synchronizing with the intentions of the commander.

Gaining situation awareness is described as a 3-leveled process (Endsley & Jones, 1997; Oxenham et al., 2006).

1. Level 1 entails perceiving important changes in the environment. A war fighter must detect important aspects of the battlefield like enemy positions, roads, other friendly war fighters, and other characteristics of the environment.
2. Level 2 then focuses on the relation of those important changes to the goals that the entity has set for itself during the mission. Comprehending the relation between the environment and the goal of the mission is a more complex cognitive step for entities than level 1. The understanding of emergent properties is to be analysed and ranked in importance and severity. A war fighter for example must realize that the emergence of an enemy war fighter and its behaviour has consequences for the actions of itself and friendly war fighters.
3. Understanding whether these consequences need vital changes in future actions is part of level 3 of creating situation awareness. Level 3 of situation awareness is a combination of both level 1 and 2, where the situation is scanned and the dynamics in the environment are properly judged. Then, the entity must act accordingly via acquired knowledge and decide what future state of the environment is caused by its actions in the present (Endsley & Jones, 1997).

2.2.6 Self-synchronization

A key concept of self-synchronization (or self-organization) is the ability of war fighters to organize themselves according to mission plans, even when the initial circumstances change (Costanza, 2003). Adapting to the changing environment by self-synchronizing with the commander's intent, is achieved by a high level of situation awareness (Yang, 2004), elaborate reconnaissance of the environment, understanding of the mission and the entities involved (Costanza, 2003).

The behaviour that results from self-synchronization is related to emergent behaviour (Alberts et al., 2000a, 2003; Costanza, 2003; Holland, 1997, 2014a; Mitchell, 2009; Yang et al., 2008). This behaviour is crucial to achieve a high level of responsiveness and tempo. This way, units can self-synchronize with the intent of the commander and thus decreases time spent on receiving and processing orders. This property results in a faster responsiveness and higher battle efficiency (Alberts et al., 2000a).

Self-synchronization is one of the key concepts the complexity theory (Holland, 1997). A high level of awareness, combined with the rule set that indicates the mission's goal are the two indicators of successful self-synchronization (Costanza, 2003).

Not every aspect of warfare can benefit equally from achieving high levels of self-synchronization. Especially supporting companies can benefit from adopting self-synchronization on the battlefield. Supplying troops beforehand, by predicting the status of supply in battlespaces, increases the battle efficiency compared to supplying them after the support request is made (Alberts et al., 2000a). This self-synchronization of predicting scenarios in future conflicts can increase the acting speed of war fighters (Boyd, 2020).

2.2.7 Speed of command

The speed of command can be characterized as the ability to quickly recognize and comprehend a conflict or scenario, determine which actions are needed with the appropriate material, explore possible options of approach, create a corresponding plan and eventually executing the plan (Alberts et al., 2000a). This line of actions can also be rephrased as orient, observe, decide and act (Boyd, 2020; Revay et al., 2017). Re-planning the initial command takes time, in which combat effectiveness is lost. Reducing this amount of planning time increases combat effectiveness (Wesensten et al., 2005a). Implementing NCW principles in army operations increases the speed of command, which in turn then increases the combat efficiency (Alberts et al., 2000a; Wesensten et al., 2005a). Essentially, the speed of command can be explained through a concept within military science, called the Observe, Orient, Decide and Act (OODA) loop.

2.2.8 OODA loop

A crucial aspect of warfare is to create plans and gain an advantage over the enemy by executing these plans. The process that embodies the execution of plans can be identified as the OODA-loop (Boyd, 2020; Endsley & Jones, 1997; Hill et al., 2004; Revay et al., 2017; Wesensten et al., 2005a). OODA stands for Observe, Orient, Decide and Act and is considered as a looping process. Observation is scanning all perceivable aspects within the area by reconnaissance and intelligence gathering. Then, the observed aspects are to be assessed and selected on value and nature. After the observation, it is time for the decision makers to determine which course of action is to be followed. If everything is set, actions are initiated. This sequentially initiates a new OODA loop by observing the new situation (Endsley & Jones, 1997). In other words, the OODA loop is a way to keep the plans in line with the goal of the mission. The concept of network thinking (section 2.1.1) and the small-world principle (section 2.1.2) are related to a shorter OODA loop as well, as a closely related network leads to a faster OODA loop (Alberts et al., 2003; Boyd, 2020; Revay et al., 2017).

Endsley and Jones (1997) state that the team that pursues the fastest OODA loop can eventually outmanoeuvre the team with the slower OODA. A team is therefore more efficient if it can link with the commander’s intent of the plan, without direct commandments from high command. However, Revay et al. (2017) state that fluctuations between faster and slower acting speed through OODA loops can catch the opponent off guard and by this gain an advantage. Therefore, it is more about control of this loop, rather than simply decreasing the required time, that creates battlefield supremacy over the enemy forces.

The use of this OODA loop has been accepted as a prominent model for military Command and Control (Revay et al., 2017). However, the implementation of NCW in the operational environment influences the nature of the OODA loop significantly. Because situation awareness is increased, enemy targets are recognized faster, which results in less orientation time (Porter, 2004). This means that the implementation of NCW principles in operational environments can influence the speed of command in means of completed cycles in the OODA loop. More so, implementing NCW principles gives the commanding staff the option to efficiently disorient the enemy troops by fully controlling their OODA loop cycle time (Revay et al., 2017).

2.3 ABM

Agent-based models are environments in which interactions can be modelled between autonomously interacting agents. (Macal & North, 2010). The agents evolve and learn by communicating (either interaction of conflict) with each other or with their environment (Holland, 2014a). The way they interact and behave is determined by a set of rules (Thompson & Morris-King, 2018) and is controlled by *detectors* and *effectors*. *Detectors* act as its senses to scan the environment and *effectors* react in the next timestep (Holland, 2014a). The effectors create behaviour that is based on the best option for survivability. This reactive nature results in emergent behaviour and adaptation (Cil & Mala, 2010).

Crucial in ABM theory is the identification of '*lever points'*. These lever points are small changes in the rule set of agents that have long lasting predictable effects (Holland, 2014a). Identifying these lever points during research is crucial for verifying the models.

2.3.1 Characteristics

Agents have a set of essential characteristics that determine their behaviour. These characteristics are discussed by Macal and North (2010) and Brown et al. (2005), which led to the following six statements:

1. Agents are *self-contained* and uniquely identifiable. This means that an agent can decide its actions by itself and can act accordingly on its own. As agents can be programmed uniquely, it enables heterogeneity between agents.
2. Agents are *autonomous* in their decision making. Their pre-determined set of rules gives them the ability to behave on their own without commands from the programmer for each movement.
3. The *states* of agents can be variable over time as they interact with other agents and its environment.
4. Agents *socialize* with other agents due to communications and interactions with each other. They recognize traits and characteristics of each other.

5. One of the other characteristics that fits this research is the ability of agents to behave according to a certain *goal*. Agents can learn from interactions and then behave as is fitting to this goal.

2.3.2 Validation and verification

Using ABM simulation to run simulations of different scenarios is useful as it can be done repetitively with relatively low required processing cost. Complex network connections can be modelled with ABM, as emergent behaviour and adaptability can be considered and measured in ABM simulations (Thompson & Morris-King, 2018).

The *validation* of a model is determined by the degree in which a model accurately displays the study objective (Balci, 1994a) and the system it represents (Ligtenberg et al., 2010). Validating this model to the research objective will be done by comparing the results to statements from literature that support the superiority of NCW over PCW. The *verification* of the model determines whether the model is built as close to realism as possible (Balci, 1994a). However, *verifying* simulations of CAS is a particularly difficult because the outcome of each CAS simulation is different. Therefore, there is no representative unique research that can be used to verify the outcome (Cil & Mala, 2010). Literature by Balci (1994) and Klügl, (2008) describe validation methods that will be researched further to support validation and verification methods.

2.3.3 Limitations

The major limitations of ABM are addressed in the following section (Castle & Crooks, 2006; Choi & Park, 2021):

1. Not every aspect of *social phenomena* can be modelled. Some aspects of society do not lend themselves to be modelled and should be approached differently. For instance, empirical data should not always be addressed with the use of ABM. The researcher should therefore be wary of which domains of science are to be addressed.
2. The researchers should be wary of *stereotyping* agents when programming them (Choi & Park, 2021). Over-stereotyping agents' behaviour due to a too simplistic view of an aspect could lead to poor validation of the model.
3. Researchers should be wary to draw *conclusions* from simulation results from ABM simulation if there is no empirical evidence (Choi & Park, 2021). However, most ABMs are simulating trends that are not already researched into extent. This results in no clear datasets that can be used to validate the output data from the simulations. To solve this lack of validation data, one could make use of sensitivity analysis to test the robustness of the parameters and then show the significance of the parameter in set conditions (Castle & Crooks, 2006).

4. ABMs are built for *specific purposes*, which makes the level of applicability of ABMs for different purposes low. This is caused by the necessity of an ABM to be specifically built to its research purpose.

2.3.4 Research applicability

An interesting thought about the relationship between environmental models and GIS is the nature of the data. Data within environmental models are mostly classified as processes, whereas GIS are mostly data driven (Brown et al., 2005). Therefore, it should be kept in mind how the processes like building status (destroyed or intact) and changing coordinates of ground units can be combined with stationary characteristics within the model (building posistion, defensive positions, infrastructure, etc.). The use of the GAMA software supports interaction between agents and the environment (Abar et al., 2017) taking the different natures of data into account.

As ABM simulations have the advantage of low processing needs, repetitive simulations and outputs can be analysed. Therefore, this methodology is perfect for creating empirical data and exploring processes know in the complexity theory. In the theory of complexity, single entities follow a set of behavioural rules, which evolve and learn by interaction with each other. Simulating their rule set and logging the results of their behaviour could give more insight of the new complex world of NCW principles in practice. The results of the research may be from unpredictable behaviour, but applying ABM simulation to complex systems is not a new practice in science. The following section will elaborate further on previously conducted research in this domain.

2.4 Related research

Modelling and Simulation (M&S) has a significant role in gaining intelligence and preparing ground units and command for the operation (Crino, 2001). It is important for the sake of the research to fill in a research gap in literature. Therefore, extensive literary research is done to make certain that this research fulfils that purpose. The research discussed in coming paragraphs touch upon concepts that are of interest for answering the research questions.

Kang et al. (2018) describes the problem of run time for each simulation for model simulations that resolve around network centric warfare. Here, they emphasise the importance of communication between agents for the effectiveness of NCW. This communication is necessary because the theory of SoS resolves around communication between nodes. This research emphasizes the complexity of simulations that try to entail NCW concepts. which partly relies on communication methodology. Despite the complexity of communication, Kan et al. (2018) did not emphasize the general impact of situation awareness overall.

The research by Hill et al. (2004) simulated the relation between German U-boats and Allied naval bombers in the second world war in the Bay of Biscay. They analysed literature that elaborated on speed for sub-surfaced and surfaced and time to refuel and resupply when back at port. This research served as an experiment whether ABM simulation can be realistic for simulating past scenarios. The result was an ABM that had a high likeliness of complying with combat reports of that time.

Lee et al. (2018) describe the effectiveness of communication whether the unit is in line of sight or out of sight. This is a more technical approach that focusses solely on the actors within communication performance. Issues such as failure of transmitting or receiving the message are mentioned, but also communication repeaters when communication fails to send or be received. Because communication is a vital aspect of the success of NCW, it makes sense that this is discussed elaborately. However, other aspects need to be modelled in this research in a more inclusive simulation to be closer to real-life situations.

Porche at al. (2007) used the MANA (not to be confused with GAMA) model to perform their research, which differs from the model that this research aims to use. Their research revealed that effective communication in terms of delay in messages significantly influenced overall effectiveness. Their research also made use of different scenarios, which tested the overall effectiveness of communication in different scenarios. There, the emphasis was on indirect and direct fire, with the notion of combat casualties at the end of the run. This research will be similar to the one from Porche et al. (2007), except for other implemented parameters such as mission duration, variating situation awareness and the concept of PCW added particularly to the PCW programmed team.

Vaněk et al. (2013) used ABM to assess shipping lanes in waters around Somalia that are known to have piracy. They have created a model called ‘AgentC’, which models activity of trading vessels and proposes counter actions when confronted with pirates. This research identifies vessels as ‘autonomous agents’, that were able to communicate with each other and behave by their own set of rules. The types of agents were merchant, pirate and navy ships. Each of these agents had distinctive parameters set, which determined their behaviour within the model.

2.5 Analysis

The literature in section 2.4 are examples of how the new way of warfare acts in different scenario. Examples of interactions between the U-boats and the naval bombers (Hill et al., 2004) and the communication between pirates, merchant vessels and navy ships around Somalia (Vaněk et al., 2013). These research topics are the example of ABM simulations that are developed for a specific region. These researches are supporting claims of the improved value of NCW practices, but are not capable of validating the results of other ABM simulations.

The addition of this research to existing literature is the quantitative ground of the extent in which NCW and PCW differ in predetermined mission success indicators. The addition of urban areas increases the complexity, but also the relevance of the research (see section 2.2). There is still not enough quantitative knowledge on how NCW forces operate in urban areas and to what extent it differs from PCW forces. This research aims to add in that knowledge gap.

3 METHODOLOGY

3.1 Goal of the ABM model

The model aims to answer the research questions which are stated in sections 1.3 and 1.4. Then, the research questions gave a direction for the literature research in chapter 2. This literature set the basis for understanding the complex adaptive systems, in which NCW principles are situated. The complex principles of NCW are then simulated in an ABM, with the idea to create empirical data. This data covers some aspects of the differences between PCW and NCW behaviour in different scenarios in which attributes vary in value. The data is then analysed to give empirical results regarding battlespace efficiency between NCW and PCW. A small overview of the important steps during the research process are shown in figure 7 as a conceptual model. A more elaborate version of the conceptual model is shown in appendix 1.

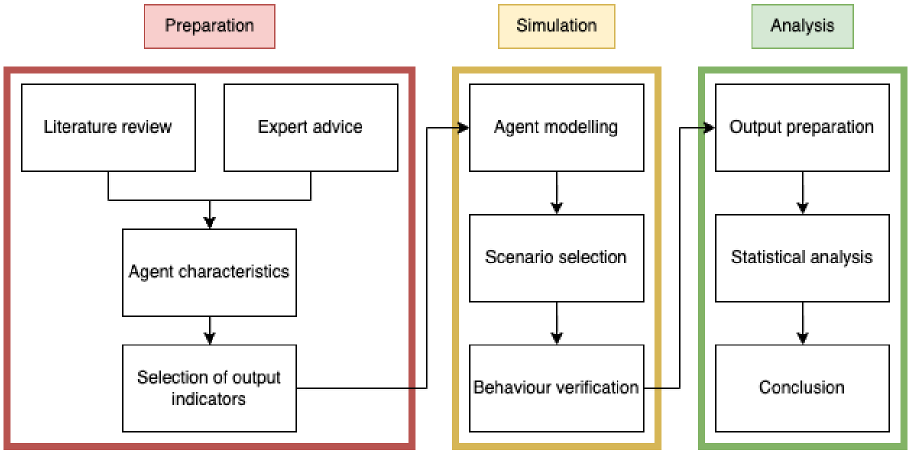


Figure 7: Simplified conceptual model.

3.1.1 Exclusion of aspects

The conceptual model includes only a small aspect of the network that is representing the successful NCW application in this research. Not all aspects could be discussed in this research, as its scope does not reach to this extent. An example of these aspects is the collaboration of army groups with naval and air forces (Hill et al., 2004; Vaněk et al., 2013), including motorized divisions and other aspects of NCW. However, this research does not directly program the effect of air- or naval force intelligence. This means that there are no air force- and vessel agents in the simulation. The Discussion chapter will elaborate further on examples of other aspects of a network that could be included in similar research.

The idea of self-organization, C2, logistics and other advantages for NCW are all included in the SA aspect in this research. According to Revay et al. (2017), Endsley & Jones (1997), the situation awareness is considered to be prominent in information age warfare. As all facets of NCW improve the battlespace efficiency of units, the theory behind these aspects is operationalized as a value of SA in this research. Further on in this research, the mention of SA will refer to the positive results of self-organization, situation awareness itself and collaboration. For instance, intelligence from reconnaissance missions is translated in a higher SA which in its turn translates in a higher manoeuvring speed (Alberts et al., 2003)**.** For further research, the connection and behaviour of naval and air forces in the model could lead to a more realistic and applied research. Other aspects that are assumed or excluded in the research are discussed in section 3.7.

3.2 Environment

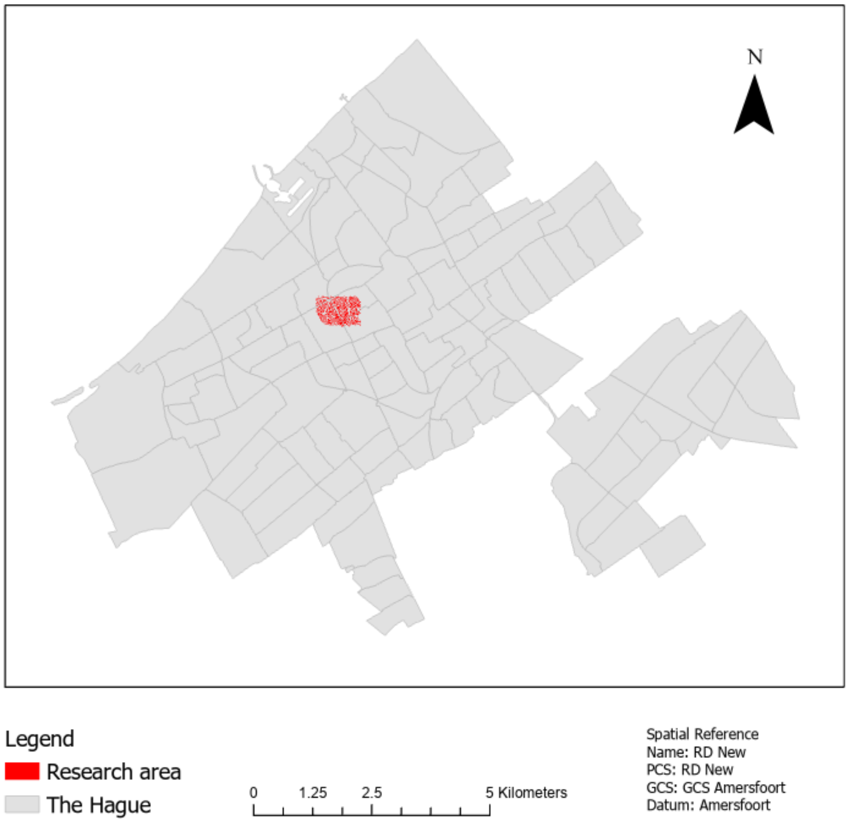


Figure 8: The urban region of The Hague and the research area

The environment is the urban region of the city The Hague (figures 8 and 9). These urban areas are prone to complex and quickly changing situations (Riper, 1997), which adds up to the complexity of warfare. The Hague has been chosen because initial scenarios required stationary targets to defend, for instance the House of Representatives or the International Court of Justice. However, the scenarios setting was no longer

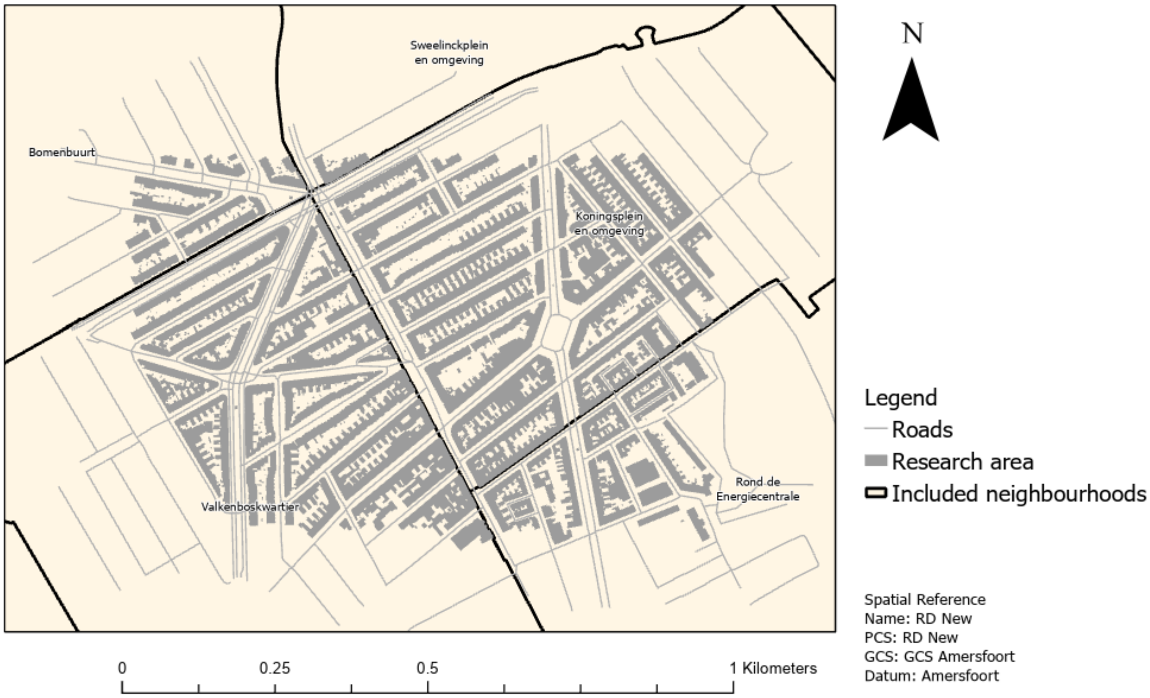


Figure 9: The research area and surrounding neighbourhoods. Source: CBS

focussed on the defence of these stationary targets. The behavioural rule set of the stationary agents would include complicated lines of coding, which were not yet mastered during the research. Therefore, both agents would be programmed to move towards each other. Despite this change of scenarios setting, the urban region of The Hague still remains a valid research area for this thesis, as the challenges of urban warfare are still being faced. More information on the scenarios setting is discussed in section 3.5 and 3.9 later this research.

A larger-scaled visualization of the area is shown in figure 9. Any urban environment can be used, as long as the data preparations described in section 3.4 are followed. Every urban city can be analysed this way if there is a database available that has data files for roads and buildings.

Figure 10: Research area in The Hague in the GAMA environment.

The eventual environment is also loaded in GAMA and is presented in figure 10. This screenshot of the environment in GAMA is showing the X, Y and Z axis in the top left corner. Even though the research area is in 2D, the 3D possibility has been kept during the research. This 3D environment did not increase the runtime of the simulations, so altering this view was not deemed necessary. The yellow coloured buildings in the southwest and the purple coloured buildings in the northeast are both possible starting positions for teams to start in. Teams cannot start in both starting positions in one simulation. The grey buildings are regular buildings that are part of the combat zone. Lastly, the roads are presented in grey as well, which serve as the road network for the agents. More on the preparation of the data is discussed in section 3.4.

3.3 Software

3.3.1 ArcGIS Pro

ArcGIS Pro has been used to conduct the data preparation steps in 3.4. This software could also be replaced by another GI system, as long as the same data preparation steps can be conducted as in this research. ArcGIS pro has been used because of the familiarity with the software. Using this software during the research ensured data quality and efficient time managed due to the skillset of the researcher.

3.3.2 GAMA

The programming software that supports this research is the GAMA Platform **(**(Grignard et al., 2013; Taillandier et al., 2019). As the latest version is still under development, version 1.8.2-RC2 is used. The platform advises this version, since this is the most stable one and less prone to crashes. The software is free to use and has supporting documentation as well (Taillandier et al., 2019). This documentation supports the older version 1.8.1 of the GAMA platform but was still similar to most of the aspects of version 1.8.2-RC2.

All the important aspects of GAMA are discussed in literature by Grignard et al. (2013), but one of the more important aspects are to be discussed in this chapter. GAMA is built up via three major code groupings: 1) global (+' grid'), in which the environments can be set, 2) species, in which the rule sets for different agent types are set; and 3) experiment, in which the outputs and visualization of the analysis are written. An example of the environment of GAMA is shown in every text block in this thesis but also in appendix 2. This appendix shows the complete code for the base model.

The agents and their behaviour are programmed in the GAMA software itself in the programming language GAML (Gama Modelling Language). This language is built especially for GAMA itself (Grignard et al., 2013).

3.3.3 Microsoft Excel

Excel has been used to prepare the extracted data from GAMA for analysis in SPSS. The data has been stripped of unnecessary column names and outputs have been combined into a single 'xslx.' file from Microsoft Excel. This file is transferred to a CSV file and exported to SPSS. The code segment that was used for this step is shown in text block 1.

```
save   (";" + cycle +
       ";" + (pcw_agents mean_of each.pcw_hp) +
       ";" + pcw_num_dead +
       ";" + nb_wounded_pcw_agents +
       ";" + (pcw_agents mean_of each.pcw_sa))
       to: "../CSV/pcw_complex_1.csv" type: "text" rewrite: false;
```

Text block 1: Command to write data as a CSV file

3.3.4 SPSS

The data that has been prepared in Microsoft Excel is put in SPSS to perform quantitative statistical analysis. SPSS is used to detect possible significance between results from the simulations. The results of these analysis has been leading for answering the main research question. More on the results is discussed in chapter 4 of this thesis.

One of the assumptions for this test is that *n* > 30 and that the outcomes are normally divided. The exploration of these assumptions are described in chapter 4. If these assumptions are true, then the Independent-Samples T Test can be performed (De Vocht, 2016). Another way to verify the model is to compare it with other studies that used the same methodology and was in the same context as this research. These studies are yet to be found but can be used for verification if available.

3.4 Data

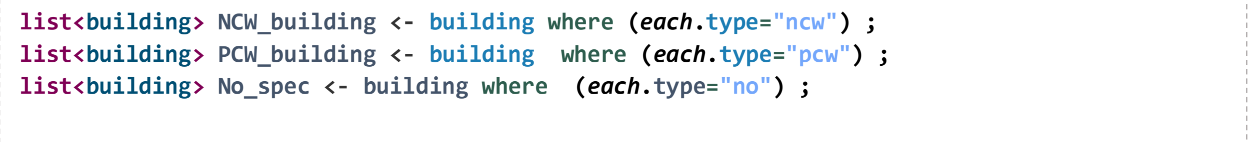
The only external data files are the road network and the buildings, from which the details will be discussed as well. The code is built as such that every urban environment can be used as a research area. This only requires selection of the area you want to use in a GI-system and adjusting the attribute table of the buildings file to create starting positions of the agents. The data preparation steps are described in the following paragraphs.

3.4.1 Roads

The data that is used for the roads is extracted as separate data files, called the 'Nationaal Wegen Bestand (NWB). The owner of the data is PDOK and the file is downloaded from the Rijkswaterstaat. It contains the road network of the Netherlands, with metadata covering the type of road, maximum speed and other attributes. The data is from the 5 December 2022 and was the most updated version when conducting this research. The required section of roads is prepared in ArcgisPRO as a Shapefile. Then, the main road file is clipped to make it possible for agents to enter the road network from any building. It was made sure that every agent could access the road, no matter what starting position they had. This was done by selecting roads that were outside of the buildings that were in this analysis. Because agents were not likely to wander on roads that had no buildings adjacent to them, this added area was not expected to result in validity issues. Figure 9 and 10 partly visualize the addition of extra roads outside the buildings.

3.4.2 Buildings

The data for the buildings originates from the BAG and is owned by PDOK. This version is updated on the 16th of February, 2022, which makes it relatively accurate representation of reality. In this file, three fields were added in the attribute table to determine whether a building is a starting position or not. These fields were "ncw", "pcw" or "no" to determine the starting positions and neutral zones. A fraction of the interaction with this attribute table in GAMA is shown in text block 2 to clarify.

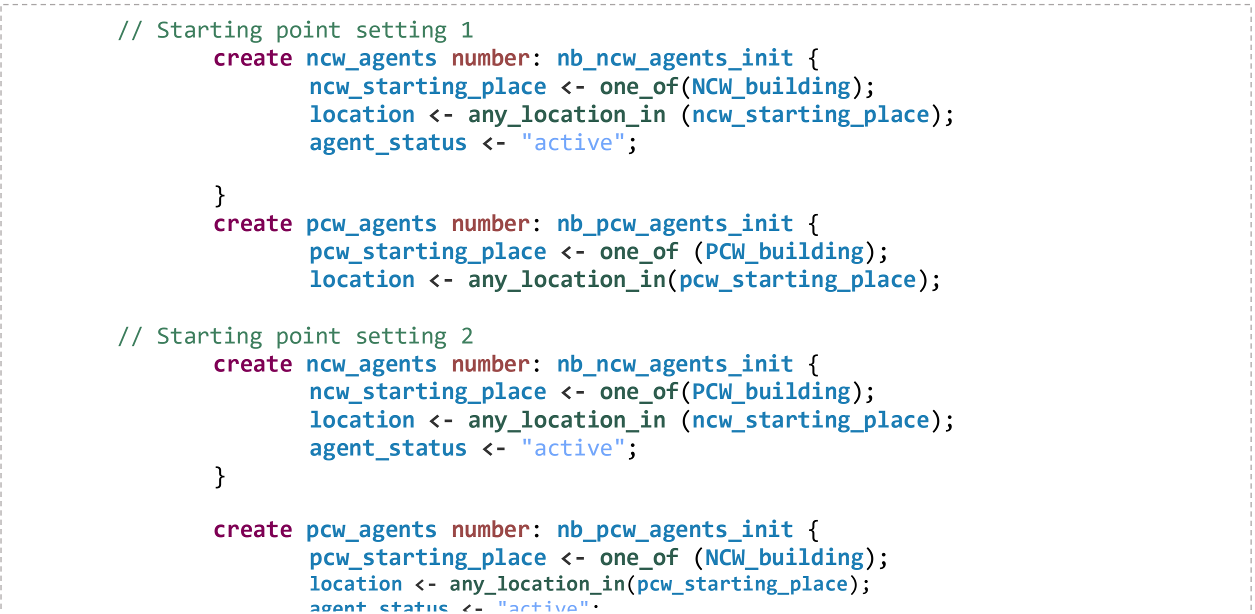


```
list<building> NCW_building <- building where (each.type="ncw") ;
list<building> PCW_building <- building  where (each.type="pcw") ;
list<building> No_spec <- building where  (each.type="no") ;
```

Text block 2: Creation of lists for starting positions

Figure 11: Part of the main display, showing the starting positions and the NCW agents (white pawns) in the south-west of the research area

The fields in text block 2 are used to visualize the buildings in the main display of GAMA (Figure 11) and to set the starting place of the agents (text block 3). The PCW programmed team will be represented by black pawn and the NCW programmed team will be represented as a white pawn. As there is a situational advantage when beginning from the south-western position, the starting positions switch for the second batch of simulations for that scenario. This locational advantage is assumed after verifying the simulation runs. Proof of this advantage is discussed in section 4.2.1. The buildings that were classified as the starting



```
    // Starting point setting 1
        create ncw_agents number: nb_ncw_agents_init {
            ncw_starting_place <- one_of(NCW_building);
            location <- any_location_in (ncw_starting_place);
            agent_status <- "active";

        }
        create pcw_agents number: nb_pcw_agents_init {
            pcw_starting_place <- one_of (PCW_building);
            location <- any_location_in(pcw_starting_place);

    // Starting point setting 2
        create ncw_agents number: nb_ncw_agents_init {
            ncw_starting_place <- one_of(PCW_building);
            location <- any_location_in (ncw_starting_place);
            agent_status <- "active";
        }

        create pcw_agents number: nb_pcw_agents_init {
            pcw_starting_place <- one_of (NCW_building);
            location <- any_location_in(pcw_starting_place);
            agent_status <- "active";
```

Text block 3: Code to set the starting point between sub-scenarios

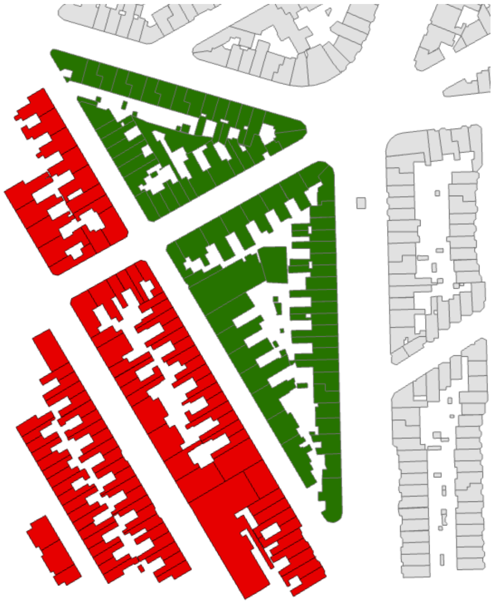


Figure 13: Deleted houses due to error

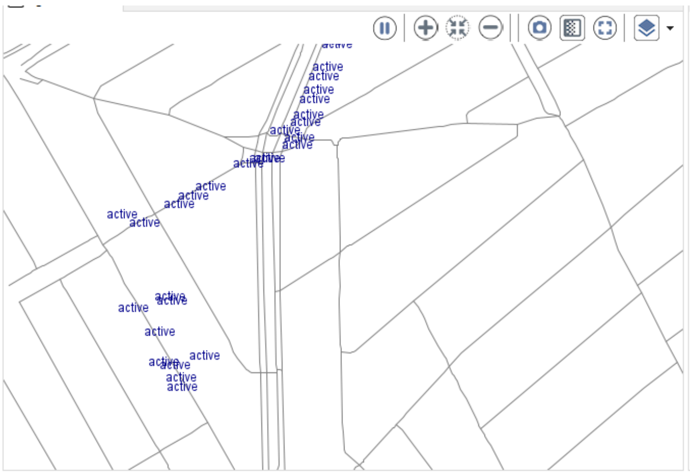


Figure 12: Display used to determine the necessary houses

point for NCW agents are switched in the second scenario. This precaution proved to be right, as is discussed in section 3.9.

One group of buildings has proven to be dysfunctional during the simulation exploration. This building group was in the southwest of the research area and is shown in figure 13 in red. Figure 12 shows that the majority of the agents is travelling along the road, but some of the agents remained in their starting position. This screenshot was taken in the GAMA environment and after some period of time has already past. This resulted in agents that did not participate in the simulation. The moving agents are located one of the main roads in the north-eastern part of the road network in figure 12. The buildings that these docile agents were starting from were therefore eliminated from the area, which solved the malfunction. This deletion has been deemed as not harmful for the validation of the research, as these buildings were on the edge of the research area. It was made sure that these buildings were indeed corrupted by repetitive simulation runs. The red buildings in figure 13 are the buildings that were deleted and the green ones were kept.

3.5 Agents: attributes and operationalization

Table 1: Constant and variable attributes

Constant attributes	**Variable attributes**
HP	SA (Situation Awareness)
Speed	SA decrease
Networked SA	SA waiting time (OODA loop)
	SA update threshold
	SA update
	Distance to reach
	Group size
	Damage per tick

Because this research aims to answer the degree of battlespace efficiency of NCW compared to PCW, the agents are programmed according to these concepts. Characteristics have been assigned to the teams in the form of attributes. These attributes are divided into two types: constant and variable. These two types determine whether a variable change in value between the different scenarios or not. The division of these types is shown in table 1.

The goal of this research is to quantitatively support the claim that NCW programmed forces are more effective than PCW programmed forces. To prove this, the difference between attributes of NCW agents and PCW agents aim to be as realistic as possible. If the values are to be selected based on which attribute has the most impact, then aspects as ‘Distance-to-reach’ and ‘Damage’ would probably come forward as important values. However, this research does not have the goal to determine which combination of aspects is the most ideal. Instead, it aims to simulate the differences between the NCW and PCW doctrine and to which extent these differences create different outcomes between scenarios. Therefore, it is important to use statement in literature and expert consultation to select values for these attributes.

3.5.1 Role of SA

SA is the main indicator of how well an agent can operate flexible to a changing environment. The ability to follow orders via emergent behaviour is key in NCW. As SA is considered a key aspect of NCW, this research will focus on the effects of SA on battlefield efficiency. Other important aspects that are discussed in the theoretical framework in section 2.2 are assumed to be dependent or related to the situation awareness of a unit. Therefore, the SA of a unit is the most leading aspect of NCW in this research and consequently determine the values of the following attributes:

- SA level
- SA decrease (per tick)
- SA update value
- SA update threshold
- SA recovery time (mimicking the OODA loop).
- Movement speed (indirectly, see section 'Speed')

Updating the SA results in the maximum SA per unit. The SA update will be done after the OODA loop has been completed. The period that the unit is dormant embodies the time that units in the field await their instructions or scan their environment. Basically, 'awaiting orders time' relates to the controlled and faster OODA loop that NCW troops are able to. While agents are awaiting orders, they are changing their status from 'active' to 'dormant'. The variables used to embody the principles of SA are in positive relation to the troops that are programmed according to NCW principles. Other agent statuses are also used to program the agents, which can be seen in the basic code in appendix 2. These 'agent status' labels were foremostly used to initiate an action or to check whether lines of code were working.

3.5.2 Variable attributes

The paragraphs 'SA level' to 'Damage' in this section will discuss the difference in value for the attributes between the scenarios. These paragraphs are each supported by a table that explains and highlights the difference. Next to this table, there is the occasional text block that shows the line of code that is related to the attribute. Sometimes a text block is added to provide some insight about how some of the attributes are given form. These pieces of coding are extracted from the model 'Base Model' that is shown in appendix 2. Each time step (or tick) in the simulation is 1 second. Therefore, values for speed and change of values is measured in seconds as well. For instance, the speed is measured in meters per second, as well as 'SA decrease per second'. Every time an attribute is different than the base value, its corresponding value is underlined and in bold font. This distinction via font is used in tables 2 until 6.

3.5.2.1 SA level

Table 2: Values for SA between the scenarios for PCW and NCW

	Min. SA level		**Max. SA level**	
Scenario	**PCW**	**NCW**	**PCW**	**NCW**
1. Reference	0.1	0.1	0.5	0.5
2. SA model	0.1	**0.5**	0.5	**1**
3. Distance-to-reach	0.1	0.1	0.5	0.5
4. Group size	0.1	0.1	0.5	0.5
5. Damage	0.1	0.1	0.5	0.5
6. Combination	0.1	**0.5**	0.5	**1**
Base value	0.1		0.5	
Altered value	**0.5**		**1**	

The SA of agents has been chosen as the main indicator to measure the network of agents. As literature by (Alberts et al., 2000a; Costanza, 2003; Endsley & Jones, 1997; Oxenham et al., 2006) supports the importance of SA, it is used in this research as well.

The differences of SA level are the used to translate the added advantage of using sensors and networking by NCW agents. NCW agents can have a better understanding of the environment when they are using sensors and external communication with command posts. Therefore, these forces have a better understanding of the environment and thus have higher levels of SA. Text block 4 shows the lines of code that determine the SA, with the addition of networked SA. More on the constant variable ‘Networked SA’ in section 3.5.3.3.

```
float ncw_sa_1 <- 0.5 min: 0.1 max: 0.5;
float ncw_sa_2 <- 0.5 update: ncw_sa_1 + ncw_networked_sa min: 0.1 max: 0.5;
```

Text block 4: Networked SA is added to initial SA to create combined SA

3.5.2.2 SA decrease

Table 3: Values for 'SA decrease' between the scenarios for PCW and NCW

	SA decrease (per tick)	
Scenario	**PCW**	**NCW**
1. Reference	0.003/0.004	0.003/0.004
2. SA	0.003/0.004	**0.002/0.003**
3. Distance-to-reach	0.003/0.004	0.003/0.004
4. Group size	0.003/0.004	0.003/0.004
5. Damage	0.003/0.004	0.003/0.004
6. Combination	0.003/0.004	**0.002/0.003**
Base value	0.003/0.004	
Altered value	**0.002/0.003**	

The levels of SA are decreasing as time progresses during combat. Only scenario 2 and 6 have differing values for SA levels. The decrease of the environmental awareness is in line with the uncertainty of combat when battles progresses. Not every assessment of a situation leads to the same amount of SA decrease. For this uncertainty, the base value for the decrease of SA per tick is either 0.002 or 0.003.

After plans are created, unforeseen events will influence the path of the plan. Therefore, the SA level will decrease as time progresses. The variable SA decrease is the only variable that is activated every tick in the simulation. The values for the SA decrease are shown in table 3 and the code is shown in text block 5.

```
reflex sa_decrease when: agent_status = "active" or agent_status = "attacking"{
   ncw_sa <- ncw_sa - ncw_sa_decrease;
   }
```

Text block 5: Code segment used to calculate the SA after SA decrease for each tick

3.5.2.3 SA update

Table 4: Values for 'SA update' between the scenarios for PCW and NCW

	SA update	
Scenario	**PCW**	**NCW**
1. Reference	0.3/0.4	0.3/0.4
2. SA	0.3/0.4	**0.4/0.5**
3. Distance-to-reach	0.3/0.4	0.3/0.4
4. Group size	0.3/0.4	0.3/0.4
5. Damage	0.3/0.4	0.3/0.4
6. Combination	0.3/0.4	**0.4/0.5**
Base value	0.3/0.4	
Altered value	**0.4/0.5**	

The attribute ‘SA update’ embodies the added SA a unit can gain by assessing its situation with the assets it has available. As networked agents have more assets to their disposal, their possible update in SA is higher than that of PCW agents. Therefore, the value for the increased SA for NCW agents is either 0.4 or 0.5 in scenarios ‘SA’ and ‘Complex’, whereas the base value for SA update is either 0.3 or 0.4. The reflex ‘SA update’ will be activated after the agent has finished its ‘SA recovery time’. After this time, the agent’s status will return to ‘active’ and continue with its movement. The code segment used for this action is shown in text block 6.

```
reflex activation when: current_date = ncw_sa_recovery_date and agent_status = "dormant" {
       ncw_sa <- ncw_sa + ncw_sa_update;
       agent_status <- "active";
       speed <- ncw_speed;
       }
```

Text block 6: Calculation of the SA after SA update when the OODA loop is completed

3.5.2.4 SA recovery time (OODA loop)

Table 5: Duration of the OODA loop ('SA recovery time') between the scenarios for PCW and NCW

	SA recovery time (s)	
Scenario	**PCW**	**NCW**
1. Reference	5.0	5.0
2. SA	5.0	**1.0**
3. Distance-to-reach	5.0	5.0
4. Group size	5.0	5.0
5. Damage	5.0	5.0
6. Combined	5.0	**1.0**
Base value	5.0	
Altered value	**1.0**	

The time that is used to perform the OODA loop (see literature in section 2.2.8) is embodied by the attribute ‘SA recovery time’. This attribute will determine the time that an agent needs to update its SA. During this time, an agent adopts the agent status ‘dormant’ and decreases its speed to 0 km/h. This decrease in speed relates to the situation in which a unit will assess their situation and decide what their next course of action will be.

There are two values in which the recovery time can vary among the simulations. For most of the scenarios, there is a recovery time of 5 seconds for units in both teams. Only for the scenarios ‘SA’ and ‘Complex’ there is a 1 second recovery time for NCW programmed troops. This relatively low time to perform the OODA loop is representative for a unit that assesses its environment constantly due to its networked properties (Boyd, 2020; Revay et al., 2017).

3.5.2.5 Distance-to-reach

Table 6: Values for 'Distance-to-reach' between the scenarios for PCW and NCW

	Distance-to-reach (m)	
Scenario	**PCW**	**NCW**
1. Reference	75.0	75.0
2. SA model	75.0	75.0
3. Distance-to-reach	75.0	**100.0**
4. Group size	75.0	75.0
5. Damage	75.0	75.0
6. Combination	75.0	**100.0**
Base value	75.0	
Altered value	**100.0**	

The value for 'Distance-to-reach' is a representation of the distance a unit needs to engage an enemy unit. The basic value is set as 75 meters and value for NCW programmed troops is set as 100 meters. This difference represents the added value of networking with sensors and the result of situation awareness. The added distance of 25 meters also implies the added value of the air force, artillery, drone strikes or other forms of conflict that results from the network between intelligence agencies, units on the ground and other instances of the military (Alberts et al., 2000b; Dillon, 2002).

3.5.2.6 Group size

Table 7: Values for 'Group size' between the scenarios for PCW and NCW

	Group size	
Scenario	**PCW**	**NCW**
1. Reference	20	20
2. SA	20	20
3. Distance-to-reach	20	20
4. Group size	20	**10**
5. Damage	20	20
6. Combination	20	**10**
Base value	20	
Altered value	**10**	

The value for the group size of the units is different for the scenarios 'Group size' and 'Complex'. Literature has suggested that military states that follow PCW doctrines show power in large quantities of one sort of platform (Anand, 2011). To simulate the PCW doctrine, the group size of the PCW group has twice as much as personnel as the 'NCW group'. Another possible disadvantage could be the slower movement of troops with more personnel. However, this aspect of negative influence on the PCW troops is not included in this research. The lower group size is therefore the only advantage that PCW have in this research, apart from the possible slower speed and beginning in the south-western part of the research area (further discussed in section 4.2.1 and shown in figures 12 and 13).

Next to group size difference, there is an assumption based on line of fire that is disadvantageous for NCW troops. Larger groups do not suffer from overcrowding when going into battle. The level of organisation of units that are cramped together does not decrease over time. Therefore, units can stand on the same spot and can engage into conflict with the same damage infliction as all the troops in front of it (see section 3.8). More elaboration on this aspect is described in the discussion chapter.

3.5.2.7 Damage

Table 8: Values for 'Damage' between the scenarios for PCW and NCW

	Damage	
Scenario	**PCW**	**NCW**
1. Reference	0.010	0.010
2. SA	0.010	0.010
3. Distance-to-reach	0.010	0.010
4. Group size	0.010	0.010
5. Damage	0.010	**0.015**
6. Combination	0.010	0.010
Base value	0.010	
Altered value	**0.015**	

The damage per tick is set as an arbitrary value of 0.010 and 0.015. The damage infliction per tick statement will only be activated if a unit from the other team is within the declared 'Distance-to-reach' value that is set for this scenario. If this enemy unit is within reach, the attacking unit will inflict the declared damage to the other unit.

The purpose of this scenario is to analyse a situation in which one group of units can access better weapons than the other team. The result will show to what extent the improvement in one aspect of the army can lead to a higher chance of mission success. The added damage is kept out of the 'Combination' scenario, because NCW principles do not focus around the improvement of damage per platform alone (Anand, 2011).

The damage is programmed as to be 'self-inflicted' when the conditions as met. This way was chosen as it was within the skillset of the researcher. It might not be the most optimal way, but it worked as intended. In the reference model, both teams inflict themselves an equal amount of damage. However, the self-inflicted damage had to be higher for the NCW troops, due to the higher damage infliction possibility of the PCW agents in the 'Damage' model.

```
        reflex damage when: agent_status = "active" or agent_status = "attacking"{
                list<pcw_agents> reachable_pcw <- pcw_agents at_distance
(ncw_distance_to_reach);
                if (! empty(reachable_pcw)){
                        agent_status <- "attacking";
                        speed <- 0.1;
                        ask one_of (reachable_pcw){
                                do damage_pcw;
                                return pcw_hp;
                        }}}
        action damage_pcw {
                pcw_hp <- pcw_hp - pcw_hp_decrease;
                }
```

Text block 7: Activation of the 'damage' reflex,

3.5.3 Constant attributes

Table 9: Values for the constant variables for all scenarios.

Attributes						
Health Points	Speed (km/h)	Networked SA decrease	Networked SA increase	Distance to network (m)	Minimum networked SA	Maximum networked SA
1	2.5 x SA x HP	0.01	0.02	5	0	0.1

This sub-section will discuss the attributes that remain constant over all the scenarios. A structured overview of the values for these constant values is shown in table 9. There are no changes in begin values for these attributes. However, the values among units may differ for these attributes. For instance, every unit has its own value for its Health Points, as this attribute does not decrease in value if one of the other agents engages in conflict. This refers back to the aspect of ABM's, in which agents are self-contained and autonomous (section 2.3.1).

3.5.3.1 Health Points (HP)

As all ground units consist of infantry, the amount of Health Points (further referenced as HP) per unit is similar among the two groups. The decrease in health points simulates the amount of time that a unit can sustain enemy fire before becoming wounded. A ground unit becomes wounded when HP <= 0.3. This condition activates the reflex that initiates the retreat. This retreat will be done by motorized vehicles, instantly when the HP of a unit <= 0.3. When a unit is wounded, it can still be attacked by other teams. However inhumane, this decision tries to simulate the aspect of a unit surrendering. Therefore, the value of terminated units is a collection of deceased units and surrendered units. The segment of coding is show in text block 7.

```
        Reflex retreat when: ncw_hp <= 0.3{
                do goto target: any_location_in (ncw_starting_place) on:road_network;
                agent_status <- "wounded";
        speed <- 2#m / #s;
        }
```

Text block 7: Code segment that regulates the conditions for an agent to retreat.

3.5.3.2 Speed

The calculation by which agents determine their speed is dependent on their health points and their SA during each ‘cycle’. As can be expected, ground forces can move efficiently when they know their surroundings. However, when a ground unit has less awareness of its surroundings, it can be assumed that it should take more time to evaluate the situation before advancing safely.

When a unit misses a part of their team due to conflict, it can move less efficiently compared to when they were on full strength. A unit can receive enemy fire, receive damage, but still be able to continue the mission. These conditions influence the speed by which agents are traveling in this research.

Therefore, the value of HP and SA are taken into account for each turn that a ground unit must determine its speed. Minimum values for speed is 1 meter per second and the maximum value is 2.5 meter per second. As urban environments are a tough environment to be in conflict in (Riper, 1997b), these values are to be believed to be representative for movement in unsure terrain.

So, both the status of SA and HP will determine the speed of the movement. This is shown in text block 9.

```
float ncw_speed <- 2.5 #km/#h update: 2.5  #km/#h * ncw_sa_2 * ncw_hp min: 1.0 #km/#h max:
2.5 #km/#h;
```

Text block 8: Calculation of the speed attribute

3.5.3.3 Networked SA

The addition of networked SA aims to simulate the added value of people communicating via voice command during combat. The reflex to increase SA via networking between agents is activated once friendly agents are located within five meters from each other. For every second that this is the case, the networked SA increases with 0.01. This action repeats itself until there are no friendly agents within five meters or when the maximum of 0.1 increased SA by network is achieved. When no friendly units are within 5 meters, the networked SA is decreasing with 0.1 per tick as long as that condition is true.

The maximum of ‘0.1’ is set to simulate the limited effect this kind of networking has. If no maximum was set, then all agents would have the same SA as fully networked agents, which is unrealistic. This gained ‘networked SA’ is added up to the current SA for every tick that the set conditions are true. The line of code in text block 9 is used to simulate this behaviour.

The result from the segment of coding in text block 9 is shown in figure 15. This figure shows the value in a display of increased networked SA for agents that are equal or less than 5 meters apart from each other. The result is increased networked SA with a minimum of 0 and a maximum of 0.1.

```
        float ncw_networked_sa <- 0.0 min: 0.0 max: 0.1;
        float ncw_networked_sa_increase <- 0.02;
        float ncw_networked_sa_decrease <- 0.01;
        float ncw_sa_1 <- 0.5 min: 0.1 max: 0.5;
        float ncw_sa_2 <- 0.5 update: ncw_sa_1 + ncw_networked_sa min: 0.1 max: 0.5;

        reflex sa_decrease_via_network  {
               ncw_networked_sa <- ncw_networked_sa - ncw_networked_sa_decrease;
               }
        reflex sa_increase_via_network when: agent_status = "active" {
               ask ncw_agents at_distance (10#meter){
                      do ncw_network_sa_increase;
                      }
               }
         action ncw_network_sa_increase {
                      ncw_networked_sa <- ncw_networked_sa + ncw_networked_sa_increase;
               }
```

Text block 9: Calculation of the networked SA attribute

The result the coding in text block 9 is a pattern in which agents situated within 5 meters from each other receive a bonus in SA as time passes. However, when they do not fulfil the set condition, their networked SA will decrease each turn with 0.1. A visualization of this pattern is shown in figure 14. In here, the most eastern units received a relatively big increase in SA due to networking among each other. However, the most southern unit has travelled solitarily, which did not lead to networking with friendly war fighters.

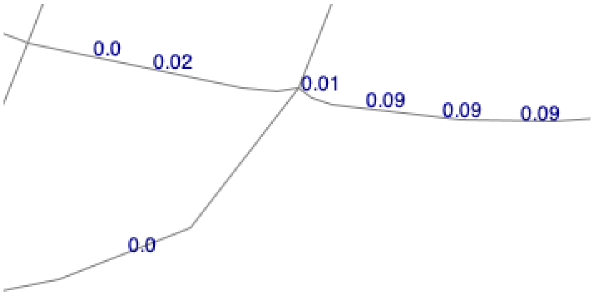


Figure 14: Difference in networked SA between agents

3.6 Interactions

There are different types of interactions that the agents will have in the simulations. During all scenarios, agents will have friendly interactions among teammates and hostile interactions with opposite team members. At first, the agents determine their speed by the level of SA and HP and their networked SA by checking the proximity for friendly agents. Secondly, the interactions will contain calculations for conflict as well, in which both of the teams can be affected. These interactions result in a change of states between at least one of the agents and changes their behaviour. These are considered as to be hostile interactions between the two agent teams.

The different interaction rules and the values for the attributes eventually lead to an order of behaviour that is shown in figure 15. This figure simplifies the steps that an agent will take when different conditions are met. The yellow rounded rectangle represent the actions that an agent will undertake during the simulation. The green diamonds represent the decisions an agent will make based on the programmed behaviour. Finally, the blue rectangle serves as a moderator for the action “Move to target”.

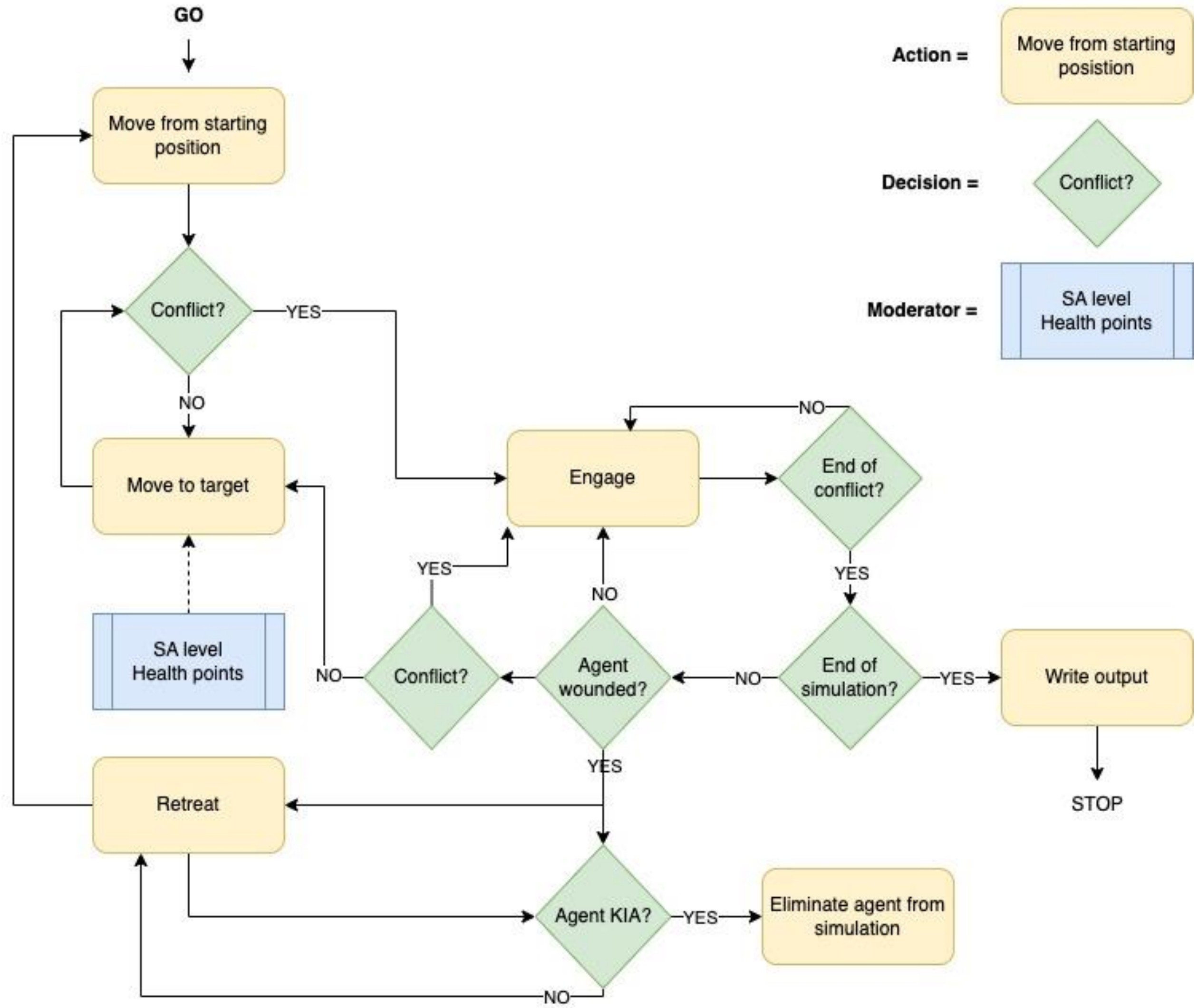


Figure 15: Agent behaviour

3.7 Assumptions

This section discusses the assumptions that are made during the research. Further elaboration of the assumptions is provided in the discussion chapter when deemed necessary.

- Both teams can engage in conflict through buildings.
- The quality of the road network does not influence the speed of the agents.
- The road does not decrease in suitability as conflict occurs on road segments.
- The only participants of the road network are the ground forces.
- The city is considered as neutral. One of the teams does not get advantages or disadvantages from communication or help with inhabitants.
- The speed of agents is determined by the attributes “Health Points” and “SA”. It is assumed speed relies on the amount of casualties that a unit has suffered and knowledge the unit has of its surroundings.
- When an agent is ‘dormant’ its speed is reduced to 0.0 km/h to simulate recalibration time.
- When agents are wounded, they return to their starting point to recover. These are considered to be out of action. These units will be returned by motorized vehicles, which will result in a fast retreat speed.
- Agents are aware of precisely which agent is closest to them.
- Agents are allowed to travel through each other to engage in combat or to retreat.
- Agents will follow the orders from command without questioning.
- Agents do not suffer from clogging effects when there is a high concentration effect. This means that multiple agents can be located on the same location.
- The agents know precisely at what distance they can engage units from the other team.
- Both teams do not prefer to take cover when engaged in conflict. When both teams engage, the usage of cover is not given as an option.

3.8 Model validation and verification

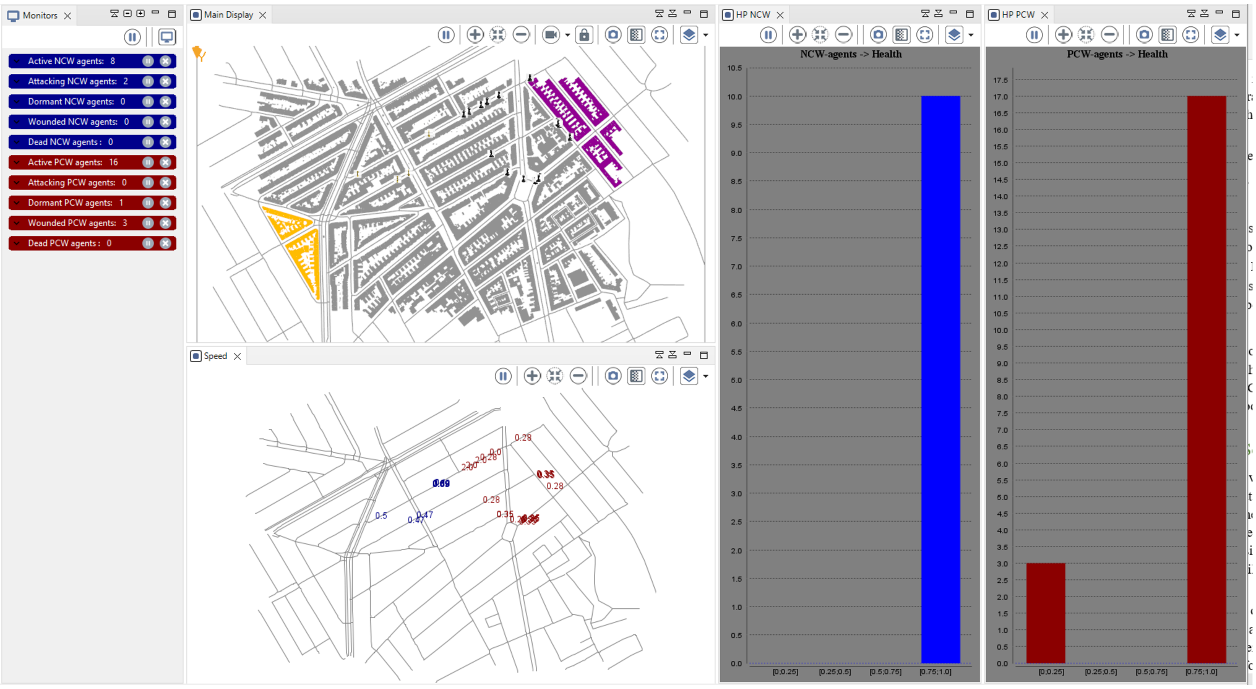
As discussed in section 2.3.2, the *validation* of a model is representative towards the study objective and the *verification* is the degree in which the model represents realistic situations (Balci, 1994a).

The validation of the research will be assessed by comparing literature that discusses NCW and PCW principles to the results from the simulations. First, multiple simulation runs have been set up to the most realistic attribute settings as possible. This is done by trial and error approval to check whether the agents behave logically. In this context, behaving logically means whether the agents follows the rules for their behaviour. Examples of these rules are actions like travelling over the road and engaging in conflict when the code implies. If behavioural rules had to be adjusted in ways that they do not represent NCW or PCW principles, then this will not be done.

The *verification* of the model determines whether the model is built as close to the real world as possible (Balci, 1994a). This will be done by assessing literature and consulting expert advice, but also by analysing the behaviour and results with common sense. To maintain a realistic representation between the values of the attributes, literature discussed in the theoretical framework and expert advice by Ir. Robert Voûte has been considered. The following points were used as focus point to decide whether the simulation is realistic enough:

- Roads are to be followed for agents to reach their destination.
- Agents cannot move through buildings.
- All agents follow the set of defined rules.
- The simulation stops when conditions are met (mission success/failure).

A reliant method that is used to verify the model settings is the use of ‘displays’ in the GAMA environment. These figures show the possibility of GAMA to display the values of attributes while the simulation is running. If changes were made in the code, this display is used to check whether the agents follow the programmed behaviour.



Active NCW agents: 8
Attacking NCW agents: 2
Dormant NCW agents: 0
Wounded NCW agents: 0
Dead NCW agents : 0
Active PCW agents: 16
Attacking PCW agents: 0
Dormant PCW agents: 1
Wounded PCW agents: 3
Dead PCW agents : 0

Figure 16: Overview of possible displays used for model verification.

Examples of these kinds of displays are shown in figure 16. In this figure, the list on the left updates the status of agents each tick for both teams (blue = NCW, red = PCW). The map with the yellow and purple coloured buildings is a visual representation of the code. Then, the map that only shows the roads shows the value for speed for each agent and its current location. For checking whether the HP is being decreased accordingly, the two histograms are set to check the distribution of HP among the different teams.

3.9 Scenarios, models and simulation

This research will be based on 6 scenarios. Each scenario resulted in 2000 simulations. Complex systems are difficult to predict due to the large amount of possible future states of a system (Mitchell, 2009). This large quantity of future states makes it difficult to spot patterns. To be able to draw meaningful conclusions, it was determined to run a relatively large amount of simulations. Additionally, distinctions were made between the simulations, which is discussed in the next section.

Both PCW and NCW teams will engage in the simulation simultaneously. The PCW team will create results starting from the south-western starting point for 500 simulations. After these 500 simulations, the team switches to the north-eastern point, from which they will do 500 simulations as well. This switch was instigated due to the perceived locational advantage between the two starting positions. This locational advantage is proven later on in section (4.2.1).

Combining these 1000 simulations with the 1000 simulation results that the NCW team has collected simultaneously, creates a total of 2000 simulations per scenario. As this research consists of 6 scenarios, a total of 6 x 2000 = 12000 simulations are run to support the research question. Each script from these 12 unique simulations is gathered in one general file. A summarized version of these results in shown in appendix 3.

An elaborate overview of the different values for each scenario is shown in appendix 1. The attributes and its values are shown in tables 2 to 9 in section 3.5. Important to notice is that the values for PCW agents remain the same for every simulation. The only attribute value changes between scenarios that are made are for the NCW programmed troops. The outcome of these scenarios are discussed in the ‘analysis’ chapter and their full documentation is added as a separate file.

3.9.1 Reference model

Scenario 1 is a combination of the simulations from ‘Basic Model 1’ and ‘Basic Model 2’. This scenario served as the reference model for the rest of the models. This means that the results of this model were used to calculate whether there was a significant difference with the other scenarios in this research (scenario 2-6). Every value of each agent is the same, as to simulate a scenario in which no team follows different warfare doctrines.

3.9.2 Themed models

The themed models each aim to discover different outcomes compared to the ‘Reference Model’. These different models are based on attributes of war fighters that were discussed in section 3.5. The goal of scenario 2: ‘SA model’ and scenario 3: ‘Distance-to-reach’ is to analyse whether some aspects of NCW can lead to a successful mission compared to the scenario 1: ‘Reference’. These themed scenarios serve as a check to analyse whether singular aspects of NCW lead to the same result as a combination of these aspects and to what extent this difference is.

3.9.2.1 Scenario 2 & 3: SA and Distance-to-reach

Scenario 2 and 3 focus on aspects that are known to be beneficial for troops following NCW principles. Scenario 2 focuses on the added effect of increased SA for NCW troops. All attributes concerning SA for the NCW units are altered to an extent in which it is beneficial for them. The overview of these differences is to be found in appendix 3. This SA influences the movement speed as well, so the movement speed has also been considered as an aspect in this model.

NCW troops have the network available to call in other aspects of the army. Examples could be a well-coordinated mission-to-fire from aspects outside the battlefield or from within the unit (see section 2.2. These added capabilities of the NCW troops is translated into an increased value for the attribute ‘Distance-to-reach’. This attribute determines the distance a unit can fire from, which is beneficial for the NCW troops in this scenario.

3.9.2.2 Scenario 4: Group size

The group size scenario has been set up to analyse the impact of a reduced group size for NCW troops. This scenario will aim to simulate the situation in which a military unit has tried to follow through NCW principles, but all these actions fail to show in real-time warfare. Examples could be an electromagnetic pulse (EMP) that disables the communication between agents (Wilson, 2008). Another example is using untrained units that are using the high-end technology that is known for NCW warfare. Essentially, this scenario aims to simulate poorly practiced NCW doctrine to an army group, and thus reducing the group size accordingly as well.

The results from this scenario were used to support the importance of well-trained soldiers that are capable of self-organisation and have high levels of SA.

3.9.2.3 Scenario 5: Damage

The ‘Damage’ scenario simulates the probability that an army group has improved its ability to inflict damage to the other team, but did not work on any aspects of the NCW doctrine. Instead, one of the army groups has solely increased the power of the used platform. Examples of this is the use of better weapons, better bullets, etcetera.

The results from this simulation were used to analyse to what extent the sole increase of platform power has. This results in an evaluation whether the mission success between the ‘Reference’ model and the ‘Base model’ differs significantly.

3.9.2.4 Scenario 6: Combination

The ‘Combination’ scenario will be used to assess the difference between fully networked agents and agents following the PCW doctrine. All attributes, except the ‘damage per tick’, attribute differ between the two teams. From them, only the group size is disadvantageous for the NCW group. All aspects concerning SA, and ‘Distance-to-reach’ are in favour for the NCW programmed troops. Only the group size is less for the NCW troops, so this attribute influences the NCW group negatively.

3.10 Model success & Model output

3.10.1 Model success

Indicators for mission success will be 1) mission duration and 2) casualties per run. These two were selected as these supported by literature as indicators of mission success (Alberts et al., 2000b; Pushkina, 2017; Strachan, 2006) and were measurable outputs for an ABM simulation. Implementing other aspects of mission success, such as high-value targets (HVT) and used logistics (Alberts et al., 2000b), might be considered for later research. The exclusions of other indicators of mission success will be discussed in later on in the 'Discussion' chapter.

The mission duration of the 'Reference model' has been compared with the mission duration of the other scenarios via statistical analysis. If the other models differ significantly in mission duration ($p<0.01$), then the mission is deemed successful in terms of duration. This decision has been based on statistical analysis in SPSS (see section 3.4.4)

Secondly, the amount of casualties and current ethical beliefs of ideal warfare were combined in measuring the second success measurement: casualties. As it is preferred to have as less casualties as possible (Alberts et al., 2000b; Pushkina, 2017; Strachan, 2006), the conditions for this type of success are relatively strict. When a scenario run led to <1 casualty per simulation (which is either wounded or KIA) only then is it deemed as successful. This decision is based on the output of the GAMA simulations, which are added as a separate file with this research.

3.10.2 Model output

The output of the model is retrieved by the line of code that is shown in text block 1 and 10. These are the same text blocks, but repeated in this chapter for readability purposes. The same line of code is used to extract the data for the NCW agents as well. The output of the models is the following: Scenario name, Cycle, HP, Wounded, KIA and SA. The output 'Cycle' represents the mission duration in seconds, and the attributes 'Wounded' and 'KIA' per simulation are accumulated as the value 'Casualties' per run.

```
save    (";" + cycle +
        ";" + (pcw_agents mean_of each.pcw_hp) +
        ";" + pcw_num_dead +
        ";" + nb_wounded_pcw_agents +
        ";" + (pcw_agents mean_of each.pcw_sa))
        to: "../CSV/pcw_complex_1.csv" type: "text" rewrite: false;
```

Text block 10: Command to write data as a CSV file

This data is written to an CSV file when the total of wounded and agents KIA of either one of the species is their starting group. So for example, if the PCW group starts with 20 units and eventually 12 PCW agents are wounded and 8 PCW agents KIA, then the total is 12 + 8 = 20. This triggers the reflex that the simulation ends and that the data is written to the assigned CSV file. Then, new simulations start which add up to the already-written data in the same file.

The SA variable will not serve as output that is to be analysed. Nevertheless, it was still exported as possible output for later research purposes or possible useful validation data. The layout of this data is similar to the one shown in table 10. This table shows the output of four simulations in the shape of a CSV. file.

Table 10: Exemplary layout of the simulation outputs as a CSV file

Scenario	Cycle	HP	Wounded	KIA	SA
Reference	2316	0.4665	0	11	0.2537
Reference	2378	0.5185	0	10	0.25505
Reference	2438	0.709473684	1	4	0.320263
Reference	2517	0.453	0	13	0.2983

4 RESULTS & ANALYSIS

This chapter will discuss the results from the analysis described in chapter 3 and is built up according to the two used indicators of mission success (section 3.10). First, the aspect of mission duration is discussed with descriptive statistics and analytical calculations of the simulation data per scenario. For this mission success indicator, the general results are discussed and elaborated into subsections discussing the scenarios. Because the scenarios differ in goal within the research, these cannot be completely covered in a general explanation of the scenarios.

Then, the second indicator of mission success is assessed per scenario as well, with details provided when necessary. This part will cover the descriptive statistics of the casualties for each scenario dataset. Each scenario section includes at least two figures and one table that elaborates further on the descriptive statistics of the simulations.

At the end of the chapter, the two indicators are combined to assess the mission success per scenario. As the mission duration and casualties are considered to be coherent to perceived mission success, these two have to be taken into account equally and coherently when assessing general mission success.

Table 11 explains the references in figures 18 to 30. Abbreviations were used for the data to enable analysis in SPSS. The order of scenarios in this chapter is based on its occurrence in section 3.9.

Abbreviation	**Scenario**
bm	Reference
SA	SA
rd	Distance-to-reach
gs	Group size
dam	Damage
cx	Combination
cx ncw	Combination values for PCW agents
cx pcw	Combination values for PCW agents

Table 11: Abbreviations linked to scenarios.

4.1 Mission duration: data exploration

The mean mission duration in every scenario has led to the bar chart that is shown in figure 17. Descriptive values regarding mission duration are shown in table 12 as well. This tables shows the descriptive statistics of all the scenarios in terms of mission duration. The most important statistic is presented in the column 'Diff. with 'Reference' (%)'. This column shows the mean mission duration difference compared to the 'Reference' scenario in minutes and relative percentage.

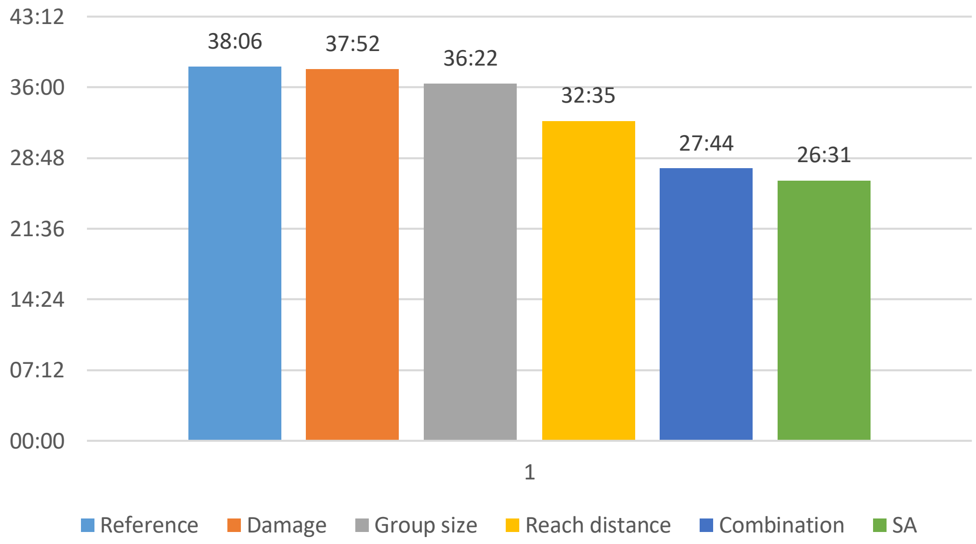


Figure 17: Mean mission duration per scenario (mm:ss)

Table 12: Descriptive statistics for mission duration in every scenario.

Scenario	Mean	Diff. with 'Reference' (%)	Min.	Max.	Std. Deviation
Reference	38:06	n/a	29:05	54:05	02:58
Damage	37:52	00:14 (-0.6)	28:11	1:06:12	03:07
Group size	36:22	01:44 (-4.5)	26:28	45:36	03:43
Distance-to-reach	32:35	05:31 (-14.5)	26:09	45:04	03:25
Combination	27:44	10:22 (-27.2)	20:19	55:08	06:00
SA	26:31	11:35 (-30.4)	20:02	51:34	04:44

At first sight, one can conclude that the ‘Combination’ and ‘SA’ scenarios have a lower mean for mission duration then the other scenarios. The ‘Reference’, ‘Damage’ and ‘Group size’ scenarios have relatively long mission durations compared to the other three scenarios. The standard deviations of the first three scenarios however, are relatively less than that of the two scenarios with the lowest mission duration time. From this statistic, one can conclude that values of mission duration generally differ more in value from the measured mean. The difference in time duration between the ‘Reference’ model and the model with the lowest mission duration is 11 minutes and 35 seconds (SA). The mission duration in the ‘SA’ scenario is 30.4% faster than that of the ‘Reference’ model. Whether the differences are significant or not will be discussed in section 4.2.

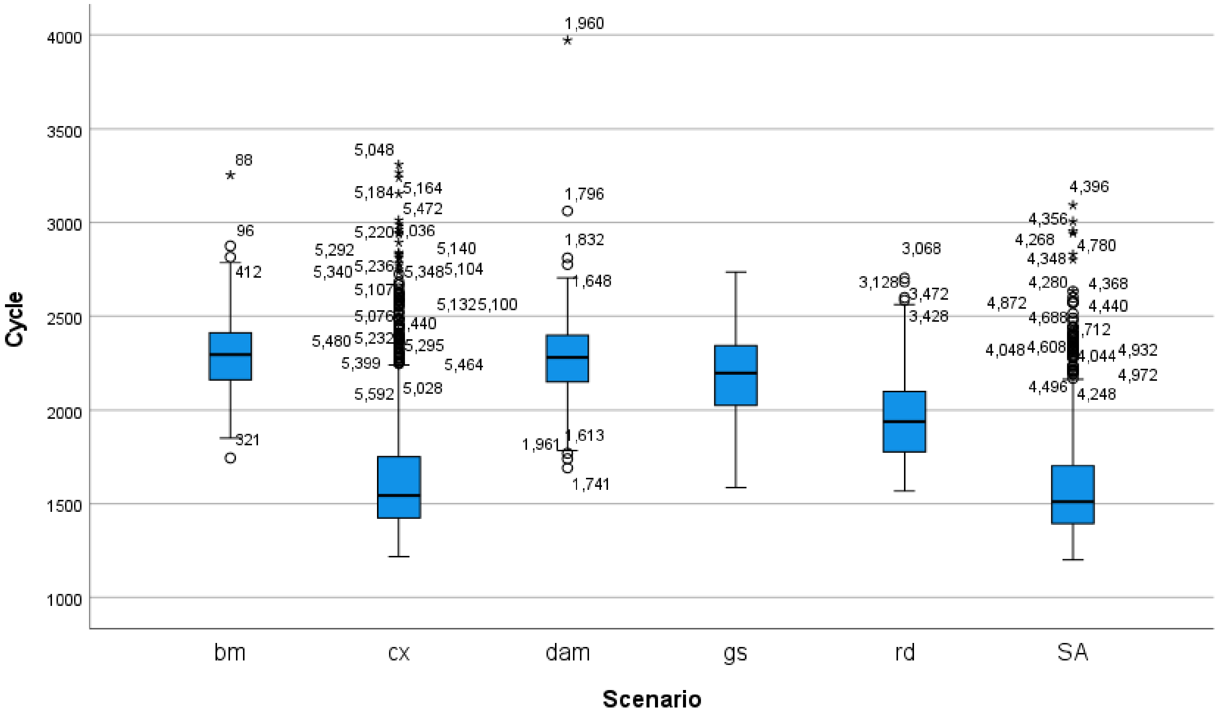


Figure 18: Boxplot of values for mission duration per scenario (1000 simulations per scenario)

The minimum and maximum mission durations for each scenario also show the difference in mission consistency. The minimum and maximum values, together with the standard deviation, give more information about the outliers in the simulations. Outliers shed a light on the consistency in values in a research, which could also be spotted in the values for minimum and maximum value. If the minimum and maximum values are high or low compared to the standard deviation but the mean and the median is similar, then there are relatively few extreme outliers.

The distribution of the outliers and the mission duration values per scenario are shown in figure 18 as a boxplot. This boxplot uses abbreviations that were needed for preparing the settings of the ‘Independent

Samples T-Tests' that is discussed later on (section 4.2). These abbreviations are shown in table 11. The boxplot in figure 18 shows a misleading large number of outliers. This is especially the case for the boxplots for 'Combination' (cx) and 'SA'. However, the IQR for both scenarios are relatively small. A relatively small IQR means that the middle halve of the values are relatively similar in value (De Vocht, 2016). Apart from the small sized boxplots, the amount of outliers has to be considered in relation to the total amount of simulations. As there are 1000 simulations per team per scenario (see section 3.9), 30 outliers per scenario is not leading to unreliable results.

4.1.1 Exploring normality of division

Before performing the Independent Samples T-Tests on the data of the mission duration between scenarios, it is important to explore the data. Exploring the data includes discovering whether the dataset is normally divided or not. Common tests as Kruskal-Wallis and Shapiro Wilk (De Vocht, 2016) are not suitable for data with n>50 and require the datatype to be ordinal. Therefore, the data must be tested and presented as Q-Q plots to test for a normal division of the data (De Vocht, 2016). These Q-Q plots are shown in figure 20, 21, 23, 25, 28 and 30. The blue dots are the mission durations per simulation. The black line is the trend line that shows whether a distribution is normally divided or not. When the blue dots and the black line align, the distribution is normally divided. It is allowed for blue the trendline to differ slightly from the black line. The Y-axis of these Q-Q plots show the expected values of the population when it is normally divided and the X-axis shows the values of mission duration in ordinal sequence.

Next to the Q-Q plots, the data has been visualized as a histogram in figures 19, 22, 24, 26, 27, 29. This visualization aims to show the kurtosis and skewness of the datasets in a different way than the Q-Q plots. Further important information about the datasets is shown in tables 13 to 18 to give additional statistical information.

4.1.1.1 Scenario 1: Reference model

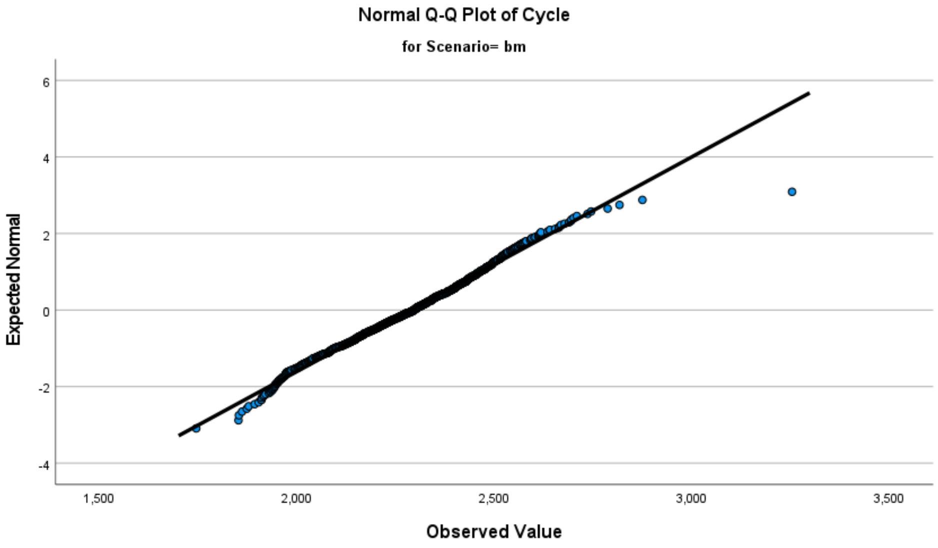


Figure 20: Q-Q plot of the dataset for the 'Reference' model

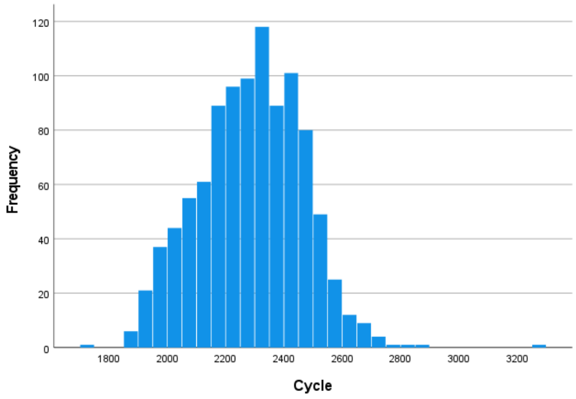


Figure 19: Histogram of the dataset for the 'Reference' model

Table 13: Descriptive statistics of the 'Reference' model

Reference	
Statistics	**Duration (mm:ss)**
Mean	38:06
Minimum	29:05
Maximum	54:05
Skewness	0.077
Kurtosis	0.415

The reference model shows an almost perfectly normally divided dataset, with a skewness of 0.077 (table 13). Figures 19 and 20 show the distribution of the values for mission duration whether they are normally divided or not. As the black line in figure 20 mostly aligns with the observations, it can be assumed that the dataset is normally divided. The observed values are almost perfectly normally divided within the mission duration values of 2000 seconds (33 minutes and 20 seconds) and 2500 seconds (41 minutes and 40 seconds). The observed values before and after this interval are lower than a normally divided dataset would expect.

4.1.1.2 Scenario 2: SA model

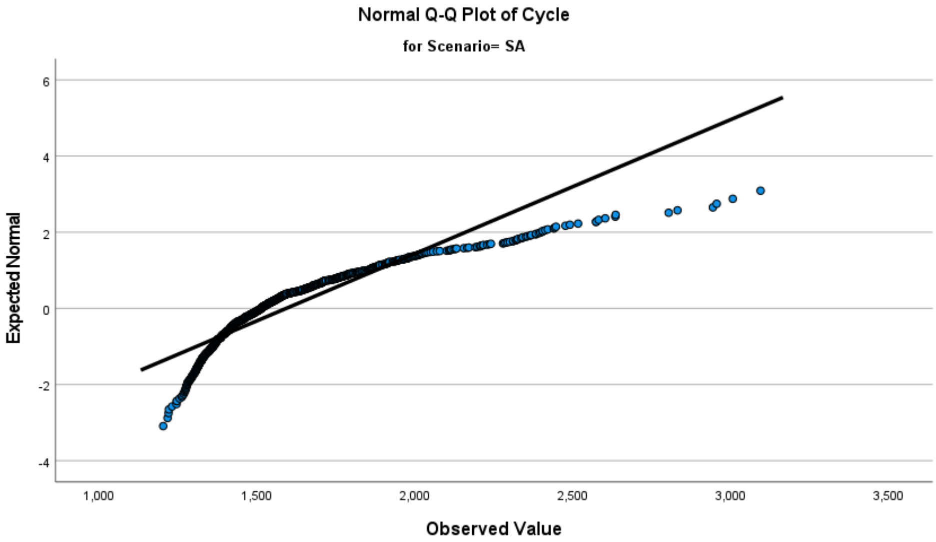


Figure 21: Q-Q plot of the dataset for the 'SA' model

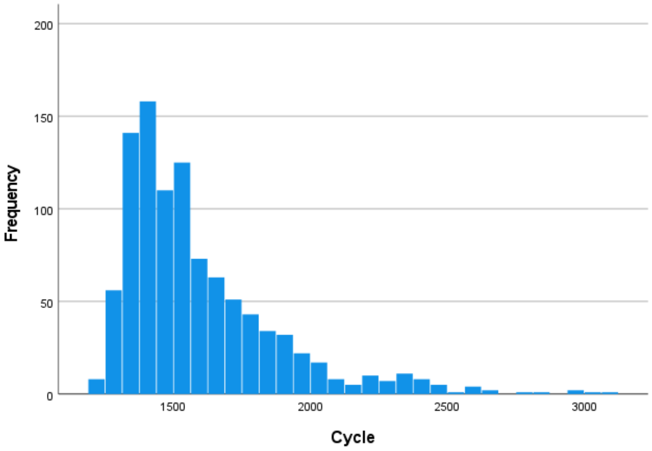


Figure 22: Histogram of the dataset for the 'SA' model

Table 14: Descriptive statistics of the 'SA' model

SA model	
Statistics	**Duration (mm:ss)**
Mean	26:31
Minimum	20:02
Maximum	51:34
Skewness	1.752
Kurtosis	3.847

The data from the 'SA' model shows positively skewed data with a value of 1.752 (table 14). This means that the median is lower than the mean and has therefore no perfect normal division. If a histogram is positively skewed, it means that the majority of the observations for this scenario is lower than the mean duration of the scenario (De Vocht, 2016). The division of the values in term of mission duration are shown in figures 21 and 22. Even though the dataset is not ideally distributed normally, both the histogram and the Q-Q plot show that the dataset is normally divided enough to perform the 'Independent Samples T-Test'. More information on the tests to analyse significant difference is elaborated in section 4.2.

4.1.1.3 Scenario 3: Distance-to-reach

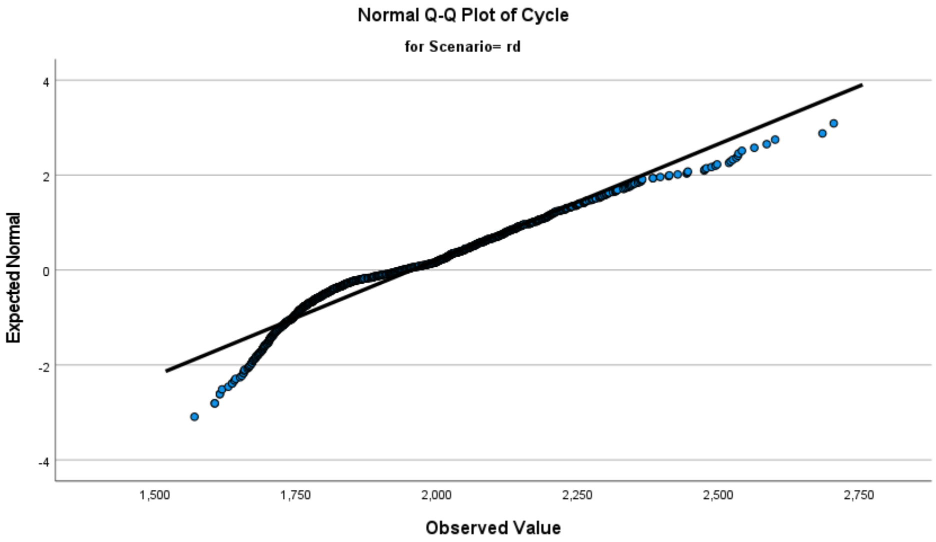


Figure 23: Q-Q plot of the dataset for the 'Distance-to-reach' model

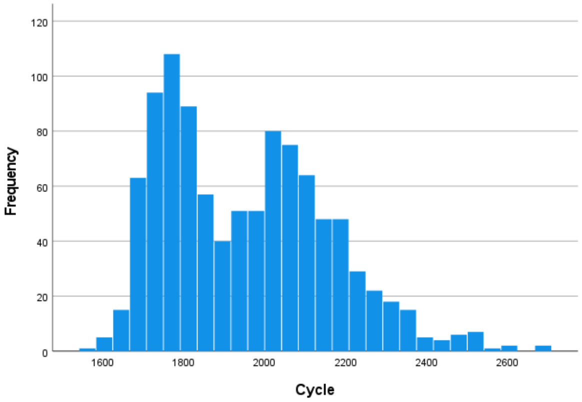


Figure 24: Histogram of the dataset for the ''Distance-to-reach' model

Table 15: Descriptive statistics of the 'Distance-to-reach' model

Distance-to-reach	
Statistics	**Duration (mm:ss)**
Mean	32:35
Minimum	26:09
Maximum	45:04
Skewness	0.584
Kurtosis	-0.176

The dataset for the 'Distance-to-reach' model has a high concentration of simulations with mission durations around the 1700 seconds (28 minutes and 20 seconds) and the 2000 seconds (33 minutes and 20 seconds), as can be seen in figure 24. The reason for this division can be deduced to the locational advantage that teams have while in starting position 1. This locational difference is further discussed in section 3.9 and will be later in this chapter in section 4.3.1.

4.1.1.4 Scenario 4: Group size

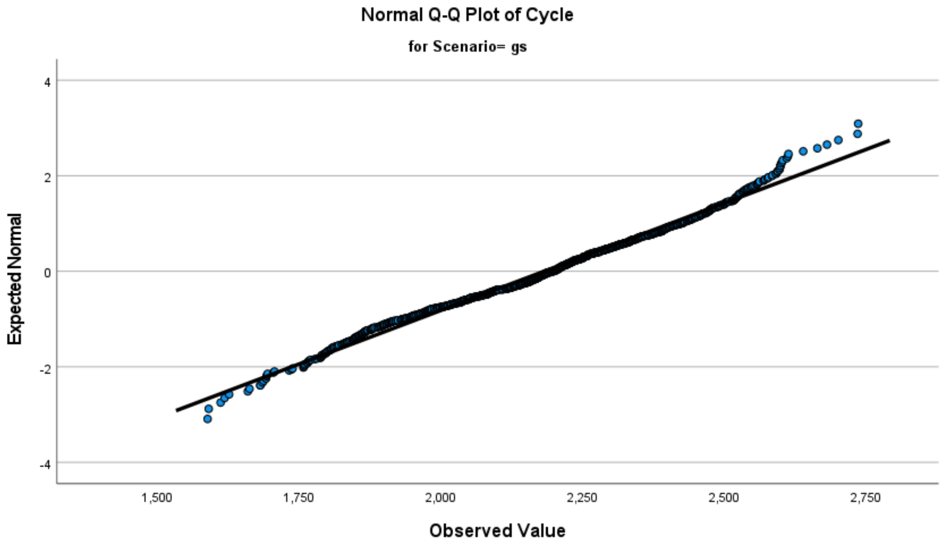


Figure 25: Q-Q plot of the dataset for the 'Group size' model

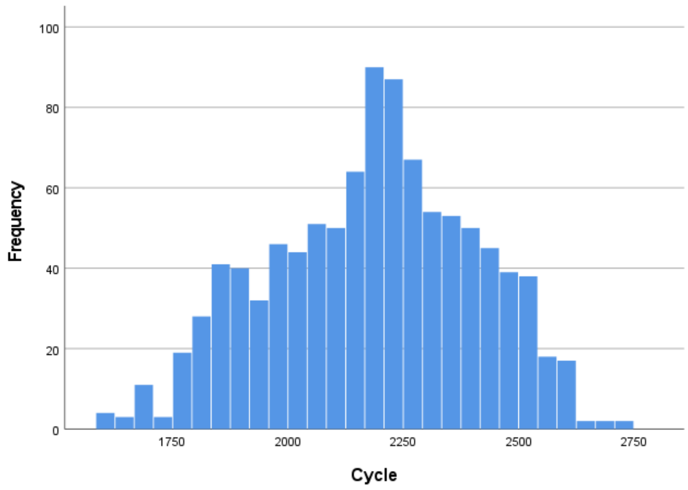


Figure 26: Histogram of the dataset for the 'Group size' model

Table 16: Descriptive statistics of the 'Group size' model

Group size	
Statistics	**Duration (mm:ss)**
Mean	36:22
Minimum	26:28
Maximum	45:36
Skewness	-0.168
Kurtosis	-0.562

The 'Group size' scenario has been chosen as a scenario setting in which the disadvantage of a smaller group is embodied (see section 3.9). Therefore, it is only important to notice whether the dataset is normally divided. The dataset is slightly negatively normally divided, but manageable to perform the analysis. Figure 25 with the Q-Q plot shows a dataset that is generally normally divided. The skewness of the historgram is also relatively normal (-0.168). The negative value for the skewness implies that the median is slightly higher than the mean value of mission duration. However, the value of -0.168 for skewness represents a relatively normally divded dataset. The kurtosis is relatively high, but the Q Q plots shows that the observed values do not differ greatly from the expected valueTherefore, this dataset can be used to calculate significant differences with the 'Reference' model.

4.1.1.5 Scenario 5: Damage

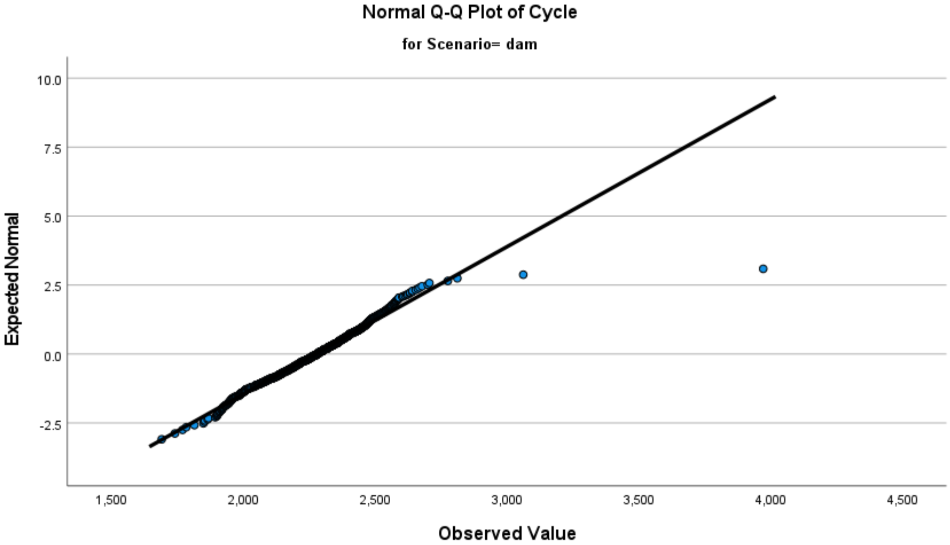


Figure 27: Q-Q plot of the dataset for the 'Damage' model

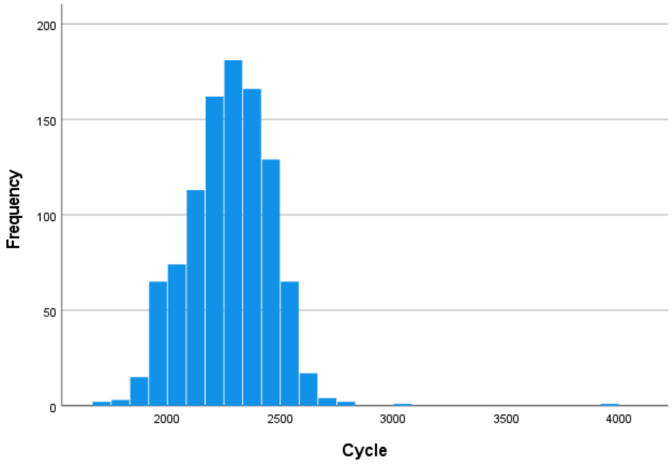


Figure 28: Histogram of the dataset for the ‘Damage’ model

Table 17: Descriptive statistics of the ‘Damage’ model

Damage model	
Statistics	**Duration (mm:ss)**
Mean	37:52
Minimum	28:11
Maximum	01:06:12
Skewness	0.628
Kurtosis	6.356

The results from the ‘Damage’ model show that the dataset has a high kurtosis level. This means that the variance of the dataset is broader in contrast to a normally divided dataset (De Vocht, 2016). However, this is caused by a few simulations that had a longer mission duration than was expected. These outliers are shown clearly in figure 27 that shows the Q-Q plot. These outliers are located around the 3000 and 4000 value of the X-axis. The extreme values are translated in the maximum observed value of 1:06:12 (hh:mm:ss) for one simulation run in the ‘Damage’ scenario. Apart from these outliers, the dataset is normally divided enough to be subject to the ‘Independent Samples T-Test’.

4.1.1.6 Scenario 6: Combination

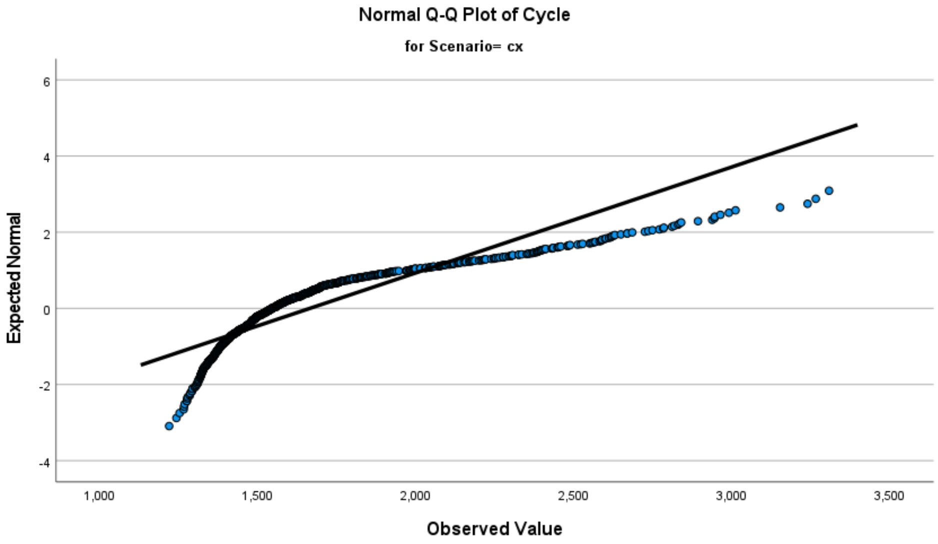


Figure 30: Q-Q plot of the dataset for the 'Combination' model

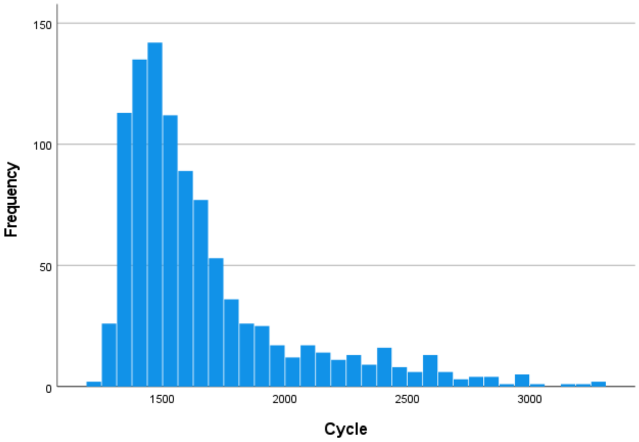


Figure 29: Histogram of the dataset for the 'Combination' model

Table 18: Descriptive statistics of the 'Combination' model

Combination	
Statistics	**Duration (mm:ss)**
Mean	27:44
Minimum	20:19
Maximum	55:08
Skewness	1.1754
Kurtosis	2.954

The 'Combination' dataset has a strong positive skewness, which translated in a lower median than mean (table 12). The strong positive skewness can be seen in figure 29 by the number of low mission durations for this type of simulations. However, this dataset has a higher kurtosis than the 'Reference' model and the 'Distance-to-reach' model. This means that the spread of values for this scenario is less equal to a normally divided dataset than the two before-mentioned scenarios. However, this dataset is still viable for performing the 'Independent Samples T-test.

4.1.2 Independent Samples T-Tests

Levene's test is a method to test whether the variance of the observations significantly differs from the Reference model (De Vocht, 2016). The results of the Levene's test is shown in table 19. The variance of the data between the reference model and the scenarios 'Group size', 'Distance-to-reach', 'Combination' and 'SA' differs significantly, with a confidence level of 99.9%. However, the variance from the 'Damage model' does not have significant differences in variance. Therefore, the significance levels are to be handled according to this status of variance (Equal variances assumed/not assumed).

All the results were measured with a 'One-sided tail'. All scenarios are to be expected to do either worse or better, so it is only necessary to measure the probability of a value occurring at one side of the normal division (one-sided tail). As can be seen, the 'Reference' model has both the longest mission duration time (table 12) as the highest amount of casualties (table 22). The latter will be discussed later in this chapter.

Even though one group of agents increases the power of the platform, the mean mission duration in the 'Damage' scenario does not differ significantly from the mean mission time of the 'Reference' scenario.

The 'Group size' scenario shows a significant difference in mission duration, from which we know is faster than the 'Reference' scenario. However, this does not immediately mean that this scenario was more successful than the 'Reference' scenario. The only result from this t-test is that the mission duration was lower than the 'Reference' model. The amount of casualties among the smaller group will be discussed later on in the chapter.

The 'Distance-to-reach', 'Combination' and 'SA' scenarios have a significant lower mission duration compared to the 'Reference' model. As shown in table 19, the outcome differs significantly with $p<0.001$.

Table 19: Results from the Independent Samples T-Test ('Reference model as reference')

	Levene's Test	**Significance**
Scenario	**Significance**	**One-Sided p**
Damage	0.639	0.048
Group size	*<0.001*	*<0.001*
Distance-to-reach	*<0.001*	*<0.001*
Combination	*<0.001*	*<0.001*
SA	*<0.001*	*<0.001*

4.2 Casualties: data exploration

All results from this analysis are influenced by the locational difference between starting positions. This aspect has been kept in mind while analysing the results and will not be mentioned separately for each scenario. Therefore, it will be discussed first, as to better understand its role in the scenarios.

4.2.1 Locational advantage

Table 20 shows the significance in amount of casualties and mission duration between simulation runs 1-500 and 501 -1000. As there is a significant difference with a 99.99 % confidence level (table 20), it can be said that there is a significant locational difference between the two starting positions. Another indicator of this locational advantage is shown in table 21. This table shows the last 4 simulations (black) of NCW agents starting at starting location 1 and the first 4 simulations (red) of NCW agents starting at starting location 2. Both simulation runs are within the SA scenario, but there are showable differences between the values for the attributes 'HP', 'Wounded' and 'Casualties'. These differences are shown in figure 31 as a histogram to show the division of the dataset for the SA scenario as well.

Table 20: Difference in mission duration and casualties between starting positions for the SA scenario

	Mission duration	**Casualties**
Significance	<0.001	<0.001

Table 21: Locational advantage shown in the SA scenario results attribute table

Scenario	Cycle	HP	KIA	Wounded	SA	Casualties
SA	1412	0.801	0	1	0.84265	1
SA	2205	0.808	0	0	0.7822	0
SA	1692	0.748947	1	4	0.784737	5
SA	1966	0.683	0	3	0.76905	3
SA	2000	0.765	0	1	0.6782	1
SA	2476	0.2645	0	20	0.6399	20
SA	1402	0.224118	3	17	0.689529	20
SA	1518	0.4615	0	10	0.7279	10

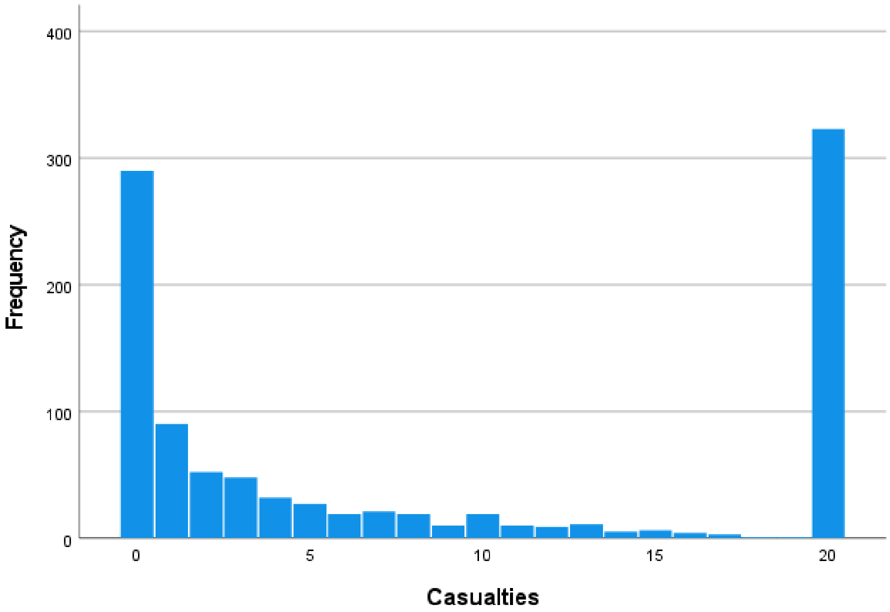


Figure 31: Histogram of the casualties per simulation in the SA scenario

To test whether there is a significant difference between the starting locations, a statistical analysis is performed. The results from this analysis are shown in table 20. This table shows that there is a significant difference between the mission duration and the number of casualties between the two sets of data within the ‘SA’ scenario. This means that there is a significant difference between the data for mission duration and casualties, because of the starting position. The assumption that was made early on in section 3.9 is therefore analytically justified.

4.2.2 Descriptive statistics

The descriptive statistics of the casualties for every scenario are shown in table 22 and figure 32. The scenarios are arranged from top to bottom based on the mean casualties per scenario. The results for this attribute is measured in percentage from the total units per team per simulation. This way, the values for ‘Casualties’ are standardized among all scenarios. The division of the dataset for each scenario are visualized in figures 32 as boxplots and figures 33 to 38 as histograms. The vertical line in these histograms shows the mean value of casualties per scenario.

The ‘Group size’ scenario has the highest casualty rate, which is 93.9% of the total assigned force for this mission. Another important notice is the low difference of mean between the ‘Reference’ and ‘Damage’ model. The lowest two means in casualties are the scenarios ‘Distance-to-reach’ and ‘Combination’. These values are respectively 2.5% and 2.3% of the task force. However, it is impossible to have a person wounded hallway in realistic terms. Therefore, the mean casualties per scenario are rounded to whole numbers to give a clearer perspective. It should be noted that the difference between the ‘Distance-to-reach’ and ‘Combination’ scenarios in the ‘Mean’ column is little to none. Therefore, the ‘raw’ data of the first column is assessed to check for mission success. The minimal casualties for all scenarios is 0, which may be due to the locational advantage discussed in section 4.3.1.

Table 22: Descriptive statistics for casualties

Scenario	**Mean**	**Mean (rounded)**	**Mean (%)**	**Min. (%)**	**Max. (%)**
Group size	9.3	9	93.9	0	100
Reference	12.75	13	63.8	0	100
Damage	10.74	11	53.7	0	100
SA	8.43	8	42.2	0	100
Distance-to-reach	0.5	1	2.5	0	30
Combination	0.46	0	2.3	0	30

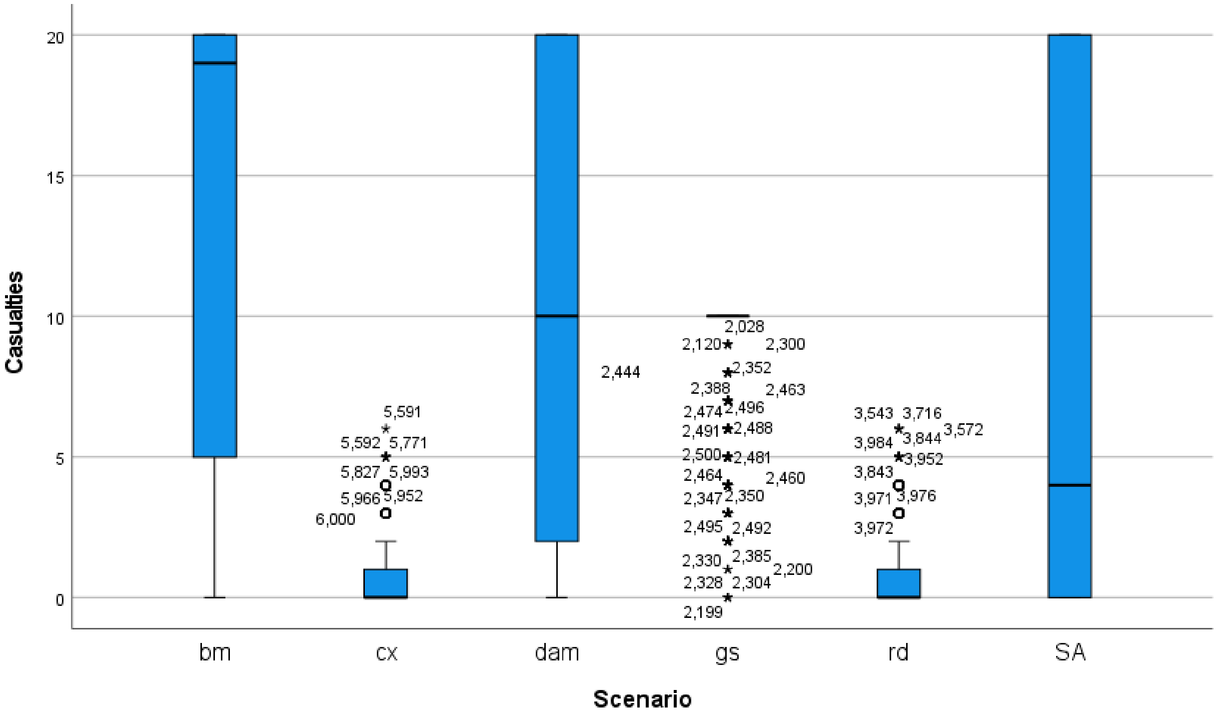


Figure 32: Boxplot of the division of the casualties for every scenario.

4.2.2.1 Reference model

The reference model shows a boxplot in which the middle 50 percent of the observed values lies between the 5 and 20 per simulation, which indicates a high spread. Therefore, the top 25 percent of the observations is automatically either 19 or 20 as well, as this value was not allowed higher. The lowest 25 percent is situated between the 0 and 5 casualties per simulation.

4.2.2.2 SA

The spread of the observations in the ‘SA’ scenario is also visualized in figure 37 as a histogram. The locational advantage is especially shown in this scenario, in which the bar for the value ’20’ is relatively large compared to the lower values. The width of the IQR is higher than any other scenario dataset. This implies more simulations with either 0 or 20 casualties within the IQR than outside it.

4.2.2.3 Group size

The outliers of the model are more than 3 IQR from the IQR box, which means that there is a low spread with relatively few extreme outliers. This translates into a small spread of values from the mean. This small IQR means that more than 96% of the observed values is ‘10’, which is the maximum for this scenario.

4.2.2.4 Damage model

The observed values for casualties in the ‘Damage’ model shows a wider IQR, with values between 2 and 20. However, the Reference model has an IQR spanning from 5 to 20. The mean between the two scenario also differs. Where the dataset for the ‘Damage’ scenario has a median of 10, the ‘Reference’ model has a median of 19. This shows that the majority of the values within the IQR of the ‘Damage’ model is lower than that of the ‘Reference’ model.

4.2.2.5 Distance-to-reach & Combination model

Because the distribution of the observed values for the attribute ‘Casualties’ is almost similar, these two scenarios are discussed simultaneously. The IQR is similar between the two scenarios except that there are two more outliers for the ‘Distance-to-reach’ scenario than for the ‘Combination’ scenario. Nevertheless, table 22 shows a difference of 0.2 percent in mean casualties between the scenarios. Therefore, this difference in outliers is deemed as insignificant.

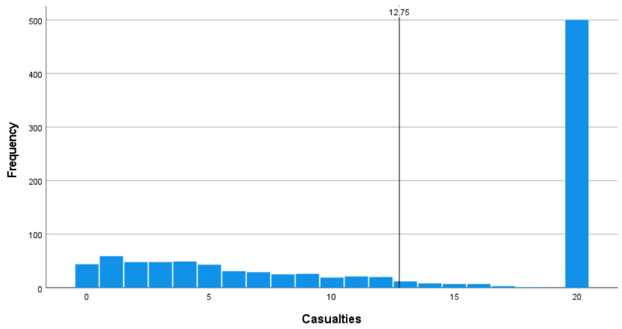


Figure 38: Reference scenario: Casualties as a histogram

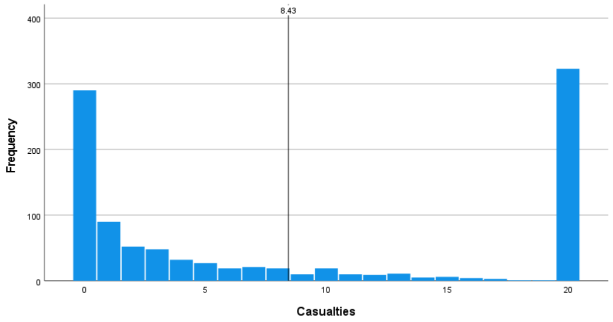


Figure 37: SA scenario: Casualties as a histogram

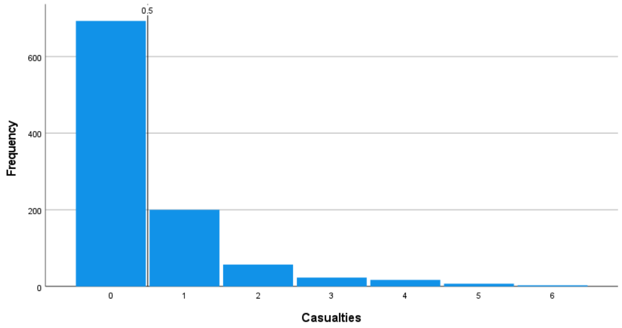


Figure 36: Distance-to-reach scenario: Casualties as a histogram

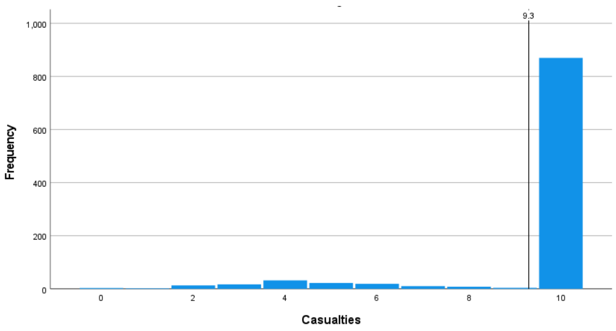


Figure 35: Group size scenario: Casualties as a histogram

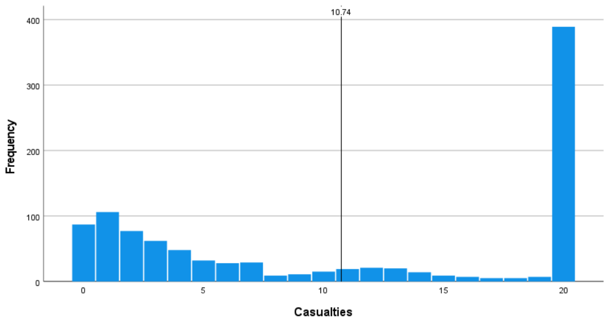


Figure 33: Damage scenario: Casualties as a histogram

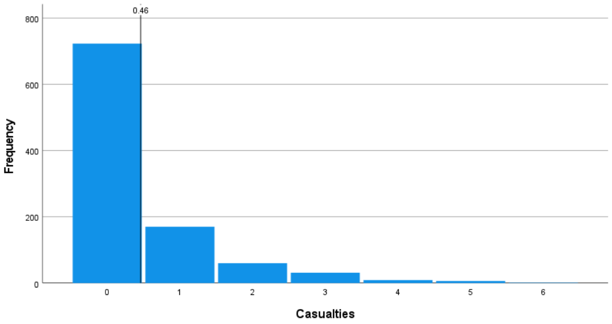


Figure 34: Combination scenario: casualties as a histogram

4.3 Mission duration & casualties

Table 23: Results according to mission success indicators

Scenario	**Mission success indicator**				
	Casualties		**Time duration**		
	Mean	**Mean (%)**	**Time duration (mm:ss)**	**Diff. with 'Reference'**	**Sig. time duration diff.**
Group size	9.3	93.9	36:22	n/a	<0.001
Reference	12.75	63.8	38:06	00:14	n/a
Damage	10.74	53.7	37:52	01:44	0.639
SA	8.43	42.2	26:31	05:31	<0.001
Distance-to-reach	0.5	2.5	32:35	10:22	<0.001
Combination	0.46	2.3	27:44	11:35	<0.001

Table 23 shows the result of the analysis altogether. The values for casualties are also in percentage of the whole, as the 'Group size' scenario has 10 starting agents instead of the standard value of 20. The scenarios that have the most favourable values per 'Mission success' indicator have their value underlined. The scenarios 'SA' and 'Combination have the most favourable values for the individual indicators. The scenario 'Combination' has the most favourable numbers in terms of casualties (mean = 0.46 per simulation), closely followed by the 'Distance-to-reach' scenario (mean = 0.5 per simulation).

The 'SA' scenario however has the most favourable mission duration, with a value of 26 minutes and 31 seconds. This differs 11 minutes and 35 seconds from the 'Reference' model. Because this scenario has a mean of 8.43 casualties per simulation, it is decided to exclude this scenario in final assessment.

Because both the 'Distance-to-reach' and 'Combination' scenario have relatively similar casualty values, possible differences in mission duration have to be analysed. To test whether the 'Distance-to-reach' and 'Combination' scenario have significantly different means for the mission duration attribute, an Independent Samples T-test is performed. Its results are shown in table 24.

Table 24: Independent Samples T-Test between 'Distance-to-reach' and 'Combination' datasets

	Levene's test	**One-tailed t-test**
Significance	<0.001	<0.001

The datasets have differing values, due to $p<0.001$ for the Levene's test. Therefore, the value for the One-tailed t-test is dependent on these unequal variances. However, there is a significant difference ($p<0,001$) concerning the mission duration between the two scenarios. This results in the 'Combination' scenario the most favourable in terms of mission duration.

4.3.1 Combination scenario: NCW vs PCW

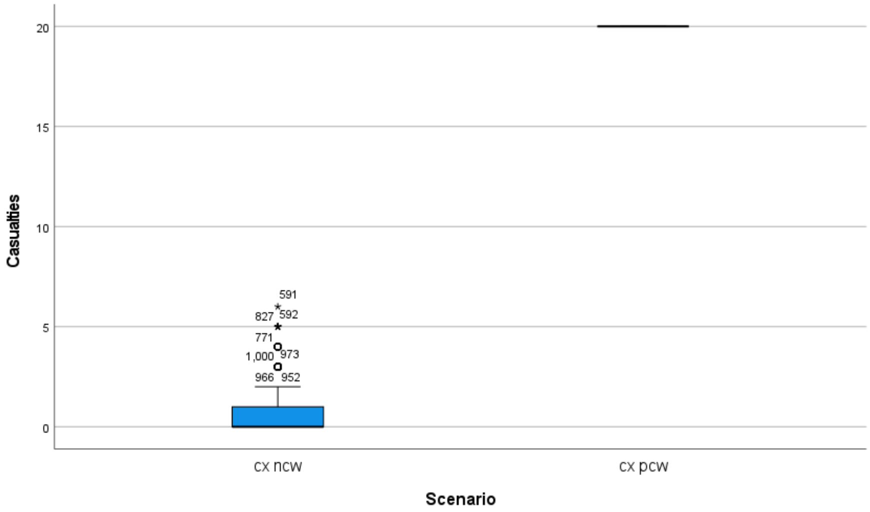


Figure 39: Casualties in the Combination scenario of both PCW and NCW teams.

As the 'Combination' scenario is the preferred scenario for the NCW troops, it is also interesting to see what the impact of this scenario is on the PCW agents in this scenario. Therefore, the division of the casualties in the 'Combination' scenario for both PCW and NCW teams are visualized in figure 39. The casualties for the NCW team equals the data as described in section 4.3. The casualties for the PCW team are a constant 20 per simulation. Keep in mind that the casualties are either wounded or terminated agents in the simulation. However, for both of these agent statuses the agent is no longer able to inflict damage and thus judged as neutralized.

4.4 Analysis

This analysis will elaborate which statements can be drawn from the results and statistical analysis performed in chapter, including descriptions about statistical relations within and between scenarios. It is important to notice that the assumptions made in this chapter are based on the environment, assumptions and scope-limitations of the research.

4.4.1 Scenario 1: Reference

The mission duration and the casualties in the reference model is the highest of all scenarios. This reference model represented a situation in which two teams engage with each other that both follow PCW principles. These circumstances, in this research, are for both mission success indicators one of the least favourable ways to conduct warfare. The only worse model outcome is that of the ‘Group-size’ model.

4.4.2 Scenario 2: SA

The units in the ‘SA’ model only had improved values for the attribute SA (and indirectly speed, see section 3.5.3.2 for this relation) .This lead to a significant difference in casualties and mission duration , depending on the starting location. The increased SA lead to a shorter OODA loop and fewer moments for the NCW troops to update their SA. This leads to more and faster movement. In this model, the increased speed and movement lead to a high casualty rate among the NCW troops, despite the perceived advantage of higher SA levels. This result emphasizes that an increased SA alone is not the solution for increased battlespace effectiveness. Other factors, such as location and engagement distance (‘Distance-to-reach’ in this research) also play a role in the effectiveness of battlespace combat.

4.4.3 Scenario 3: Distance-to-reach

A further combat reach for units was significantly better in terms of mission duration and had a lower mean of casualties than the Reference model. This indicates that units with a further combat reach are more effective than units without. Common sense might have concluded this as well, but this statistic creates scientific support on how much more effective this increased distance is compared to the other scenarios. The mission duration in this scenario is significantly shorter than that of the ‘Reference’, ‘Damage’ and ‘Group-size’ model, which indicates that this scenario is the more preferred option among the these scenarios.

The ‘SA model’ has a significantly lower mission duration than the ‘Distance-to-reach’ scenario, which wrongly indicates that the ‘SA model’ is more successful than the ‘Distance-to-reach’ model. However, the locational advantage of the southwestern starting point influences the casualties of the ‘Distance-to-reach’ model less than the ‘SA’ model (see figures 36 and 37). Therefore, the ‘Distance-to-reach’ scenario is the more preferred scenario than the ‘SA’ model in terms of casualties.

4.4.4 Scenario 4: Group-size

Scenario 5: Group-size is the worst scenario of all the scenarios. The group size is set to NCW standards but no further improvement positively affects the combat effectiveness. This resulted in a percentage of is 93.9% of neutralized agents. This is the highest percentage of all scenarios. The mission duration is shorter than that of the ‘Reference’ and ‘Damage’ model, but the casualties were almost always maximal. This implies that NCW agents were neutralized faster than in the two forementioned scenarios. In this scenario, a short mission duration is not an indicator of mission success for the NCW troops.

This casualty rate implies more than a least favourable way of warfare in terms of morale and ethical issues. It is also the least favourable scenario when looking at the bigger picture of a possible front line. If complete units are destroyed at the frontline, the enemy forces can advance into relatively unopposed terrain. Other scenarios have less casualties per simulation, even though they were on the losing side. These losing troops can retreat to more favourable positions and hold their ground there. If a unit is almost completely destroyed, it is not able to defend the front line anymore.

The ‘Group-size’ model is the worst scenario of all six scenarios, due to the high casualty rate and paired middle-ranged mission duration. This scenario should be avoided at all costs.

4.4.5 Scenario 5: Damage

Only increasing the damage of one group in the ‘Damage’ model does not significantly increase the mission duration, compared to the ‘Reference’ model (table 12). The decrease of health in conflict was 50 percent more for the PCW group, but the casualties did not go below the threshold of a mean of 1 per simulation for the NCW group. This means that only increasing the damage does not significantly increase the mission success compared to the ‘Reference’ scenario.

This scenario is only more effective in terms of casualties than the ‘Reference’ model. There is no significant difference in mission duration, which indicates that missions are not more successful if only the inflicted damage is increased.

4.4.6 Scenario 6: Combination

The ‘Combination’ model is, in terms of general mission effectiveness, the most successful. The mission duration is not as short as the ‘SA’ model, but the mean casualties between these two is scenarios lower for the ‘Combination’ model.

The success threshold for casualties was set to less than 1 per simulation, which was achieved for both the ‘Distance-to-reach’ model and the ‘Combination’ model. However, the mission duration of the ‘Combination’ model was significantly faster than the ‘Distance-to-reach’ model. Therefore, the Combination model is deemed as the best scenario of all the six scenarios.

To compare the casualties in the ‘Combination’ model for both teams, figure 39 was made. This shows that there is a clear difference in casualties between the two teams. The casualty rate of NCW troops for the ‘Reference’ and ‘Combination’ model differs visibly, but the casualty rate between PCW and NCW troops in the ‘Combination’ model also differs greatly. The boxplot in figure 39 shows this difference, which adds up to the combat effectiveness of NCW programmed agents. The amount of casualties for the PCW group is always 20, even when taking the possible locational advantage into account. The result of these total numbers in casualties are discussed in section 4.2, which applies to the PCW troops as well. The ‘Combination’ model has high casualty rates for the PCW programmed agents, which gives the NCW troops the possibility to advance. The addition of shorter mission duration compared to the ‘Reference’ model makes this scenario even more favourable.

Important notes on the implementation of the ‘Combination’ model, is the realization of vital aspects of NCW. These actors are discussed in the chapter 2 with referencing to literature. These include technological, educational and structural differences between the PCW doctrine. If the results from the ‘Combination’ model are to be achieved, the matters discussed in chapter 2 should be put through adequately. A potentially successful operation can turn into results similar to the least effective ‘Group-size’ scenario if forementioned improvements are not realized.

5 DISCUSSION

5.1 Process and Limitations

This section will discuss every aspect that was encountered during the process, including limitations before starting the research as well as occurring thoughts during the final programming stages. It is aimed as clarification for which actions could improve the validity of the process, but also to show the process of the research.

5.1.1 Long lines of code.

Every aspect of the programming was a new skill that had to be learned. Some aspects could have been done faster and more efficient, but efficient coding had to be learned first. Not only the speed of the simulations was affected by this learning curve, but the processing time as well. Lines of code, such as the movement of agents towards their target is a clear example of this discussion point.

The lines of code in text block 11 are an example of the extensive coding that initially let the agent move towards each other. It is not expected for the reader to precisely understand what is tried to accomplish in text block 12. This is more an indication of how extensive some lines of code were. The colour of the code in text block 11 is caused by a different interface between the different installation of GAMA on different hardware.

```
reflex move_to_intercept_pcw when: agent_status = "active" and (! empty
(intercept_pcw))and (empty (follow_pcw)) and (empty(reachable_pcw)) {
       ask pcw_agents at_distance(distance_to_intercept) {
              myself.targetpcw    self;
                     }
              do goto target: one_of(targetpcw) on:road_network;
              speed    20#km/#h;
       }
reflex move_to_follow_pcw when: agent_status = "active" and ( ! empty(follow_pcw)){
       ask pcw_agents at_distance(distance_to_follow) {
                     myself.targetpcw    self;
                     }
              do goto target: one_of(targetpcw) on:road_network;
              speed    10 #km/#h;
              }
reflex move_to_reachable_pcw when: agent_status = "active" and ( ! empty (reachable_pcw)){
       ask pcw_agents at_distance(distance_to_reach) {
                     myself.targetpcw    self;
                     }
                     do goto target: one_of(targetpcw) on:road_network;
              speed    5#km/#h;
```

Text block 11: Extensive code used to inefficiently move the agent

The code in text block 11 only caused agents to go to the starting places of the opposite team. Therefore, alternatives had to be found. The solution of this problem is shown in text block 12 and shows how straightforward the solution is. This code line ensures that agents move towards each other, based on the nearest opposite team member. The simple change is the function 'agent' that can be determined as target for every tick.

```
reflex move_to_target when: agent_status = "active" and ncw_hp > 0.3  {
        agent targetpcw <- pcw_agents closest_to(self);
        do goto target: targetpcw on:road_network;
        speed <- ncw_speed;
}
```

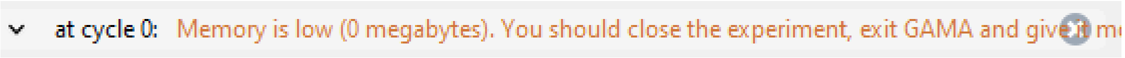
Text block 12: Short efficient code the move the target

Because there has been no experience with this type of coding, flaws might have been undetected during the process. However, numerous revisions and a lot of tutorials have been performed to ensure the quality of the code.

Another aspect of the long lines of code is the long computation times. A solution for this is to enable the use of more processors for the simulations. There were issues in changing the seed (which is the input per simulation) of every simulation to unique and at the same time using more processors. However, when assigning more processors, it caused the software to use the same seed for separate simulations that run simultaneously. The solution was to only assign one processor, which resulted in a longer computational time. This could have been avoided by more knowledge of the software, but it was solved this way whatsoever.

5.1.2 3D

Previously stated use of 3D simulation is considered to be too demanding for the software. Luckily, it was not yet necessary for this research to include 3D buildings for better understanding of the unit's movement. Another reason why 3D has not been implemented is the available memory of the hardware that was used. The software enabled the user to access 4096 MB of free space on the computer. This was enough for 2D visualizations, but proved to be too demanding for the assigned memory during the simulations runs. The resulting error message is shown in figure 17. The simulations where this error occurred created output that did not seem to be corrupted. Despite this error message, no action was needed to increase the software memory. The only downside was the increased simulation time due to less available programming space.



```
at cycle 0: Memory is low (0 megabytes). You should close the experiment, exit GAMA and give it m
```

Figure 40: Error message due to limitation

Increasing this memory could only be done by internal actions in the software (via an .inti file or via an unstable website of GAMA). Therefore, it was determined during the research that the extra effort of enabling more workspace was not worth the extra value of implementing a 3D environment or less processing speed. Using this 3D environment did not fit in the scope that the research has been set, but might be useful for further research.

The implementation of a 3D environment might be useful for further analysis, as the behaviour of the agents can become smarter and more complex. Aspects as looking for cover and rules of engagement can be better understood as a user when the environment is more realistic. Other aspects as Line of Sight (LoS) could be implemented with 3D as well. More on the LoS and other possible further research is discussed in section 5.3.4.

5.2 Opportunities for further research

Further research could be performed on some findings during the process. The reason that these were not implemented is the available time and the learning curve of understanding GAML. The path that was taken during the research required learning GAML, which was not a given trait of mine. However, there were a few points that came to light during the coding and discussions with Robert that are worth mentioning.

Implementing the aspects of the model in the next section increases the model validity, but also the complexity of the environment. The following aspects are therefore worth mentioning, but to be implemented in possible future research.

5.2.1 No preference of joint confrontation

Agents prefer singular confrontation instead of combined confrontation. Even though joint confrontation might lead to an advantageous position in conflict, this research does not take this aspect into account. It might be possible to program this behaviour in close combat via communication between the agents and complex lines of codes. However more favourable, this combined approach is left out of the research due to complexity issues and the set scope.

5.2.2 Morale

Real-time warfare is not purely a statistical numbers ‘game’, but one of morale as well. If the morale of war fighters is low, their battlespace efficiency can decrease as well (Strachan, 2006)). This mental aspect is not simulated in this research. Ideas of simulating this aspect could be by counting the casualties within an amount of meters into consideration when calculating unit morale. If a certain number of conflicts or casualties is detected, a reflex could be triggered to retreat. This retreat will then be triggered without the HP being lower than 0.3 HP, as is the case in this research. The current simulation embodies agent behaviour as if the results of combat do not influence them at all, which is a rather unrealistic point of view. The implementation of combat morale might be advantageous for NCW troops, as they have significantly less casualties per simulation (see section 4.3.1)

5.2.3 Destruction of roads

The destruction of roads could have added a more dynamic and realistic environment for the agents to behave in. Adding this feature in the research will improve the validity and realism of the simulation. The destruction of the environment could be interesting to measure the effect of a changing road network. However, this alteration of the environment was not implemented in the research, as it was more important to focus on the scope that was determined beforehand. It is therefore suggested that this feature might be implemented in future research.

5.2.4 Line of Sight (LoS)

The line of sight could be implemented in the research to increase the validity. However, adding the LoS was beyond the expertise of this research, as it includes relatively complicated lines of coding. Now, both PCW and NCW teams can 'look through buildings', as if they were not there. These buildings currently only serve as a visualization aspect. If the LoS is modelled, PCW agents in the 'NCW model' might lose faster because NCW agents could make use of sensors to detect PCW when not in their LoS. In this research however, both teams are able to use the advantages that NCW troops have because of their network. This causes the PCW agents to have an unrealistic advantage compared to NCW agents.

Implementing the LoS in an ABM simulation using GAMA can be done by studying and using one of the example models in the GAMA library. This tutorial embodied the random movement of one agent, whereas this research made use of multiple agents. This could strain the computing power of the used hardware.

5.2.5 Open space negation

It was initially thought that the GAMA Platform requires nodes for agents to move over. This was proven untrue, later in the research process. This created the situation that agents were not able to move next to buildings for cover or through parks that were not accessible by roads. Passable buildings due to their nature or by events such as explosions are not taken into account either.

The implementation of these 'events' can be programmed as a similar name in GAMA. The event of a random building exploding close to combat can be called upon by the GAMA user or called automatically during the simulation. However, this revelation came almost at the end of the research. For this reason, it was not implemented in the research but discussed as a possible improvement. It is not assured that this change in the research would also work for the coding settings that this research is already in.

5.2.6 No misses in conflict

It is assumed that every encounter is successful. Therefore, there are no misses in the simulation between the teams. The only variation in received damage per second is processed in the ‘Distance-to-reach’, ‘Damage’ and ‘Combination’ models. Including the variable in which a chance of a successful hit nuances the damage per second. The current research, however, does not take the chance-to-hit into account. Adding a ‘chance-to-hit’ might increase the validation of the research. By doing this, the programmer should be aware of creating too much advantages for the NCW agents without supporting them by literature. Because there was no indication that there were significant differences in chance-to-hit, they are not taken into account in this research.

5.2.7 Unlimited supplies and High-Value Targets (HVT)

During combat, there is the assumption of equal ranks between the team members and no depletion of resources. These indicators stated by Alberts et al. (2000b) are not taken into account in this research, because this required more advanced programming. Even though they were stated to be important, I saw no way how to implement this in the research. The implementation could be done, if I had more experience with GAMA. An increased number of indicators for mission success can be referenced to in future research.

5.2.8 Conflict with nearest opposite team member

The agents of both teams are able to select the nearest opposite team member at every tick in the simulation. This results in agents recalibrating their path towards the nearest enemy every second of the simulation. This is not a realistic situation, as the team members are not able to know the location of the opposite team at every moment. Therefore, the target of the agent should be recalibrated with an interval. This interval will then be set according to literature and advice from experts in the field. The ideal way to simulate a more realistic method to select the target might be figured out in future research.

5.2.9 Unconditional engagement

Agents engage into combat even though they know that they might suffer significant casualties. Their instructions are to engage the enemy without the possibility to tactically retreat. The only opportunity for retreat is when an agent has less than 0.3 HP left. This is an arbitrary chosen limit, from which agents are programmed to retreat. Differences in doctrines might change this value. For instance, if armies have a high value for the lives of troops, they will retreat sooner. However, not all armies have the same value for the health of their troops. Therefore, these retreat orders are open for discussion.

5.2.10 Wounded vs killed

Future research could focus on the difference between scenarios and the division between wounded and ‘killed’ at the end of the simulation. During this research, both wounded and killed was summed up in a general number for casualty. The point of view was to count the amount of agents that are neutralized, instead of the severity of damage they received. However, it might be informative in future research to investigate the influence of different scenarios on the different type of ‘casualty’.

5.2.11 Neutral city

It is assumed that inhabitants of the city are neutral, so they do not engage in conflict. In reality, the loyalty of cities is dependable on the morality of the citizens and the nature of the attackers. If the defenders are seen as positive occupants, citizens might be more willing to help. However, if the city is occupied by hostile forces, it could be more prone to resistance.

In this simulation however, the city is seen as neutral. No interactions between the environment and the agents is done that is instigated by citizens. Citizens could be implemented as separate agents that interact with military agents depending on their nature. Other interactions between the agents and the city could be simulated by changing the state of the infrastructure. However, these elaborate interactions are not implemented in this research, as the scope did not cover this subject.

5.2.12 Locational advantage

The locational advantage has been elaborated in section 4.3.1, so no further details are discussed here. Instead, ways to solve this locational advantage are discussed. This uneven advantage might be solved by performing the analysis in more urban regions in the same city. Urban regions in other cities could also clarify more on the role of locational advantage, but the street pattern must be similar enough to create comparable data. Clarifying the relation between behaviour and location could be in the form of spotting patterns between the simulations that encounter locational awareness. The addition of varying urban regions might also result in interesting new findings about how some locations have more advantage than other regions.

5.2.13 Rural vs urban

The research area includes urban areas, but does not focus on how NCW behaves in rural areas. Adding the rural area as an extended environment might lead to interesting insights. Even though urban areas are more complex in terms of warfare than rural areas, it is not to be assumed that rural areas are more easy comprehend. Future research might focus on the behaviour of war fighters following the NCW doctrine in rural areas. This could be focussed on solely a rural area, or on both urban and rural areas. However, this is up to the research gap that is to be filled when assessing the environmental extent of the research.

5.2.14 Elevation

Elevation also plays an important role within the strategic planning. However, because the research environment is urban and the Netherlands is not known to have cities with a lot of relief, this has not been taken into account. Another aspect of elevation is the use of buildings from which agents can fire from higher places. The implementation of this aspect of elevation needs a more extensive research as how to correctly process that. This could be a subject for future research as well.

6 CONCLUSION

6.1 Summarization / Introduction

This research focussed on the efficiency of ground troops in conflict that follow two different warfare principles. The behaviour of these troops is programmed with an ABM software called GAMA and analysed by performing simulations in urban regions. The results from these simulations were then used to perform quantitative analysis to answer the following research question:

To what extent can the efficiency of NCW and PCW managed ground forces be measured with 2D simulation, and what behavioural ruleset fits NCW and PCW principles?

The main research question has been divided in sub-questions, which helped answering the main question. The main question is answered by answering the sub questions separately. Therefore, these will be discussed in order of appearance. A summary of every sub question answer is given at the end of each sub-question.

6.1.1 SQ 1: What are the main differences in characteristics between NCW and PCW principles?

This sub question is answered in the Literature review in chapter 2. Urban warfare in general follows rules of the complexity theory. Properties as emergence, adaptation and network thinking are known to be reoccurring in warfare, so it is important to keep these aspects of complexity in mind when dealing with NCW as well. Networked agents that follow NCW principles are actively aware of their situation, use sensors to gain intelligence and able to synchronize their behaviour autonomously with the general intent of the mission (OODA loop). The power of NCW lies within the added value of the network they create. Performing NCW in the battlespace requires war fighters to be connected with each other and aware of the initial intent of the plan to control their OODA loop.

Agents that act according to PCW principles rely on the quantity and the power of the weapon they use in combat. PCW related missions rely on deploying a large number of units to confront the enemy units. This more traditional way of warfare does not prefer simultaneous engagement of multiple platforms during combat. Instead, the goal of PCW in practice is to overwhelm the enemy team with a singular type of platform.

Therefore, the main difference between NCW- and PCW characteristics is the level of technological involvement, simultaneous engagement of different platforms and the nature of the OODA loop.

6.1.2 SQ 2: How can NCW and PCW principles be translated into programming language and which characteristics should be implemented?

Because the complex behaviour of warfare experiences emergence, it is hard to program these future events. Programming a future, abstract, unforeseen action with coding language that writes commands is hard to accomplish. Therefore, the behavioural rules were based on setting conditions in which the agents are to behave. Trying to program behaviour that is expected to happen goes against the idea of complexity. Therefore, two behavioural rule sets were formed that set the basis to basic behaviour. Simulating behavioural rules to simulate the aspect of emergence was avoided in this research.

The properties that were programmed into the research were selected by importance and applicability to be programmed in GAMA. The result of this selection was the set of attributes shown in table 1. The starting values for the constant variables (HP, Speed and networked SA) were similar among all teams and all scenarios. However, the variable attributes (SA, Distance-to-reach, Group size and damage) can differ per scenario. Variation and interaction between these variables are the basis of the different scenarios. Finally, the variation between the characteristics and scenarios helped with answering the main question.

Concluding this sub-question, behavioural rule sets were written for the agents. These agents formed behaviour that was partly emergent, partly programmed. The behavioural rule set for both NCW and PCW doctrines were based on literature, expert advice and how well the characteristic was able to be programmed.

6.1.3 SQ 3: How applicable is the GAMA software with simulating a complex system such as NCW and PCW.

The GAMA software supported programming the behavioural rule set for simulating a complex system as an ABM to some extent. The documentation provided by GAMA was sufficient enough for the basic programming tasks. However, the provided tutorials only guided the user through the more basic aspects of GAMA. For more advanced improvements of the research, it was required to have more experience with the software and the language. Examples of advanced improvements are including aspects as adaptation and agent-environment correspondence.

In short, programming an ABM in GAMA is relatively user-friendly when sticking to the basics. Simulating complex systems in GAMA works as well, as long as the principles of complexity are followed through. It is beneficial if the user already has experience with GAMA/GAML when aiming to create more advanced simulations.

6.1.4 SQ 4: What outputs are to be selected from the simulation to analysis possible patterns and relations between scenarios?

The outputs that were used for the analysis are the cycle that the simulation ended and the casualty count. The mission duration was retrieved from the cycle value, which represented seconds. The casualty value however was combined with ‘wounded’ and killed agents. Agents were wounded when their HP < 0.3 and killed when HP < 0. This research did not elaborate further on the relation between scenarios and amount of wounded/killed per scenario, but this could be done in the future as well. This same possibility counts for values of HP and SA per scenario.

So, for this research, ‘Cycle’ and a combination of ‘Wounded’ and ‘KIA’ were used as simulation outputs to analyse the patterns from and relations between the scenarios.

6.2 Reference to literature

The results of the research agree with the literary statements in chapter 2 concerning the improved mission duration for NCW troops. Troops with NCW characteristics are proven to conclude mission faster than troops with PCW characteristics. The most successful model is 10 minutes and 22 (27.1%) seconds faster than the Reference model.

The number of casualties in the ‘Combination’ scenario is also in line with the increased attention to ethical issues regarding loss of life during combat. The ‘Combination’ and ‘Distance-to-reach’ scenario both pass the criteria of less than 1 casualty on average, but the ‘Combination’ scenario has a significant shorter mission duration. This shows that the combination of the actors related to the NCW doctrine result in shorter mission durations, while simultaneously limit the casualty rate.

NCW practices discussed in literature are only effective if all characteristics of NCW are fulfilled. Therefore, it is to the utmost importance that the technological, structural and mental changes in warfare thinking are followed through in detail. Otherwise, unfavourable scenarios such as scenario 4: Group size, will happen.

6.3 Strengths of the research

The quantitative nature of the results has shown statistical proof that the NCW doctrine is more efficient than the PCW doctrine. The basis of this research is based on repetitive simulations, differentiating only by scenario setting. This creates a solid database for answering the research questions. The quantitative nature of this research has therefore created solid scientific grounds to prove the effects of NCW characteristics in urban areas for ground units.

Simulating complex systems is proven to be difficult to implement, as emergent properties are hard to program. However, this research has simulated the complex behaviour of agents in a way that the results can be measured and monitored. The basic settings of this complex system have been set and from this research on, the system can be modified by adding more rules of behaviour.

The set-up of the research enables the user to reproduce the research in different regions. This could be both rural regions and different urban regions. After importing the required data and alterations of the attribute tables in a GI-system, the data is ready to be visualized in GAMA. This enables the user to import any desired urban region, as long as the required data is available.

This research has been conducted completely with open source data and software (section 3.3 and 3.4). This makes the research easy to reproduce to check for validity or adjust the settings. The documentation of the software is also open-access and many tutorials enable self-learning. A prerequisite is some knowledge about programming and some advice or time to become familiar with the software.

6.4 Addition to science & following research

The related research section showed that there was already some use of ABM simulation to research military issues. The research in this thesis adds up to the existing research that already exists concerning the simulation of NCW principles in military affairs. In addition, this research can be used as a base for future research to expand it with more advanced characteristics to increase validity.

The nuance of this research is the urban region this research uses as environment. The complexity of warfare is more complex in urban regions than in macro levels or rural regions. Therefore, the results from this research help in understanding the complex behaviour of agents that occurs in urban warfare.

The research can be extended in a more elaborate research by adding the aspects that were mentioned in section 5.3. One of the two most important improvements is the alteration of the code by a more experienced programmer. Some improvements simply require more experience in programming to be optimally programmed. The second important feature for future research is the addition of LoS, which improves the validity of the research greatly. An important condition for including these improvements is hardware that is able to work with the increased demand for processing power.

6.5 Conclusion

The rising interest to NCW principles in the world of military affairs has led to the start of this research. Literature has claimed that armies following NCW characteristics are more efficient than armies following PCW characteristics. However, there was little quantitative proof of these claims, as all warfare scenarios are unique. Therefore, this research aimed to support this claim by literature by creating quantitative proof.

This thesis supports the claim that NCW ground troops have higher successful completion rates than PCW troops. The simulation to proof this was built in GAMA and the agents behaved according to a constructed rule set. Each decision was based on literature and expert advice in order to ascertain the validity of the research.

Only the combination of all aspects that are linked to NCW principles result in successful mission completion. The indicators for mission success were the mission duration and the casualty rate. Scenario 2: 'SA' had the best results for the mission duration and scenario 3: 'Distance-to-reach had similar results for mean casualty per simulation as the 'Combination' scenario. However, the combination of all the aspects of NCW led to the best results, in terms of the chosen mission success criteria.

Even though some aspects could be improved in future research, this thesis has created a basic environment to test the behaviour of NCW programmed troops in urban regions. The environment can be changed and software is available to everybody.

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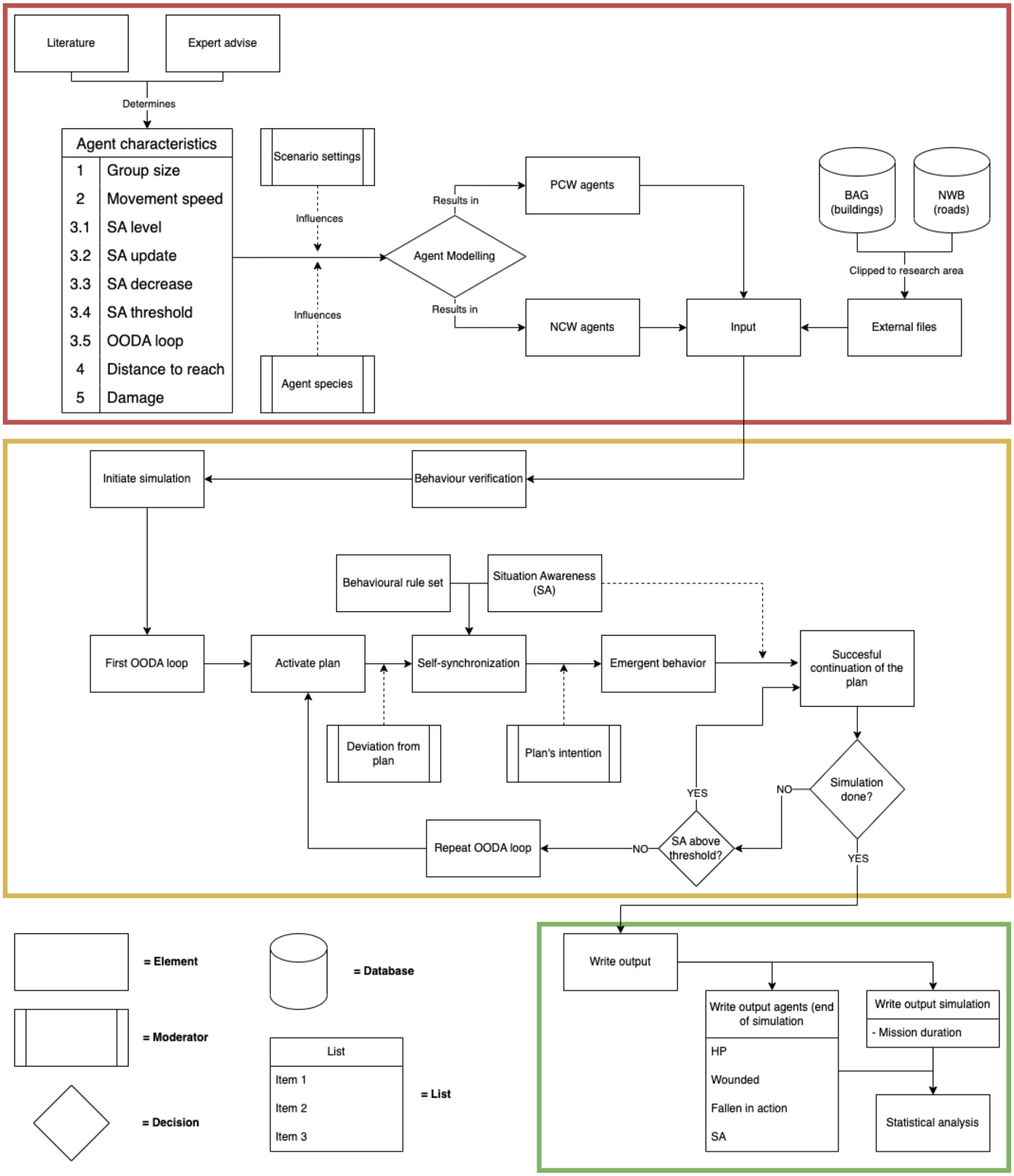
8 APPENDICES

Appendix 1: Extended CM



Appendix 2: Base code

```
/*
* Name: Analysis template
* Author: 5853370
* Description:
* The green lines above the segments of code describe the actions of these segments. These are short
descriptions, further elaboration of more important segments are discussed in the main report.
*/
model Analysistemplate


//      The set-up of the model is created in the Global section
global {

// Setting the start date and the length of each tick in the simulation.
        date starting_date <- date("2023 01 01 09 00 00","yyyy MM dd HH mm ss");
        float step <- 1#s;
        int nb_ncw_agents_init <- 20;
        int nb_pcw_agents_init <- 20;

//Importing files like buildings, roads and boundaries of the environment.
        file shape_file_buildings <- file("../includes/Buildings_adapted.shp");
        file shape_file_roads <- file("../includes/Roads_3.shp");
        file shape_file_bounds <- file("../includes/Roads_3.shp");
        geometry shape <- envelope(shape_file_bounds);
        graph road_network;


// Defining some general attributes so they can be accessed later on in the project.
        int nb_ncw_agents -> {length(ncw_agents)} ;
        int nb_pcw_agents -> {length(pcw_agents)} ;
        string agent_status <- "active";
        float ncw_speed;
        float pcw_speed;
        float pcw_sa_1;
        float pcw_sa_2;
        float ncw_sa_1;
        float ncw_sa_2;
        float pcw_hp <- 1.0;
        float ncw_hp <- 1.0;
        building pcw_starting_place <- nil;
        building ncw_starting_place <- nil;
        int ncw_num_dead <- 0 max: nb_ncw_agents_init;
        int pcw_num_dead <- 0 max: nb_pcw_agents_init;

// This creates the lists that are used to monitor the status in which agents are currently present.
        // NCW-agents monitor
        int nb_active_ncw_agents <-  nb_ncw_agents_init update: ncw_agents  count (each.agent_status =
"active");
        int nb_dormant_ncw_agents  <- nb_ncw_agents_init update: ncw_agents count (each.agent_status =
"dormant");
        int nb_attacking_ncw_agents <- nb_ncw_agents_init update: ncw_agents count (each.agent_status =
"attacking");
        int nb_wounded_ncw_agents <- nb_ncw_agents_init update: ncw_agents count (each.ncw_is_wounded);
        int nb_dead_ncw_agents <- 0 + ncw_num_dead update: 0 + ncw_num_dead;

        //PCW-agents monitor
        int nb_active_pcw_agents <- nb_pcw_agents_init update: pcw_agents count (each.agent_status =
"active");
        int nb_dormant_pcw_agents <- nb_pcw_agents_init update: pcw_agents count (each.agent_status =
"dormant");
        int nb_attacking_pcw_agents <- nb_pcw_agents_init update: pcw_agents count (each.agent_status =
"attacking");
        int nb_wounded_pcw_agents <- nb_pcw_agents_init update: pcw_agents count (each.pcw_is_wounded);
        int nb_dead_pcw_agents <- 0 + pcw_num_dead update: 0 +  pcw_num_dead;

// Creates the species in the project and possibly from what files they are created
```

```
        init {

// Assigns the imported road file as the node on which the agents are traveling.
                create road from: shape_file_roads ;
                road_network <- as_edge_graph(road);

// Creates lists of buildings according to which type they are assigned to using the imported shapefile
attribute table

                create building from: shape_file_buildings with: [type::string(read ("Start_type"))]{
                        if type = "ncw" {
                                color <- #blue;
                        }
                        else if type = "pcw" {
                                color <- #red;
                        }
                        else if type = "no" {
                                color <- #grey;
                        }
                }
                list<building> NCW_building <- building where (each.type="ncw") ;
                list<building> PCW_building <- building  where (each.type="pcw") ;
                list<building> No_spec <- building where (each.type="no") ;

// The agents and their starting location accordingly.
                create ncw_agents number: nb_ncw_agents_init {
                        ncw_starting_place <- one_of(NCW_building) ;
                        location <- any_location_in (ncw_starting_place) ;
                        agent_status <- "active";
                }
                create pcw_agents number: nb_pcw_agents_init {
                        pcw_starting_place <- one_of(PCW_building) ;
                        location <- any_location_in(pcw_starting_place) ;
                        agent_status <- "active";
                }
                ask nb_ncw_agents_init among ncw_agents {
                        agent_status <- "active";
                }
                ask nb_pcw_agents_init among pcw_agents {
                        agent_status <- "active";
                }

        }

 // Writing the data used for analysis in the designated 'csv' file.
        reflex write_data when: ((nb_wounded_ncw_agents + nb_dead_ncw_agents) = nb_ncw_agents_init) or
((nb_wounded_pcw_agents + nb_dead_pcw_agents) = nb_pcw_agents_init) {
                save    ("Basic model" + ";" + cycle +
                                  ";" + (pcw_agents mean_of each.pcw_hp) +
                                  ";" + pcw_num_dead +
                                  ";" + nb_wounded_pcw_agents +
                                  ";" + (pcw_agents mean_of each.pcw_sa_2))
                                to: "E:/GIMA/GIMA/Thesis/Data/New_data/pcw_basic_1.csv" type: "text"
rewrite: false;

                save    ("Basic model" + ";" + cycle +
                                ";" + (ncw_agents mean_of each.ncw_hp) +
                                ";" + ncw_num_dead +
                                ";" + nb_wounded_ncw_agents +
                                ";" + (ncw_agents mean_of each.ncw_sa_2))
                                to: "E:/GIMA/GIMA/Thesis/Data/New_data/ncw_basic_1.csv" type: "text"
rewrite: false;
        }
}
// The creation of buildings and roads as species to be able to visualize them in the display
species building {
        string type;
        rgb color <- #grey;
        aspect base {
```

```
                draw shape color: color;
        }
}
species road {
        string type;
        aspect road {
                draw shape color: #grey ;
        }
}

species ncw_agents skills:[moving] {

        image_file ncw_image <- image_file ("../includes/white_pawn.jpg");
    string agent_status <- "active";
        float ncw_speed <- 2.5 #km/#h update: 2.5  #km/#h * ncw_sa_2 * ncw_hp min: 1.0 #km/#h max: 2.5
#km/#h;
        date ncw_sa_recovery_date <- date ("");

// Changeable attributes

/*sa*/  float ncw_sa_1 <- 0.5 min: 0.1 max: 0.5;
/*sa*/  float ncw_sa_2 <- 0.5 update: ncw_sa_1 + ncw_networked_sa min: 0.1 max: 0.5;
/*sa*/  float ncw_sa_update <- rnd (0.3, 0.4, 0.1);
/*sa*/  float ncw_sa_decrease <- rnd (0.003, 0.004, 0.001);
/*sa*/  float ncw_sa_recovery_time <- 5.0#s;
/*sa*/  float ncw_sa_threshold <- 0.1;

/*damage*/                              float ncw_hp_decrease <- 0.01;

/*Distance-to-reach*/   float ncw_distance_to_reach <- 75#m;

// SA that is created by communication with team members.
        float ncw_networked_sa <- 0.0 min: 0.0 max: 0.1;
        float ncw_networked_sa_increase <- 0.02;
        float ncw_networked_sa_decrease <- 0.01;

// HP values, HP damage taken per tick and distance needed to encounter agents from the other team.
        float ncw_hp <- 1.0 min: 0.0 max: 1.0;

// Attributes used to differentiate agents between being wounded or killed.
        bool ncw_is_wounded <- false;
        int ncw_is_dead <- 0 max: nb_ncw_agents_init;

// Setting targets for the agents to move to.
        reflex move_to_target when: agent_status = "active" and ncw_hp > 0.3  {
                agent targetpcw <- pcw_agents closest_to(self);
                do goto target: targetpcw on:road_network;
                speed <- ncw_speed;
        }

// Agents retreat to their starting point when severly wounded.
        reflex retreat when: ncw_hp <= 0.3 and ncw_hp > 0.0 {
                do goto target: any_location_in (ncw_starting_place) on:road_network;
                agent_status <- "wounded";
                ncw_is_wounded <- true;
        speed <- 2#m / #s;
        }

// Used to fulfill conditions for when the simulation should end.
    reflex end_simulation_logistics when: ncw_hp <= 0.0{
        agent_status <- "dead";
        ncw_num_dead <- ncw_num_dead + 1;
        ncw_is_wounded <- false;
        return ncw_num_dead;
    }

// The termination of agents when they reach a certain 'HP' value.
        reflex termination when: ncw_hp <= 0.0 {
                do die;
```

```
                }

// The decrease of SA
    reflex sa_decrease when: agent_status = "active" or agent_status = "attacking"{
        ncw_sa_1 <- ncw_sa_1 - ncw_sa_decrease;
        }

// Starting the period that agents need when they start to increase their SA.
    reflex dormant when: ncw_sa_1 <= ncw_sa_threshold and agent_status = "active"{
        agent_status <- "dormant";
        ncw_sa_recovery_date <- (current_date add_seconds (ncw_sa_recovery_time));
        speed <- 0.0;
                }

// Activating the agent with regained SA.
        reflex activation when: current_date = ncw_sa_recovery_date and agent_status = "dormant" {
                ncw_sa_1 <- ncw_sa_1 + ncw_sa_update;
                agent_status <- "active";
                speed <- ncw_speed;
                }

// Creates SA from communication with neighbouring friendly agents and calls upon the action that
increases the SA.
     reflex sa_decrease_via_network  {
                ncw_networked_sa <- ncw_networked_sa - ncw_networked_sa_decrease;
                }
         reflex sa_increase_via_network when: agent_status = "active" {
                ask ncw_agents at_distance (10#meter){
                        do ncw_network_sa_increase;
                        }
                }
// Action called upon to increase the SA.

         action ncw_network_sa_increase {
                        ncw_networked_sa <- ncw_networked_sa + ncw_networked_sa_increase;
                }
// Called upon when the agent takes damage. It then self-inflicts set amount.
        action damage_ncw {
        ncw_hp <- ncw_hp - ncw_hp_decrease;
        }

// Calls upon the action that is determined in the other species when within the distance declared in the
attribute 'ncw_distance_to_reach'.
        reflex damage when: agent_status = "active" or agent_status = "attacking"{
                list<pcw_agents> reachable_pcw <- pcw_agents at_distance (ncw_distance_to_reach);
        if (! empty(reachable_pcw)){
                agent_status <- "attacking";
                speed <- 0.1;
                ask one_of (reachable_pcw){
                        do damage_pcw;
                        return pcw_hp;
                        }
                }
        }

// Transfers the status of the agent back to active when no target are closeby.
    reflex attacking_to_active when: agent_status = "attacking" {
                list<pcw_agents> attackable_pcw <- pcw_agents at_distance (ncw_distance_to_reach
                ) ;
                if (empty (attackable_pcw)){
                agent_status <- "active";
                        }
                }

// Creates sets of aspects to visualize declared attributes.
        aspect info {
                draw string (agent_status) size: 3 color: #darkblue;
                }
        aspect icon{
```

```
                draw ncw_image size: 20;
        }
        }

species pcw_agents skills: [moving]  {

    string agent_status <- "active";
        float pcw_speed <- 2.5 #km/#h update: 2.5 #km/#h * pcw_sa_2 * pcw_hp min: 1.0 #km/#h max: 2.5
#km/#h;
        image_file pcw_image <- image_file ("../includes/black_pawn.png");
        date pcw_sa_recovery_date <- date ("");

/*sa*/                  float pcw_sa_1 <- 0.5 min: 0.1 max: 0.5;

/*sa*/                  float pcw_sa_2 <- 0.5 update: pcw_sa_1 + pcw_networked_sa min: 0.1 max: 0.5;
/*sa*/                  float pcw_sa_update <- rnd (0.3, 0.4, 0.1);

/*sa*/                  float pcw_sa_decrease <- rnd (0.003, 0.004, 0.001);

/*sa*/                  float pcw_sa_recovery_time <- 5.0#s;

/*sa*/                  float pcw_sa_threshold <- 0.1;

/*damage*/              float pcw_hp_decrease <- 0.01;

/*Distance-to-reach*/   float pcw_distance_to_reach <- 75#m;

        float pcw_networked_sa <- 0.0 min: 0.0 max: 0.1;
        float pcw_networked_sa_increase <- 0.02;
        float pcw_networked_sa_decrease <- 0.01;
        float pcw_hp <- 1.0 min: 0.0 max: 1.0;

        bool pcw_is_wounded <- false;
        int pcw_is_dead <- 0 max: nb_pcw_agents_init;

        reflex move_to_target when: agent_status = "active" and pcw_hp > 0.3  {
                agent targetncw <- ncw_agents closest_to(self);
        do goto target: targetncw on:road_network;
                speed <- pcw_speed;
        }
        reflex retreat when: pcw_hp <= 0.3 {
                do goto target: any_location_in (pcw_starting_place) on: road_network;
                agent_status <- "wounded";
                pcw_is_wounded <- true;
        speed <- 2 #m / #s;
        }
      reflex death_summation when: pcw_hp <= 0.0{
        agent_status <- "dead";
        pcw_is_wounded <- false;
        pcw_num_dead <- pcw_num_dead + 1;
        return pcw_num_dead;
        }
        reflex die when: pcw_hp <= 0.0 {
                do die;
                }

        reflex sa_decrease when: agent_status = "active" or agent_status = "attacking"{
        pcw_sa_1 <- pcw_sa_1 - pcw_sa_decrease;
        }
    reflex dormant when: pcw_sa_1 <= pcw_sa_threshold and agent_status = "active"{
                agent_status <- "dormant";
                pcw_sa_recovery_date <- (current_date add_seconds (pcw_sa_recovery_time));
                speed <- 0.0;
        }
        reflex activation when: current_date = pcw_sa_recovery_date and agent_status = "dormant" {
                pcw_sa_1 <- pcw_sa_1 + pcw_sa_update;
                agent_status <- "active";
                speed <- pcw_speed;
                        }
```

```
        reflex attacking_to_active when: agent_status = "attacking" {
                list<ncw_agents> reachable_ncw <- ncw_agents at_distance (pcw_distance_to_reach) ;
                        if (empty (reachable_ncw)){
                agent_status <- "active";
                }
        }
     reflex sa_decrease_via_network {
                pcw_networked_sa <- pcw_networked_sa - pcw_networked_sa_decrease;
                }

         reflex sa_increase_via_network when: agent_status = "active" {
                ask pcw_agents at_distance (10#meter){
                        do pcw_network_sa_increase;
                        }
                }
         action pcw_network_sa_increase {
                        pcw_networked_sa <- pcw_networked_sa + pcw_networked_sa_increase;
                }

   reflex damage when: agent_status = "active" or agent_status = "attacking"{
                list<ncw_agents> reachable_ncw <- ncw_agents at_distance (pcw_distance_to_reach);
        if (! empty(reachable_ncw)){
                        agent_status <- "attacking";
                speed <- 0.1;
                ask one_of (reachable_ncw){
                        do damage_ncw;
                        return ncw_hp;
                }
        }
    }
        action damage_pcw {
        pcw_hp <- pcw_hp - pcw_hp_decrease;
        }
        aspect info {
                draw string (agent_status) size: 3 color: #darkred;
                }
        aspect icon{
                draw pcw_image size: 20;
        }
        }

experiment "Sandbox Batch File" type: batch repeat: 500 keep_seed: false parallel: 1 until:
((nb_wounded_ncw_agents + nb_dead_ncw_agents) = nb_ncw_agents_init) or ((nb_wounded_pcw_agents +
nb_dead_pcw_agents) = nb_pcw_agents_init) {
}
```

Appendix 3: Overview of the attribute values per scenario

Scenario type	Scenario	SA Level		SA Threshold		SA Decrease		SA Update		SA Recovery Time (steps)		Distance to Reach (m)		Group Size		Damage (per tick)	
Reference	1. Reference model	0.5	0.5	0.1	0.1	0,003 or 0,004	0,003 or 0,004	0,2 or 0,3	0,2 or 0,3	5.0	5.0	75	75	20	20	0.01	0.01
Themed models	2. SA	0.5	**1.0**	0.1	**0.5**	0,003 or 0,004	**0,002 or 0,003**	0,2 or 0,3	**0,3 or 0,4**	5.0	**1.0**	75	75	20	20	0.01	0.01
	3. Distance to reach	0.5	0.5	0.1	0.1	0,003 or 0,004	0,003 or 0,004	0,2 or 0,3	0,2 or 0,3	5.0	5.0	75	**100**	20	20	0.01	0.01
	4. Group size	0.5	0.5	0.1	0.1	0,003 or 0,004	0,003 or 0,004	0,2 or 0,3	0,2 or 0,3	5.0	5.0	75	75	20	**10**	0.01	0.01
	5. Damage	0.5	0.5	0.1	0.1	0,003 or 0,004	0,003 or 0,004	0,2 or 0,3	0,2 or 0,3	5.0	5.0	75	75	20	20	0.01	**0.015**
Combination	6. Combination	0.5	**1.0**	0.1	**0.5**	0,003 or 0,004	**0,002 or 0,003**	0,2 or 0,3	**0,3 or 0,4**	5.0	**1.0**	75	**100**	20	**10**	0.01	0.01