Exploration of paths leading to major power war

A thesis of an Agent-Based Modelling exploration of pathways leading to major power wars

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Preface and acknowledgements

This report is the result of a graduation trajectory at the faculty TPM, Systems Engineering, Policy Analysis and Management (SEPAM) program at the TU Delft. As such, it is the culmination of a two year program with the aim of obtaining the degree Master of Science (MSc).

When the time had come to find a research topic to write my thesis in, I sought out external parties that were interested in Agent-Based Modelling (ABM). Through one of my teachers, I came into contact with Willem Auping, who, in addition to being an external PhD candidate at the TU Delft, is also an analyst at the Hague Centre for Strategic Studies (HCSS). Willem and his colleague Tim Sweijs, as well as the rest of HCSS, presented me with the opportunity to do an internship and work with all the great people at HCSS, for which I am very grateful.

The context of this research and my internship at HCSS has been aimed at expanding the thinking of policy makers and others. The exploratory nature of this research allowed me to look at decades-old problems with a fresh perspective.

I would like to thank HCSS and the people there for providing me with this opportunity. I found the time I spent at HCSS very interesting and I was definitely inspired by all the work that is being done. In particularly, I would like to thank Tim Sweijs and Willem Auping at HCSS. They tirelessly helped me with my research and made everything possible. Also, the feedback provided by Stephan de Spiegeleire at various times throughout the process was very helpful.

In addition to the people at HCSS, I would like to thank the members of my graduation committee. First, I would like to thank Jan Kwakkel for serving as my first supervisor and for helping me sort out all the details and problems with the workbench. Also, your feedback in writing was immensely appreciated. Professor De Bruijn I would like to thank for his insightful questions and his repeated efforts to push me to make sure that everything would be understandable for practitioners. Finally, Igor Nikolic provided me with useful suggestions and helped me improve my model with these.

Roderik Luteijn

April 7, 2015
Executive summary

Major power wars are among the deadliest events in human history. These wars among major power states cause destruction on a vast scale, but their origins are highly debated on. States may seek to expand their power, increase their own security, gain resources or wage war for different purposes. A large collection of theories is available regarding these motives, but conclusive evidence remains elusive.

Previous research into major power wars has mostly taken place within the field of International Relations. In this research, the use of statistical model to estimate aggregate relations among predictors and major power wars has been common. This method has however led to mixed results with scholars unable to agree on conflicting and partially overlapping theories. The method suffers from certain key characteristics of the problem, such as the lack of a large amount of samples. It therefor seems reasonable to take a different approach. In order to provide a new fresh look onto this topic, the following question will be answered in this thesis:

What pathways can be identified in the interactions among nations that lead to a major power war?

Two distinct methods are used to look into this question. First, an extensive literature study is performed of the available theories, the paths to major power suggested by these theories and the evidence in support of these. Additionally, a review is done of the models that have previously been constructed studying similar topics. Second, an agent based model is constructed from the point of view of generative science. In this research, the generative science approach is posed as a viable alternative to previously used methods. Generative science is not strictly deductive (or inductive), but is aimed at explaining the emergence of macroscopic societal regularities. As such, a model is used in which the interactions between states may be used to study the emergent behavior of interest. In tandem with this approach, uncertainty was used for the inputs and for analysis of the outputs on the basis of Scenario discovery.

Out of extensive experimentation with the model, the following results and conclusions were obtained:

- Polarity is the amount of major powers in the system and thus also the amount of major powers that could possibly be involved in a major power war. It was found that in a bipolar world, i.e. with two major powers, fewer conflicts would escalate to major power war than in a multipolar world. In a multipolar world, there are more major powers and thus more
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potential for wars, especially because a multipolar world allows for multiple dissatisfied contenders.

- Polarization is an expression of how hostile states are, taking into account their own relation and their allies. It was found that major power wars are fought most of the time under conditions of high polarization. In practical terms this means that when a high degree of polarization is present, there are far fewer restraints to waging wars in the form of mutual allies. Low values of polarization at the initiation of a war are however also present, in which case polarization may be concluded to be not enough of a restraint to prevent war.

- Interdependence is the manner in which states are mutually dependent on each other, most often expressed in terms of exports and imports. Interdependent states are hypothesized not to wage war in the so-called liberal thesis. The vast majority of all major power wars in the outcomes occur under conditions of low interdependence. These major powers thus have no trade relations, or a very small volume of trade, and are thus not restrained by the potential loss of welfare. However, under conditions of extreme dissatisfaction and high interdependence, war is still a possibility.

- During the cold war, most states would be either ideologically similar to the US or to the USSR. It was then hypothesized that ideologically similar states do not fight among each other. In the results, the major powers fighting against each other are not very dissimilar or very much alike. Instead, most major power wars are fought under a medium ideological dissimilarity. The similarity of the fighting states is based on the difference in various cultural traits.

- Power transitions among the most powerful states in the system appear to be very often adjacent to major power wars. Both before and after major power wars, power transitions are very often found. When a rising state threatens to overtake the previously dominant state, this is expected to lead to conflict over who is the dominant state. Additionally, the destructive nature of major power wars may lead to a change in power relations and may cause a transition by itself.

- Power parity is often mentioned a necessary condition for fighting among major powers. In the model outcomes, it was found that a majority of wars is indeed fought at power parity. Power disparity among fighting powers is however possible if the weaker power is very risk acceptant and has an emphasis on potential spoils in its utility calculation.
The power of a state typically goes through a variety of different conditions over time. The power of a state may be stagnant, or newly rising, but generally goes through a number of potential points on the power curve of states. States fight at various points in their respective power curve, so-called inflection points. It was expected that declining states would often fight rising states, but it was found that most often rising states fight each other.

- Perceptual uncertainty allows for both sides to a conflict to think they will win a confrontation. Even though most states correctly assess their opponents, miscalculations do occur.

- Finally, dissatisfaction with the status quo will cause states to become far more risk acceptant and fight more wars.

The implications for policy and policy makers are threefold. First, certain aspects may be indicated as barriers to the occurrence of major power wars. If these aspects are in place, very few major power wars occur. In the model outcomes, high interdependence, low polarization and highly accurate information regarding capabilities may be marked as barriers to the occurrence of major power wars. If these conditions are present, war is not impossible, but does appear to occur less frequent. Second, certain circumstances may be deemed high risk situations. Certain aspects of states may make them more prone to waging wars and thus may warrant caution. In the model outcomes, extremely high risk appetite due to dissatisfaction is very high risk. Additionally, power transitions present similar risky situations, as well as power parity.
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1. Introduction

1.1. Context: a changing world
During the 20th century the world saw the devastating effects of two world wars. These two wars were among the deadliest and most devastating of its kind with many million deaths, civilian and military, and billions of dollars in damages. These two world wars can be grouped into the category of major power war (MPW). These wars are fought among major powers and tend to be fought on a far larger scale than other types of wars. When the example of the two world wars is taken, WWI was fought between Germany and Austria-Hungary on one side and Britain, France, Russia, and the United States on the other side. WWII was fought between Germany and Japan on one side, and Britain, France, Soviet Union, and the United States on the other side. In addition to these major powers, various minor states were involved through alliances and other commitments. Through the involvement of major powers, these wars have been far more deadly than any war that followed (Pinker, 2011). The results of these wars have been rather drastic in other aspects as well. Entire countries seized to exist or emerged rather suddenly. The world map was drastically redrawn as a result of these wars.

The most striking conclusion from the wars over the past 70 years may be the lack of large scale wars since WWII. Indeed, no major power wars have occurred since WWII. Wars have occurred since WWII, but these have been relatively small scale events. Additionally, most of these wars have been civil wars in specific geographic regions such as south-east Asia and Africa. At the time of this writing, this is a 70 year period without any such wars and a relatively peaceful world. MPWs may safely be grouped into the category of black swan events (Taleb, 2007): very high impact but low probability events. This relatively peaceful period has led some to question the likelihood of a MPW ever occurring again.

When looking back at the post-WWII era, the world has been very stable for most of that period. The United States and the Soviet Union emerged as the winners of WWII and remained the only two major powers up until the 90’s. The fall of the Soviet Union was a major change in the configuration of the world’s nations, but did lead to a stable unipolar system led by the United States. The stability of this unipolar configuration has come to question in recent years considering the world is changing.

The most notable change in the world has been the rise of the so-called BRICS (Brazil, Russia, India, China, and South-Africa) (Sachs, 2004). These former developing countries have experienced large
growth for long periods of time. These states have become large and powerful, and are either on the brink of becoming major powers or recently became major powers. They have the potential to become major powers through the sheer size of their population and resources/economic strength. Within these BRICS, China and Russia are of particular interest. China has such a large population and manufacturing strength that it has been able to acquire significant military strength as well. The combination of these three aspects makes China very much a contender to become a major power (Yuan, 2000). Russia experienced a difficult economic situation following the collapse of the Soviet Union. However, due to a resources boom starting in the late 90’s, Russia’s economy has soared (Ahrend, 2005). Since the annexation of the Crimea in the spring of 2014, this Russian economy experienced a sharp decline however (Galpin, 2015). Nevertheless, the economic strength comes in addition to Russia’s significant military forces. A large part of the material is a Soviet Union legacy, but may still form a significant military force (Gvosdev, 2014).

The one remaining major power after the collapse of the Soviet Union has been in a state of relative decline since the 90s. This does however not mean that the US is no longer powerful. The US still retains the strongest military forces of any state and has been spending more on military than the next few countries combined over the past decades (T. R. Cusack & Don Ward, 1981). This military spending relies heavily on the economic strength of the US. Despite outsourcing of manufacturing and a move to services, this economic prowess remains. A large population and various resource deposits aid in this economic strength.

The traditional home to major powers had been the European continent for centuries. WWII left the former major powers here unable to retain that position. In efforts to jointly regain a position of power, far-reaching integration efforts have been made among the states in Europe. The core of this integration has been cooperation and economic strength. When taken together, the member states of the EU have a GDP and population that exceed in size the US (World Bank, 2015). The military capabilities and spending are however not on the same level. Due to a lack of integration of military forces, repeated calls have been made for the creation of an EU army. The combination of forces may correct for the observation that currently the combined military forces are far weaker than the US (Sparrow, 2015). This is partially compensated for by a fairly advanced military of various member states of the EU. These combined military forces may not be on the same level as the US, but are definitely formidable (Majumdar, 2015). A major problem for the EU is a lack of resource deposits that are needed. It is, therefore, dependent on various other countries for its resources (Harsem, 2011). Through alliances and other attachments (colonial or otherwise), they have been able to trade for these resources. The traditional military alliance with the US has come under pressure however
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when the US invaded Afghanistan and Iraq against the wishes of most of the EU. This signifies a changing US-EU relationship, in which the EU is more likely to assert its own agenda.

A surge in the power of BRICS, as well as a more independent EU, is in the presence of a declining major power. In the light of a history with major wars among major powers, are such wars even still possible in the modern time? Or, is the changing configuration of the world just a prelude to new and devastating wars?

1.2. Problem introduction

The devastating nature of major power wars has led to extensive studies on the topic. The systematic analysis of major power wars, and war in more general terms, was popularized by the Correlates of War (CoW) project (Singer, 1972). This comprehensive dataset contains a large amount of historical records concerning wars, macroeconomic data, and more. This database represents one of the most comprehensive attempts at gathering data systematically and using this data to test a wide range of hypotheses regarding wars and other topics within International Relations.

Statistical models exploring the significance of predictors and key variables for major power wars have produced certain regularities. These models have however been limited by the very nature of the problem: (1) a large number of potential factors, (2) large amount and complicated interactions, and (3) a small set of cases. The result of these difficulties has been a confusing set of theories and evidence. Performing data analysis on such rare events has yielded a large amount of conflicting evidence. Scholars have thus been unable to agree on the validity of the set of theories represented by the models which provide conflicting and overlapping predictions. What remains is a large set of theories on which no agreement may be reached because the method is by nature likely to produce conflicting claims.

1.3. Problem formalization

1.3.1. Knowledge gap

Various theories on the origins of war explain some of the root causes of major power wars. Each of these theories proposes at least one path that might lead to a major power war. Some of these paths have common features or overlap in certain aspects. It can even be said that most of the theories do not preclude each other and are concurrent explanations. None of the proponents of the theories have provided conclusive evidence for their theory. For every theory, studies exist claiming the opposite. Despite the inconclusive nature of this evidence, these theories are still likely candidates for explaining some of the causes of major power wars.
The existing studies aimed at explaining the occurrence of major power wars are mostly deductive studies. Deductive science within social sciences typically involves gathering macroeconomic data and estimating aggregate relations econometrically (J. Epstein, 1999). These deductive studies have, however, failed to provide convincing proof regarding the validity of the theories. In this research, a different approach to these theories and explaining major power wars is used. Building on the work of Epstein in generative social science, the aim is to offer a generative theory on how major power wars occur. In generative theory, deterministic rules and parameters are used to generate local behavior of actors from which systemic behavior emerges. By modelling individual or the smallest level components, exploration of explanations for the emergent phenomenon becomes possible (Nikolic & Dijkema, 2010). Generative social science is based on the idea that by growing local interactions among actors, complex overarching behavior can emerge. Therefore, when the interactions between states and the internal processes of states are duplicated in a simulation model, structures will emerge that should resemble the observed behavior of the international system. One particularly appealing aspect of generative social science is the ability to experiment with the models, where empirical experiments tend to be impossible in IR.

1.3.2. Research questions
The main research question for this project is:

| What pathways can be identified in the interactions among nations that lead to a major power war? |

Considering the potential explanations of the origins of major power wars, what pathways can be identified that lead to major power war? Specifically, which (initial) conditions and actions can lead to major power wars? How are these conditions influenced by interstate trade, minor wars and other types of exchanges?

The following sub questions will provide an in-depth exploration of various parts of this topic:

1. **What theoretical and empirically/historically pathways have been identified in scientific literatures that lead to (major power) war?**

   In an extensive literature review, pathways are identified and evaluated for their explanatory value. Empirical evidence provided by previous studies will be of specific importance in this aspect. Historic examples of the major power wars provide us with examples of pathways that did indeed lead to major power wars. The results of this literature review can be found in chapter 3.
2. **What theories have been previously applied in modelling studies and can be applied to this modelling study?**

A large amount of studies has already been performed on topics such as polarity and interdependence. Even though most of these studies used a strictly deductive or are outdated, useful elements might be found in these studies that can be reused in the current research. A limited number of studies has also attempted to use agent based modelling to build models related to security studies. Elements such as operationalization of variables, parameter values and more might be obtained from these studies.

3. **What pathways are generated by decentralized local interactions of heterogeneous bounded rational agents that lead to a (major power) war?**

In the generative social science approach of Epstein (J. Epstein, 1996), this question seeks to explain the behavior of interest by proposing an Agent-Based Model. This model will use the interactions among pairs of states that act bounded rational to create a model of the states of the world. Within the model, specific attention will be paid to wars among states and how these wars may develop into a major power war.

### 1.4. Reading guide

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2. Research approach

This chapter provides a description of the methods and tools used. First, an explanation is given of the perspective used in this research. In the light of this perspective, the research methods were chosen (2.2). Second, for the specific implementation of the research method, the framework described by Van Dam et. Al. was used (2.3). Final, the tool used in this research was Netlogo (2.4), alongside the EMA workbench (2.5).

2.1. Perspective

Most studies in IR over the past several decades have used deductive approaches to generate and test theories. Deductive science within social sciences typically involves gathering macroeconomic data and estimating aggregate relations econometrically (J. Epstein, 1999). This general approach has however not generated theories regarding the origins of war that can stand the test of evidence. The evidence issues mentioned previously are therefore a clear example that deductive sciences as conducted in IR are unlikely to provide the sort of insights that scholars are looking for.

As an alternative to inductive and deductive sciences, generative science may be applied (J. Epstein, 1996). Generative science is not strictly deductive (or inductive), but is aimed at explaining the emergence of macroscopic societal regularities (J. Epstein, 1999). Central to this approach is the question: “How could decentralized local interactions of heterogeneous autonomous agents generate the given regularity?” (J. Epstein, 1999, p. 41). In this question, five key aspects are present that represent the defining characteristics of a generativist study. First, heterogeneity of the element being studied, being people, states or something else. There is no universal actor, every human being is different. It is therefore sensible to allow for heterogeneity in your agents. These agents are not mere machines that follow orders, but rather are able to make their own decisions. These decision-making abilities are limited, however, and based on incomplete information, a principle known as bounded rationality. As they move around in some landscape of interest, the interactions of these agents generate the behavior of interest. In order to answer this question, the following experiment is performed: “Situate an initial population of autonomous heterogeneous agents in a relevant spatial environment; allow them to interact according to simple local rules, and thereby generate – or grow – the macroscopic regularity from the bottom up.” (J. Epstein, 1999, p. 42)

The generativist’s research does not aim to give definite answers explaining a certain regularity of interest. It rather aims to demonstrate that a certain specification of interaction is sufficient to generate the macrostructure. Thus, multiple specifications may all yield the same macrostructure.
Every specification is a candidate explanation of the macrostructure of interest. The basic motto of generative sciences is “If you didn’t grow it, you didn’t explain it” (J. Epstein, 1999, p. 42) In this research project, the local interactions are the interactions between states such as trade and conflicts. These interactions over time will allow for wars being fought out between states. The structure of interest is the major power war, which is considered a special form of warfare that only arises under a specific set of circumstances.

The choice for the use of a generative approach to explaining major power wars is in the first place inspired by the evidence issues explained previously. The “regular” deductive approaches are not providing any new answers and thus an alternative is needed. In addition to this observation, the ability to experiment with policy directions in the models to be generated is important. Such experiments are impossible to perform in the real world. Finally, understanding or agreement over the overall behavior is not required to be able to grow the behavior that leads to major power wars (Borshchev & Filippov, 2004). States as actors are fairly complex, but this approach only requires modelling of the interactions needed to generate the overarching structure of interest.

Finally, this model is not a forecast of what will happen. Rather, it is an exploration of many different outcomes that show similar regularities to the real world. Any relations found in the model are there for possible explanations for what happens in the real world, but no more than possible explanations.

2.2. Agent-Based Modeling
Agent-Based Modeling (ABM) was chosen as the modelling paradigm to be used in this research, considering the generativist perspective. Provided with this generativist point of departure previously discussed, this choice seemed to be a sensible. There are close ties between generativist science and ABM and they are commonly used together (e.g., Epstein, 1996). In fact, they share several properties, most notably heterogeneity, autonomy and local interactions. In an agent-based model, agent characteristics can be assigned as the modeler desires, often through use of stochastic functions. The agents are not controlled directly by the modeler, unless so desired, and thus experience autonomy. Finally, agent interactions are typically defined pairwise. These strong similarities exist between generative sciences properties and ABM, which makes combining them a sensible choice.

Quantitative exploration of the origins of major power wars is enabled through ABM. Specifically, computational experiments may be performed with the model created in order to gain a deeper understanding. Specifically, Exploratory Modeling Analysis (EMA) will be used to experiment with the
model and perform analyses. EMA is a “methodology for performing a systematic exploration of different combinations of assumptions about system structure, uncertain trends, uncertain parameter values, and different models” (Pruyt & Kwakkel, 2014). The EMA approach is used to first explore the model outcomes for potential generativist explanations for the major power wars. Additionally, scenarios are generated for further experimentation with policy options.

The need for exploration and extensive experimentation originates from the multitude of sources of uncertainty that can be expected in the model. First, the usage of ABM as a method generates certain stochastic uncertainties. The order in which the individual agents execute their code as well as the use of random seeds creates uncertainty in the outcomes (Railsback & Grimm, 2011). In addition to the methodology, the input for the model is also highly uncertain. The “true” values of certain inputs are highly debatable. This requires a wide range of potential for these inputs to be used in order to account for all possible values. On occasion, input uncertainty may translate into the need for stochastic elements in the model. These elements are needed for simulation of behaviors observed in real world. However, this requires a large amount of replications in order to remove potential bias that might skew results (Railsback & Grimm, 2011). The result of these uncertainties is that extensive experimentation and exploration is required in order to compensate for the high amount of uncertainty in the model.

### 2.3. ABM framework

The modelling process used in this research is based on the methods presented in the book Agent-based modeling of socio-technical systems (Dam, Nikolic, & Lukszo, 2012). This book prescribes a 10 step method for creating an agent based model, as presented in Figure 1. A quick overview of the steps is given in this section, as well as numerous references throughout the text may be found to these steps. For a more thorough explanation of the steps, the reader is referred to the book.

![Figure 1 Modelling Process based on (Dam et al., 2012)](image-url)
2.4. **Netlogo**
The model is implemented in the software Netlogo (Wilensky, 1999). The choice for this software was made on the basis of high accessibility. Netlogo is a fairly easy to use environment that is available even to non-programmers. Also, a large library of previously implemented models is available for study as well as numerous online forums and an extensive manual. It has been widely used in various research projects in a variety of fields and has been commonly embraced within the ABM community. Personal familiarity with the tool as well as the availability of expertise at the faculty finally made the choice for Netlogo a sensible one.

The choice to use Netlogo does have its downsides. The modeling possibilities within Netlogo are limited when compared to a full programming language. Certain features have not been implemented in Netlogo, most likely to increase ease of use for novice users. More complex or extensive models may, therefore, not be implemented in Netlogo, which does harm the potential for expanding the model (Kasmire, Nikolic, & Dijkema, 2013).

2.5. **Experimentation and data analysis**
In order to facilitate experimentation and data analysis for the model, the EMA workbench software is used (J. H. Kwakkel, 2011). This software connects to Netlogo and allows for extensive experimentation with uncertain inputs as well as data analytics. The open source nature of the software may be adapted to suit the needs of the modeler. It must be mentioned that Netlogo does have a built-in function for experimentation, called Behaviorspace. This functionality, however, severely lacks speed and potential for adaption, and will, therefore, not be used.

The methodology used in combination with the EMA workbench software is Scenario Discovery, in addition to Patient Rule Induction Method (PRIM). EMA encompasses the use of computational experiments to allow for analysis of complex and uncertain systems (Bankes, 1993). The method is not aimed at finding a single optimal model that is the best predictor. It is however designed to deal with deep uncertainty often present when insufficient knowledge is present. It sees the model as a plausible hypothesis about the structure of the real system. Parametric, structural and methodological uncertainties are then included (Briggs & Weinstein, 2012). This allows for the analysis of a wide range of scenarios considering the various uncertainties present.

In order to facilitate model exploration and to evaluate a wide range of model outcomes, the scenario discovery technique is used. This technique is designed to address problems that are characterized by a large amount of uncertain inputs (J. Kwakkel, Auping, & Pruyl, 2013). In order to account of the uncertain nature of the inputs of the model, rather than using a single model state,
multiple alternatives are used in the analysis. These alternatives are chosen on the basis of an initial exploration of the model outcomes. Unexpected or strange outcomes are likely sources of these alternatives. These scenarios will then be analyzed through use of the PRIM algorithm in order to identify those combinations of inputs that explain the outcomes of interest.

The PRIM algorithm was presented by Friedman and Fisher (1999). It is an algorithm for identifying regions within the input parameter space that produce a certain output (Friedman & Fisher, 1999). These regions are identified through an iterative process of peeling and pasting. This process selects boxes of parameters that describe a certain part of the outcome space. PRIM will be used in the analysis of the results in order to identify groups of parameters that may explain certain model behavior.

The results obtained with methods described in these 5 paragraphs are presented in chapter 7 and several appendices. In the following chapters, the theoretical background of the various aspects of the model is presented. Then, the model is described and the results are presented.
3. Literature review of pathways

In this chapter an overview of the literature within IR is presented that deals specific with the origins of major power wars or more generally speaking the origins of war and conflict. Six major areas of research are discussed in sections 3.1 – 3.6. A complete overview of the discussion is presented in section 3.7 with all paths, their source and a short summary. The literature presented here forms the basis for the model conceptualization further on.

3.1. Polarity

3.1.1. Example
The first set of theories centers around the idea that the number of poles in a system and changes herein cause major power wars. The general idea of polarity can be understood through a historic example.

During the period known as the Cold War, the distribution of power among the states of the world was called bipolar. This meant that at the time two states were vastly more powerful than all the other nations, which made these two states major powers. These major powers (US and USSR) both acted as poles around which the other nations rallied through alliances and other associations. This resulted in the world being divided (or polarized) into two camps surrounding the two major powers. These two major powers engaged in competitive behavior that created a very volatile situation.

3.1.2. Definitions of polarity
The degree of polarity is typically defined as the number of major powers in the world (Geller & Singer, 1998). Given the degree of polarity, three distinct configurations can be distinguished.

A bipolar configuration describes the situation where two major powers of approximately equal capabilities exist. These two major powers are each individually vastly more powerful than all other states, but are unable to dominate each other.

A multipolar configuration describes the situation where three or more major powers of approximately equal capabilities exist. The major powers are all rather powerful, but often unable to defeat another major power by itself. Throughout history, only a small number of states have even been a major power, and a very large number of major powers are, therefore, unlikely. It is however possible for multiple states to be major powers, even though more than a handful is unlikely.
A unipolar configuration describes the situation where only one major power exists and no other states have approximately equal capabilities. This single major power is vastly more powerful than all other states over a range of aspects including military and economic capabilities. This preponderance in power allows a major power (referred to as the hegemon) to act unilateral. Much of the traditional IR literature does not acknowledge unipolarity as a potential configuration, most notably in the form of Waltz (1979) and only sees bipolarity or multipolarity as options. Such literature implies that a unipolar configuration is by definition temporary, considering other states will aim to catch up with the hegemon. A unipolar configuration however does not allow for major power war and will not be discussed any further.

3.1.3. Paths to war

**Bipolarity**

In a bipolar world, often a rather unique balance of power and systems of alliances is present. Balancing of power is far more difficult in a bipolar world due to the rigid nature of the configuration (Woolsey & Morgenthau, 1950). For instance, the role of balancer as played by Great Britain prior to WWI would be impossible in a bipolar world (Goddard, 2008). In this period in time, Great Britain would align itself with the weaker of the continental powers in order to prevent any power from dominating continental Europe. Such a role requires at least one of the major powers to be flexible in its allegiances. However, in a world with only two major powers, there is no third major power capable of balancing. Thus, external balancing is not possible due to a lack of unaligned major powers.

Despite the lack of a balancing state, other forms of balancing are still possible. Some minor states may be unaligned and often have no choice but to join the alliance of either major power to ensure their survival. Collective security through banding together of minor states is more difficult when there is a preponderance of power in the hands of the two major powers. The size of the alliance of minor states required to acquire similar levels of power is so large that the alliance is almost by definition instable (Singer & Deutsch, 1964). In addition to the failure of collective security, major powers will attempt to persuade these states to join their alliance in order to prevent the opposing major power from aligning with them. The result is a world with two highly competitive blocks of alliances, consisting of major powers and minor states that need each other for their security (Nakagawa, Sejima, & Fujimoto, 2010). This process is likely to severely polarize the world into two camps. These camps are likely to be roughly balanced in terms of power. In turn, the loss of any ally, no matter how minor, is vital (Waltz, 1979). This was expressed in the US strategy of soviet/communism containment (Vasquez, 2009). Minor wars involving allies may thus bloom into a major war where major powers defend their respective allies.
A bipolar world tends to breed competition among major powers. These major powers often perceive the world as a zero-sum game (Rosecrance, 1966): one’s gain the is the other’s loss. This attitude creates fertile ground for arms races and other competitive behavior (Friedberg, 1993). First, severe distrust creates an atmosphere where major powers build capabilities out of a perpetual belief that the other major power will strike first. Consequently, once one of the sides has a sustained advantage, it is theorized to be likely to attack preventively (Rosecrance, 1966).

**Multipolarity**

A multipolar world is a world which is by definition suited to balancing of power. The availability of multiple major powers drastically increases the amount of potential alliances. Balancing of power also may lead to war under certain circumstances. For instance, two or more major powers are able to join forces in order to destroy a third (Waltz, 1979). According to the realist school of thought, this makes a multipolar configuration unstable by default (Waltz, 1979). It requires constant vigilance of major powers and the knowledge that even major powers may be destroyed creates distrust. Thus, the balancing of power among great powers involves a flexible system of alliances where allies can be enemies the next day (Waltz, 1979). The intentions and capabilities of opponents are highly uncertain due to the flexibility of the configuration of the world. The multipolar world thus is very much changing world.

In addition to the changed nature of balancing in a multipolar world, the bargaining processes among actors are increasingly difficult with more players (Waltz, 1979). Reaching agreements with multiple players requires taking into account the diversity in the interests of the parties to agreements (Singer & Deutsch, 1964). Smaller shares for each players and larger costs of enforcing agreements due to the increased amount of players further complicate bargaining. The odds of a freeriding behavior occurring among the major powers drastically increase (Morrow, 1991). All of these aspects lead to a smaller chance of peaceful resolution of issues, increased distrust among states, and thus a larger likelihood of wars occurring.

In final instance, a multipolar configuration increases the amount of interdependence among the states. In general, interdependence is theorized to lead to conflict and conflict leads to war (Waltz, 1979), as further discussed in section 3.3.3. The reason for the increase in interdependence is that as the number of major powers increases, the spheres of influence tend to be smaller. A higher ratio of major powers to minor powers allows for smaller spheres of influence on average. As these spheres get smaller, major powers are more likely to depend on other major powers in order to secure its resources and such. In a multipolar world, an increase in major powers means an increase in interdependence.
3.1.4. Stabilizing effects

Bipolarity
In the case of alliance blocks in a bipolar world, an analogy may be drawn to market size in the field of economics (Waltz, 1979). Within economics, the argument is made that a market with fewer players is more stable. To this effect, according to the theory, a market with only two (large) players is the most stable. First, a large power differential in comparison to potential new entrants discourages such entry. In IR, the cost of obtaining power parity and challenging an established major power is comparable to high barriers to entry in a market. Second, a decrease in the amount of firms in a market decreases the cost of enforcing agreements among the parties. Thus, bargaining solutions are possible among states and war is less often needed to resolve an issue. The opportunity costs of interactions and competition among states appear to be highest in a bipolar world (James & Brecher, 1988). Finally, there is a shared interest of the firms to maintain the status quo in order to stave off the high costs of competition; in IR the costs of competition may be found in arms races and potentially conflict.

In addition to the analogy to economics, three additional theories have been put forward by the proponents of bipolarity. First, the decrease in interdependence experienced in a bipolar world, stabilizes the world (Waltz, 1979). The reasoning here is that the major powers are less dependent on each other than are the smaller powers. Bipolarity is the minimal interdependence configuration and thus the most stable. Second, a decrease uncertainty among states leads to less wars being fought. Uncertainty creates the circumstances for wars because wars are only fought when there is the conviction from both sides that it could be won (Waltz, 1979). In a bipolar world, there is little uncertainty regarding who the opponent is and thus enough attention may be paid to this state to ascertain its capabilities. Third, the two major powers and their alliances experience nearly constant pressure and a recurrence of crisis (Waltz, 1979). This allows for a learning effect and decreases the uncertainty regarding the opponent. One author has expressed that “the world’s most peaceful place is at the brink of war” (Rosecrance, 1966). With low levels of uncertainty, the world is reduced to a two player game with perfect information in which war is highly unlikely.

Multipolarity
As expressed in the paths to war section of multipolarity, a multipolar world is highly suitable for a balancing of power policy. Various authors (Geller & Singer, 1998; Goddard, 2008; Woolsey & Morgenthau, 1950) have argued that this balancing potential makes multipolarity a stable system. Through the process of engaging in alliances, the major powers in the system balance each other’s power. If one state experiences a rise in power, changes in the alliances will be made to reflect this changed distribution of power. In general, it can be said that alliances tend to be fluid and change
Exploration of paths leading to major power war

over the course of time and thereby cause restraint among major powers. Through the balance of power, predatory behavior of states can be stopped or limited through the alliances structures.

The increased amount of major powers in a multipolar system changes the nature and degree of uncertainty regarding opponents and allies. A multitude of major powers allows for more interaction opportunities among these powers (Singer & Deutsch, 1964). Even though the absolute amount of interaction opportunities increases, the total amount of attention a state can pay to all its contenders together remains the same. Waging a war requires a minimal amount of attention to be paid to a specific actor (or learning opportunities) in order to decrease the uncertainty regarding capabilities. If states are unable to assess their probability of winning with a certain degree of certainty, they are likely not interested in waging war.

3.2. Power transitions

3.2.1. Example
A second set of theories is based on the idea that major power war occurs when a state grows in power and starts to threaten the position of more powerful states. A historic example of a power transition:

In the period leading up to World War II, Germany was rising in power. It had recovered from the devastation of WWI and was now a major power again. After growing to power parity with previously dominant powers, Germany demanded a larger role among major powers. However, other nations were fearful of Germany’s rise in the context of their previous experiences with German and were reluctant to give up their own power positions. One explanation for the occurrence of World War II is that Germany attempted to change its position through waging a major power war (Levy & Thompson, 2010).

3.2.2. Definition of power transitions
Power transitions are typically defined as the situation where a rising state overtakes the previously dominant state in power (Kugler & Organski, 1989). Their relative power relations, combined with dissatisfaction with the status quo may breed conflict between the status quo and the contender (Efird, Genna, & Kugler, 2003). The dominant state is often the winner of a previous major power war. Authors such as Gilpin assume that the most powerful state in the system, the hegemon, builds an international system to reflect and protect its interests (Gilpin, 1981). Various roles may be chosen by this dominant state, such as a balancing of power approach, or the imposition of hegemonic rule (Rosecrance, 2013). Challengers will not attempt to change the system unless the
expected benefits of intervening exceed the expected costs (Gilpin, 1981). If a potential challenger does claim a more prominent role, the dominant state is often unwilling to support claims of challengers (Organski, 1958).

The power distribution among states is not a static configuration, as states go through cycles of power (Doran & Parsons, 1980; Doran, 1989). States may experience internal growth, which allows them to rise from obscurity to prominence. Decline is however also a possibility, especially concerning previously dominant states. Dominant forces overstretch their empire and often wage wars for defensive/preventive purposes (Lebow & Valentino, 2009). Other states (relatively) rise in power due to realization of unused potential (Baldwin et al., 1980). The relative positions of states in the power cycle allows for a different level of effectiveness of foreign policy, but also different costs of executing policies.

3.2.3. Paths to war
A power transition creates the circumstances in which a war might occur between major powers that compete and the hegemon. A necessary condition for war is found in power parity between challenger and status-quo dominant state (Lemke, 1997; Tammen, 2006). The specific type of war concerned here is called hegemonic war, in which dominant powers and challengers fight over dominance (Vasquez, 2009), and is often combined with a power transition (Organski, 1981). At the point of power transition, conflict potentially arises from the dominant state defending its position as the dominant state and thus waging a preventative war. Alternatively, when the challenger demands a large role and is denied this, it attacks the dominant state. As the dominant state declines in power and another state rises to power, the latter will be capable of changing the international system, and presumably will be motivated to do so (Vasquez, 2009).

The power transition theory requires additionally that a degree of dissatisfaction is present with the challenger. All states will have a certain amount of satisfaction with current world order. It is expected that the hegemon is satisfied with the system it has created. The hegemon invokes either positive or negative reactions based on its chosen role (such as hegemonic ruler or balancer). The attitudes of other states vary based on the assertiveness of the hegemon and the nature of the interactions. War is less likely, however, if the challenging power is satisfied with the existing international order (Kim, 1992). Various peaceful power transitions may be explained by this idea, such as the Britain-US power transition.

3.2.4. Stabilizing effects
In the theory regarding power transitions and war, no paths have been found that stabilize the interactions among states other than that satisfied challengers do not initiate wars. Despite the lack
Exploration of paths leading to major power war

of specific paths to stability, several observations questioning the thesis that war is caused by power transition are proposed by different authors. Most notably, power transitions may be the result of war, rather than be the cause of it (Lebow & Valentino, 2009). The destruction of major powers wars, as well as spoils of war; result in a changed distribution of capabilities. Kim looks at this causality from the reverse perspective, arguing that there is a strong relationship between power parity and dissatisfaction (Kim, 1992). Kim maintains that dissatisfaction with the status quo is a more important indicator of war than changes in the power balance, a finding supported by Lemke and Werner (Kim, 1992; Lemke & Werner, 1996).

Finally, in historic examples both peaceful and war-prone power transitions may be found. Examples of a war in power transition (e.g., France-Prussia prior to 1870) and a Peaceful transition (e.g., United States-Britain in the nineteenth century) are both present.

3.3. Interdependence

3.3.1. Example
The third theory centers on the idea that all nations are mutually dependent on each other and this interdependence inhibits or promotes occurrence of major power wars. An example of interdependence:

The United States borrows large amounts of money from the world’s financial markets to fulfill its financing needs. The single biggest lender on this market is China, which makes the US dependent on China for its government financing needs. China’s economic growth on the other hand is primary fueled by exports to and manufacturing for the US.

3.3.2. Definition of interdependence
Economic interdependence has been largely ignored by most of the IR scholars (Levy & Thompson, 2010). Despite this lack of attention to interdependence, it is still expected to have an important impact on the occurrence of war. Interdependence is typically defined as a situation where states are mutually dependent on each other. Dependence in this case refers to the high costs of terminating the relationship (Streeten, 2001). The cost of ending a relationship may be found in the cost of finding a suitable replacement, or in general the decrease of income from the relationship. The interdependence of a state X with a specific partner Y in a given year is defined as:

\[ \text{Interdependence}_{XY} = \frac{\text{Exports}^{XY} + \text{Imports}^{XY}}{\text{GDP}_X + \text{GDP}_Y} \] (Oneal & Russet, 1997).
A classification of the type of interdependence is based on the type of benefits arising from the interdependence, being either positive sum or negative sum. Positive sums of interdependence refers to mutual beneficiary relationships such as collective security arrangements (Rosecrance et al., 1977). Negative sums of interdependence refers to the situation where both parties experience the relationship negatively, but staying in this relationship is more beneficial than exiting (Baldwin et al., 1980). It may be noted a different classification of interdependence may be found in the horizontal or vertical nature of interdependence. Horizontal or vulnerability interdependence indicates the avenues over which exchanges occur, based on transaction research (Tetrault, 1980). The classification refers to the extremely high opportunity costs of disruption of avenues over which transactions occur (Waltz, 1979). Nye and Keohane describe it as “a state of being determined or significantly affected by external forces” or “as a condition in which events in one part of the world covary with events in other parts of the world” (p. 8, Nye & Keohane, 1977).

3.3.3. Paths to War

Interdependence changes the utility calculation that states perform in order to decide whether to go to war. In the cost-benefit assessment, the costs of a war are increased by the lost welfare associated with potential trade losses (Polachek, 1980). This loss of welfare extends to third parties and if a conflict occurs between states, third party states could become involved to safeguard their own interests. Their utility from doing nothing might be so negative that they will join the war. Additionally, other states might want to join as well, resulting in further enlargement of the conflict. Thus, enlargement of the conflict or war is achieved through interdependence without formal agreements or exchanges prompting the enlargement.

In addition to enlargement of wars, asymmetry in the mutual dependence might lead to wars as well (Bearce & Fisher, 2003). In most inter-state relationships, the dependency is not symmetric and perceived different by both parties. Highly dependent states are likely to want to decrease the dependency due to its potential negative effects. In fact, trade may even impoverish the less powerful, due to an imbalance in benefits (Barbieri, 1996). Additionally, the less dependent side might be tempted to coerce the other side (Nye & Keohane, 1977). Especially in the case of major powers, competition for control over resources will tempt the use of force to put other states in a position of dependence (Barbieri, 1996).

One of the results of engaging in trade relationships is the ability to grow the national income, which can then be invested in other means such as the buildup of military capabilities. One-sided buildup may lead to a security dilemma among states and a host of other undesirable effects (Snyder, 1984). This one-sided buildup may be used in efforts to decrease dependencies in trade relations or to
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preemptively attack other states. The security dilemma arises when the other state perceives the military buildup as a threat, even though its purpose may be strictly defensive. It then has a choice to also build capabilities, leading to an arms race, or accept the asymmetry in military capabilities. The result is that trading with unfriendly states becomes less desirable. Trade can be said to create a negative security externality in the form of distrust among trading partners and potentially lead to preventative wars (Gowa, 1995).

3.3.4. Stabilizing effects

Interdependence is theorized to bring about stability and decreases the occurrence of wars by increasing the costs of going to war. This may make going to war become infeasible (Oneal & Russet, 1997). As an illustration of this principle, conflict may make certain goods unavailable, thereby damaging a states’ economy and abilities. Even if trade with a relatively minor trading partner is no longer possible, this might entail high costs due to increased dependence on other trading partners. The cost of switching trading partners might be so prohibitively large that it is infeasible to wage war, making the state dependent on this partner and a good relationship with this partner (Nye & Keohane, 1977). Knowledge of this fact and the dependencies might facilitate the creation of a "security community" (Deutsch, 1968), in which wars are highly unlikely due to high costs of terminating relationships.

In addition to increasing the costs of war, symmetry in the mutual dependence might stabilize the interaction as well. Trade benefits both parties in the relationship, giving each party an interest in the survival and wellbeing of the other (Oneal & Russet, 1997). Symmetric relations promote peace, while asymmetric relations create conflict (Wallensteen, 1973). Briefly stated, going to war in a symmetric relationship hurts both the attacker and the defender (Baldwin et al., 1980). In other words, going to war is like shooting oneself in the foot. Former US Foreign Secretary Hillary Rodham Clinton asked in reference to China “How do you deal toughly with your banker?” (MacAskill, 2010).

3.4. Rivalry

3.4.1. Example

The fourth theory centers on the idea that pairs of states engage in a competition over control of certain key resources. An example of a rivalry:

Following the unification of the northern German states under Prussian rule, France and Prussia engaged in a series of disputes and wars. One major war was fought out in 1870-1871 and resulted in a Prussian victory. Several minor conflicts involving colonial possessions and the former provinces of
the Ottoman Empire followed. Both parties sought to forge alliances as a means of restraining the other party and to control the continent through alliances.

3.4.2. Definition of rivalry
Rivalries often are a form of competition over certain scarce goods such as power, resources, and territory (Goertz & Diehl, 1993). They are typically characterized by “a sustained mutually contingent hostile interaction” (Vasquez, 2009). Mutually contingent refers to the policy of either state being viewed in the light of impact on the other state. Hostile interaction refers to the objective to hurt the rival rather than to gain something substantive. This objective is a form of thinking often associated with zero-sum games. The beginning and end of a rivalry is often hard to pinpoint exactly, as rivalries are more a process than an event. It involves at least multiple militarized conflicts between the same two states over a given timespan (e.g., Diehl required a minimum of 3 disputes(Diehl, 1985)). Multiple militarized disputes between rivals are part of an ongoing process over time and shouldn’t be viewed as singular events (Goertz & Diehl, 1993).

3.4.3. Paths to war
In general it can be said that a rivalry sets the stage for war, but does not cause it directly. Rivalries provide the stage for multiple successive crises among the same states, but a crisis doesn’t mean war erupts.

Two distinct paths to war have been identified within rivalries. The first path suggests a one-on-one war among rivals involving a territorial dispute. Other origins of disputes such as religion may also be possible, but territorial disputes seem to be the most prevalent. Strong emotions, as well as the number and length of interstate borders among rivals increases uncertainty (Midlarsky, 1974). The second path involves rivals without a territorial dispute join an ongoing war because of contagion factors (Vasquez, 1996). The Korea war of the 1950’s and the Vietnam war of 1960’s and 70’s can be seen as such wars. When rivals do not have any borders in common, crisis often erupts through conflicts between mutual allies, so-called proxy wars (Goertz & Diehl, 1993).

When a rivalry has come into existence among states, it tends to become a way of life for these states (Vasquez, 1996). The repetitive nature of hostile interactions leads to a vicious circle of disagreement–negative acts–hostility (Vasquez, 2009). The vicious circle often exists for long periods of time until either party is defeated or a solution is negotiated. However, relative parity is often present among rivals, making victory through conquest unlikely.
3.5. Balance of power

3.5.1. Example
The fifth theory centers on the idea that states seek to balance power through alliance structures. An example of a balance of power can be found in the period 1815 – 1914, also referred to as the Concert of Europe (Goddard, 2008).

In this period, in Europe multiple major powers coexisted. These major powers engaged in alliances with the main motivation of balancing the power of other major powers. Changes in the power of states meant that these alliances had to change often to reflect the new balance. The alliances often entailed conflicting obligations to multiple parties in order to restrain the major powers. It should be noted that balance of war policies did not expressly oppose war but rather served as a means of limiting their scope and frequency (Kissinger, 1994).

3.5.2. Definition of balance of power
In general, the balance of power theory poses that a country with a preponderance of power cannot be expected to behave in moderation (Waltz, 1979). It will seek to expand at the expense of others, unless it finds an obstacle in its way. Such an obstacle may be found in other countries that form a balancing alliance. The balance is restored in the system at roughly equal military capabilities for both alliances.

3.5.3. Paths to war
Balancing of power leads to alliance formation among major powers. Balancers will seek to achieve roughly parity of power among the major powers. The problem with power parity is however that war is more likely at power parity (Geller & Singer, 1998). The reasoning here is that war occurs when both parties feel like they are able to win. Logically both parties cannot win and this inconsistency is due to uncertainty in the perception of power. Both parties perceive their own power and their opponent’s power with a certain degree of uncertainty. When either party has a preponderance of power, near certainty on who will prevail is present. Thus, in a preponderance situation, parties will restrain from waging wars and acquiesce to the stronger party (Organski, 1981).

Balance of power is only a temporary solution to an imbalance of power. Doran poses that when a state feels threatened by a more powerful state, it will always seek to form alliances (Doran, 2000a). This is of course the central prediction of balance of power. However, the alliance does not change the growth rates and the relative growth or decline of states. Thus, the balance of power needs to be reestablished time and time again. If the power of specific states is very fluid, the result may be that war is fought with the alliances as established before the changes occurred. States may also wage a
3.5.4. Stabilizing factors
In a bipolar world, two major powers are bound to focus on the other and to balance their power. In a bipolar world, the balancing is mainly done through internal means in the form of buildup of armaments. Throughout the cold war, an arms race between the US and USSR demonstrated this tendency to maintain the balance of power at the status quo. Alliances are desirable in such a world, but not essential to the survival of the major powers. The balance of power expects weaker states to join the weaker side in the conflict (Waltz, 1993). The stronger side will press its own policies upon them and the weaker side will yield more to get support. Thus the balance of power in a bipolar world causes balance and restraint among the two alliances.

In addition to balancing through military alliances, soft balancing also is possible (Pape, 2005). Soft balancing is the use of diplomatic measures to frustrate the opponent rather than to actively balance against it. In a bipolar or multipolar world, a weaker pole (i.e., China) can use soft balancing in order to be able to both increase military capabilities and at the same time not pose a direct threat to the hegemon (Art, Brooks, Wohlforth, Lieber, & Alexander, 2005). Compelling arguments are given that the EU is increasing its military capabilities to decrease dependence and perhaps to balance against the US (Brooks & Wohlforth, 2005).

3.6. Arms races

3.6.1. Example
The sixth theory centers on the idea that competition and rivalries among states may lead to arms races. An historic example:

*During the Cold War, a rivalry was present between the US and the USSR. In the light of this rivalry, a military arms buildup occurred by both states. The military budget of the USSR is said to have been between 17 and 19% of their national income during most of the Cold War in order to keep up with the US.*

3.6.2. Definition or arms races
Scientific exploration of the concept of arms races arguably revolves around the work of Richardson, most notably in his mathematical restating of arms races (Richardson, Wright, & Lienau, 1960). The goal of this study was a general exploration of the nature of changes in the level of armaments of
states. Arms races can be viewed as a subset of these changes in the form of an extraordinary build-
up of armaments. A prerequisite is that some form of rivalry or competition is present among these
two states. Concurrent buildups of armaments in the UK and Italy in the early 20th century were
responses to other events and not to each other (Wallace, 1979). Depending on the definition used
of arms race, a military budget of 10% of GDP might be used as a threshold before declaring a
buildup an arms race (Caspary, 1967).

Three hypotheses are at the center of the work of Richardson (Caspary, 1967). First, a fear of an
imbalance in military strength, combined with a perception of threat, will prompt the arms buildup
to the same level as the opponent. Second, the cost of building armaments puts a strain on the
economy of a country and thus limits the total level of arms build-up. Third, states will spend a
minimum amount on its military, even in the absence of a specific threat. The arms race model that is
subsequently proposed by Richardson can be described in terms of two coupled linear differential
equations, as shown in Equation 2.

When an arms race is viewed in the context of game theory, it can be viewed as a prisoner’s dilemma
with bounded rationality. Rather than possessing perfect information regarding the opponent,
conceptions regarding payoffs, intentions, and strength of the opponent form a perceptual
dilemma (Plous, 1987). Viewing the players as rational actors, their preferences can be stated as
follows: (1) both sides prefer mutual disarmament to all other outcomes; (2) both sides want above
all to avoid disarming while the other side arms; (3) both sides perceive the other side as wanting
above all to arm while they disarm (Plous, 1987).

3.6.3. Paths to war
Arms races are no guarantee for the occurrence of war, but rather provide a window of opportunity,
which is referenced to as the tinderbox hypothesis (Morrow, 1989). Arms races create a flammable
situation where a small spark is all that is needed to create war. During an arms race, one of the
parties may hold a temporary advantage. During such a period of strategic advantage, the stronger
party might decide to go to war. The decision to go to war depends on expectation of future relative
distributions of power and whether this will improve or decline. The arms race escalates into war
only when both parties decide it is in their interest to fight. Larger amplitude arms races increase the
likelihood of a state choosing to fight now rather than later (Morrow, 1989). Different time horizons
for actors might lead to different assessments of the willingness to fight.

3.6.4. Stabilizing factors
While arms races may create a very volatile situation, there are also those that point to the stabilizing
effects of arms races. For instance, one of the most extensive arms races ever, the Cold War, never
Exploration of paths leading to major power war
directly led to a war. A reason for this might be that competition between rivals is channeled into the acquisition of arms (Gray, 1971). This focus takes attention away from employment of arms and thus decreases likelihood of war. Also, the concept of deterrence might influence this likelihood. Due to the buildup of weapons, the costliness of war greatly increases for both parties. The cost benefit may therefor never be positive enough to risk waging war.

Very little data-based research has been conducted on arms races and whether or not arms races cause wars. Those studies that did attempt to explain arms race found rather a diverse set of results. The problem may lie in the fact that arms race predictors experience high degree of multicollinearity (Anderton, 1989). Those predictors that may be used for arms race also explain rivalries and other items that may explain the origins of war.

3.7. Summary

<table>
<thead>
<tr>
<th>Theory</th>
<th>Path</th>
<th>Source</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bipolarity</td>
<td>lack of a balancer</td>
<td>(Woolsey &amp; Morgenthau, 1950)</td>
<td>Without a major power to align itself with the stronger state, balancing becomes more difficult</td>
</tr>
<tr>
<td>Bipolarity</td>
<td>polarization/competitive blocks</td>
<td>(Rosecrance, 1966)</td>
<td>Competition among blocks may lead to arms races and in general a more volatile situation</td>
</tr>
<tr>
<td>Multipolarity</td>
<td>flexibility/changing world</td>
<td>(Waltz, 1979)</td>
<td>Alliances are flexible and a permanent amount of distrust is present in the relationships among states</td>
</tr>
<tr>
<td>Power transition</td>
<td>power parity and dissatisfaction with status quo lead to war</td>
<td>(Efird, Genna, &amp; Kugler, 2003)</td>
<td>If a status quo hegemon and a dissatisfied major power arise at power parity, both may have incentive to fight the war, expecting to win.</td>
</tr>
<tr>
<td>Power transition</td>
<td>dissatisfaction with SQ taken into account in utility</td>
<td>(Gilpin, 1981)</td>
<td>Dissatisfaction changes the utility calculus of states: it makes states more willing to take risks in order to gain a larger foreign policy role</td>
</tr>
<tr>
<td>Interdependence</td>
<td>changed cost benefit in utility</td>
<td>(Polachek, 1980)</td>
<td>Interdependence may draw neutral states into wars because of their respective interests in the states involved</td>
</tr>
<tr>
<td>Rivalries</td>
<td>Vicious circle/repeated hostile interactions</td>
<td>(Vasquez, 1996)</td>
<td>Vicious circles of hostile interactions may sustain conflict indefinitely</td>
</tr>
<tr>
<td>Balance of power</td>
<td>Temporary solution/eventual use of force</td>
<td>(Doran, 2000b)/Keohane &amp; Nye, 1989</td>
<td>The balance of power is only a temporary solution and subject to constant renegotiating</td>
</tr>
<tr>
<td>Arms races</td>
<td>Window of opportunity/temporary advantage</td>
<td>(Morrow, 1989)</td>
<td>If one state has a temporary advantage, it may use this to attack preemptively</td>
</tr>
</tbody>
</table>
Exploration of paths leading to major power war

<table>
<thead>
<tr>
<th>Theory</th>
<th>Stabilizing effect</th>
<th>Source</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bipolarity</td>
<td>relative size determines survival/deterrence</td>
<td>(Waltz, 1979)</td>
<td>Large power differentials between the two poles and the other states means that these two major powers will not be attacked by third parties</td>
</tr>
<tr>
<td>Bipolarity</td>
<td>decrease in uncertainty</td>
<td>(Waltz, 1979, Rosecrance, 1966)</td>
<td>If the opponent is known (i.e., the other major power), all attention may be focused on decreasing uncertainty here</td>
</tr>
<tr>
<td>Multipolarity</td>
<td>balancing/alliances</td>
<td>(Geller &amp; Singer, 1998; Goddard, 2008; Woolsey &amp; Morgenthau, 1950)</td>
<td>Flexible alliance arrangement may be used to balance against aggressive major powers, thereby containing them</td>
</tr>
<tr>
<td>Power transition</td>
<td>result of war, rather than cause</td>
<td>(Lebow &amp; Valentino, 2009)</td>
<td>Power transitions are the result of the destruction of war</td>
</tr>
<tr>
<td>Interdependence</td>
<td>changed cost benefit in utility</td>
<td>(Oneal &amp; Russet, 1997)</td>
<td>If a war is fought and trade relations are severed, states may suffer great economic damage as a result</td>
</tr>
<tr>
<td>Balance of power</td>
<td>Restraint through conflicting alliances</td>
<td>(Waltz, 1993)</td>
<td>Conflict alliance arrangements will limit contagion of wars</td>
</tr>
<tr>
<td>Arms races</td>
<td>Focus on acquiring arms rather than fighting</td>
<td>(Gray, 1971)</td>
<td>If all attention is focused on acquiring arms, the use of arms becomes of secondary importance</td>
</tr>
</tbody>
</table>
4. ABM in International Relations

In this chapter an overview is given of those scientific studies that combined the study of IR and simulation methods, with specific attention paid to those authors using agent-based methods. Many of these studies are attempts to apply one or more theories from chapter 3 in a model in order to provide evidence for the theory itself. In section 4.1, four major initiatives are discussed that provide the ground work for this research. In section 4.2 an overview is given of those studies that studied particular aspects of IR in isolation using simulation techniques. Finally, section 4.3 provides an overview of all these models and the theories they are based on.

4.1. Similar studies
Within the field of IR, several authors have applied Agent-Based Modelling (ABM) or related methods to the study of war. The four (groups of) authors discussed in this section provide us with especially helpful models that are similar to the models to be constructed.

4.1.1. Initial work
Arguably the first scientific study to apply Agent-Based Modelling in the study of war was performed by Bremer and Mihalka in their paper “Machiavelli in machina: Or politics among hexagons” (Bremer & Mihalka, 1977). The aim of this study was to test the realist assumptions that form the basis of many studies within IR. For this purpose, they created a facsimile world in a simulator where these assumptions could be tested. Specifically, they would test whether or not a balance of power arrangement (section 3.5) would arise from the interactions of state or if the interactions would lead to a single dominating power.

Bremer and Mihalka created a world consisting of 98 states, represented by hexagons. Each of these hexagons is a cellular automaton (Neumann & Burks, 1966). The states that are implemented in the model are very simplified representations of what a “real” state might look like. Based on the power variables of states, states are able to take multiple actions such as form alliances or wage wars. These alliances can be used to aid them in waging wars. The initial 98 states are transformed through a process of conquest into a world with only a few states that control considerable resources.

Even though at the time of writing this model is 37 years old, it still provides useful information for this research. As mentioned, this model provides the first geopolitical world simulation by using cellular automata. The application of uncertainty in the perception of power by states can be incorporated into the model to be created. Despite the interesting work of the authors, this model
does present with severe limitations. The authors noticed a tendency for the model to produce similar results in all iterations (Bremer & Mihalka, 1977). The models would almost always result in global domination by a single state. A situation with prolonged existence of small states is unlikely unless the model was heavily edited. An explanation of this may lie in the limited complexity of the model as well as the predatory nature of the states. A single utility function is used for all the different states, based on the assumption of homogeneity. Unfortunately these issues mean that the model has very limited applicability to the real world. The work of Bremer and Mihalka was implemented and further expanded upon in two simulators, which will be discussed next.

4.1.2. Geosim and successors

![Figure 2: Screenshot of Geosim (Cederman, 1994)](image)

Geosim is a simulation framework inspired by the work of Bremer and Mihalka (Bremer & Mihalka, 1977), discussed in multiple papers (Cederman & Girardin, 2005; Cederman, 1994, 2002, 2003). Different accentuations were placed in the various papers, such as polarity of the world (see also section 3.1) (Cederman, 1994) or the level of security experienced by states (Cederman, 2002). Generally speaking however, it is a direct translation of the model proposed by Bremer and Mihalka, implemented in more advanced software environment.

In the Geosim model, wars are rational decisions made by states. The decision involves either a preemptive attack or a claim on a neighboring territory. Unprovoked attacks occur with a low probability, following power laws regarding size and occurrence. This model of wars is extended in the GeoContest implementation of Geosim (Weidmann & Cederman, 2007). In this extension, states may employ a multitude of strategies that display predatory behaviors, collective security or other strategies. Specific elements of emergence are present, such as polarity (Cederman, 1994), borders (Cederman, 2002), and war size (Cederman, 2003). Flexibility of the model framework allows for testing of a multitude of different phenomena. However, the aspect of uncertainty is not addressed in the paper describing the model.
4.1.3. EARTH
EARTH (Exploring Alternative Realpolitik Theses) is a simulator similar to GeoSim, but developed independently (T. Cusack & Stoll, 1990, 1994). Rather than attempting to confirm realist theories, the authors set out to prove that even in a realist world, collective action is possible. Collective action by states in order to gain collective security is a way for states to enhance their security to ensure they are not conquered or dominated by a hegemon. Generally collective security is not accepted among realist scholars and even ridiculed for resulting in the outcomes it tries to avoid (T. Cusack & Stoll, 1994). The model was replicated by Duffy a few years later (Duffy, 1992), but with a few changes. He introduced parallel initiation of conflicts and introduced a different implementation of uncertainty. The uncertainty aspect is implemented by means of probability distribution describing the accuracy of the perception of states. States perceive power with an average misperception of zero and a standard deviation that are the same across all states. Uncertainty of the power of other states now is flexible over time and varies over all states.

Figure 3: Configuration of 98 states (T. Cusack & Stoll, 1990)

Even though EARTH is yet another implementation of the same basic model, the conclusions drawn are rather different. The authors drew conclusions counter to traditional realist assessments on the basis of the model. They concluded that in a realist world with a relatively high probability of war, cooperation does occur among states. Selfishly interested states will choose to cooperate to gain collective security and thereby prove that collective security is possible. This possibility of cooperation allowed for more than one equilibrium to form in the model, thereby addressing one of the main objections to previous models.

4.1.4. Sugarscape
As the fourth model that has made large contributions to the field of ABM and social studies, Epstein and Axtell created the model called Sugarscape (J. Epstein, 1996). This model is different from previous models in the sense that it is an implementation of agents rather than just cellular automata. This model is then also often considered the first large scale Agent-Based Model simulation. Rather than speak in strictly economic or power terms, the model revolves around sugar that is produces per cell on the grid and consumed by the agents. The agents are analogue to real
human beings in the sense that they move about, consume a certain amount of resources. They are capable of dying, reproducing, performing combat and more. Depending on the specific model configuration, all of these behaviors are possible.

Tribes of agents wage combat against other tribes in order to gain dominance in the Sugarscape. Every individual agent is capable of fighting an agent of another tribe. The choice to fight is however only made when they find a weaker target and retaliation of other agents has a low probability. Depending on the configuration of the cells (i.e., distribution of resources across the landscape), multiple stable equilibria are possible within the model. This model represents a big step towards more realistic modelling of a world. It serves as an analogy to how the real world “works” and can be used to explore the effects of various social phenomena such as population dynamics and wars. Diverse phenomena can be studied due to flexibility of the simulation. The agents can be expanded rather easily and display a variety of behavior. Despite the flexibility, the simulation is still a very simplified world model though. The conclusions that can be drawn from the model are therefore rather limited.

4.2. Partial models

In addition to models simulating entire (artificial) worlds and the dynamics found herein, there are various models that describe parts of the dynamics that may be found in a geopolitical model. In this section examples of models will be discussed concerned with combat, trade, alliances, civil violence, and conflict escalation.

4.2.1. Combat simulation

A geopolitical simulation often requires that states have the means to wage wars to settle differences. The expected outcomes of such wars are often critical to the decision to start or escalate a war. Combat/war simulations have therefor been used extensively to predict outcomes, most often in military context. In the book “Artificial War” (Ilachinski, 2004), an overview is given of a large scale research project by the United States military and the simulator they developed. As part of a larger agenda of military research in planning, a simulator called Einstein was developed to simulate (realistic) battlefield outcomes. This simulator was born out of a need for non-linear solutions to problems faced by the military. Most notably, a desire for accurate battlefield simulations was present. One of the most important innovations here is a move from differential equations of attrition to non-linear emergent behaviors.

This simulator provides a more realistic simulation of combat then most previous models. The extensive autonomy of the agents and the decision-making capabilities based on expected utility and
personal agent preferences that go with it are useful implementations for further research. It should however be noted that this specific simulator has only limited applicability in the sense it lacks the wider societal context desired.

4.2.2. Trade and conflict
Bearce and Fisher have proposed a model of trade and conflict (Bearce & Fisher, 2002, 2003). Their aim was to test the influence of trade on the occurrence of conflicts. To this end, they implemented a simulation of inter-state trade combined with a limited model of warfare. In their simulation, every state has an endowment of some idiosyncratic good, analogue to the presence of vital resources. These goods may be trade and such trade relations may be changed based on Pareto improvement for both states.

The model provides a fairly simple and yet useful approximation of the emergence of trade networks among states. Even though the simulation of war among states is rather simplistic, the authors are able to show that trade inhibits conflict in most circumstances. The authors do note that the factors promoting trade and military conquest overlap in certain aspects, limiting the validity of their conclusion regarding the link between trade and conflict.

4.2.3. Social networks of alliances
A relatively large number of studies were found specifically aimed at studying how alliances might emerge from the relationships among states. First, Nakagawa et al. proposed a model of the formation of alliances in a bipolar world (Nakagawa et al., 2010). Their model is specifically aimed at representing the competition among the major powers in such a configuration. A security dilemma is introduced between the two major powers in the model where both major powers start augmenting their power through alliances with unaligned states. Both major powers will attempt to court the unaligned states and thus compete against each other. This competition continues until there are no unaligned states left and a form of Nash equilibrium is attained. This model is a fairly abstract model in the sense that the security dilemma only presents itself because it is introduced exogenous. Despite this assumption, the balancing of power through alliances emerges from the model in a useful implementation.

Second, a model of the effects of alliances on third parties was presented (Warren, 2010). This model attempts to replicate changes in alliance configurations based on how the alliances themselves evolve. If a new alliance is formed, or an alliance is broken, attitudes among states change. Such a change in attitudes is likely to result in new preferences in alliances. The resulting model is a very dynamic alliance structure where the facilitators of changes in alliances are changes in other alliances.
Third, a model aimed at replicating the attitudes among states and the perception thereof was constructed (Oh, Gemelli, & Wright, 2004). Rather than taking knowledge of attitudes for granted, this model introduces a perceptual uncertainty regarding the attitudes of other states. This perceptual uncertainty introduces a wider variance in utility when deciding whether or not to support another agent. This perceptual dilemma can also be witnessed in assessing the power of opponents and other aspects of geopolitics.

Fourth, a representation of the effects of interdependence and alliances on the amount of conflict is modeled (Maoz, 2006). This model introduces an additional type of formal relationship other than alliances in the form of cliques. These cliques are groups of states that have similar interests on a given topic. Interdependence is attained through the combination of alliances and cliques and the conflicting obligations they might entail.

4.2.4. Models of civil violence
The final category of models deals with the occurrence of civil violence and wars. Following the collapse of the Soviet Union, much of the work in IR appears to have focused on explaining civil wars (Florea, 2012).

Epstein, whom also authored the previously discussed Sugarscape model, presented two models of civil violence (J. Epstein, 2002). The first of these models deals with a central authority seeking to suppress a rebellion among its citizens. To replicate this behavior, agents are divided into cops and citizens. Citizens experience hardship (endogenous) as a measure of dissatisfaction with status quo and the legitimacy of the regime (exogenous). The citizens are bounded rational, and are assigned a risk averseness factor, on the basis of which they either rebel or not. The cops aim to suppress the rebellion by arresting rebelling agents and putting them in jail. The other model by Epstein features many of the same aspects, but is different in the sense that a central authority aims to suppress violence between two ethnic groups. The model can produce behaviors representing ethnic cleansing, safe-havens and peacekeeping forces. Both of these models show how civil violence can emerge from the activation of a small group of initial rebels. Additionally, they show how suppressive actions by the government often produce even more rebellion.

A different agent-based model represents the link between resources and civil violence (Ravi, Miodownik, & Nart, 2008). Agents are part of separate ethnic groups, each occupying certain territories. The model described here is aimed at civil violence, but can easily be translated to warring states. Conflict arises between groups over who controls a certain area and thus the resources contained within. Based on the income generated from the resources, military capabilities are built and wars are waged.
Cioffi-revilla presents a number of models linking bottom-up emergence of social unrest and the resulting state failures and civil violence (Cioffi-Revilla, Luke, & Parker, 2007; Cioffi-Revilla & Rouleau, 2009; Cioffi-revilla & Rouleau, 2010). These models are implemented in the Mason framework, which was specifically developed for these studies. Rebeland is an ABM that simulates the occurrence of civil unrest (Cioffi-Revilla & Rouleau, 2010). In this model a government raises taxes and uses these funds to build military forces. Certain issues impact the general population for which the government has set a policy. Satisfaction with this policy causes a certain amount of stress among the population. Civil unrest might erupt if the government policies fail to limit the amount of stress. An extension of Rebeland is found in Afriland (Cioffi-Revilla & Rouleau, 2009). By introducing a regional look at civil unrest, borders play a role as well as cross border linkage of issues in this model. This allows for a more realistic representation of the contagion of civil wars within Africa.

### 4.3. Summary

<table>
<thead>
<tr>
<th>Model</th>
<th>Source</th>
<th>Theories</th>
<th>Relevant findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machiavelli in machina</td>
<td>Bremer &amp; Mihalka, 1977</td>
<td>Balance of power</td>
<td>Dominance of a single state under realist assumptions</td>
</tr>
<tr>
<td>Geosim</td>
<td>L. Cederman, 1994, 2002, 2003</td>
<td>Balance of power, polarity, war size</td>
<td>Emergence of various phenomena such as polarity</td>
</tr>
<tr>
<td>EARTH</td>
<td>Cusack &amp; Stoll, 1990, 1994</td>
<td>Collective security</td>
<td>Even under realist assumptions, collective security through alliances is possible</td>
</tr>
<tr>
<td>Sugarscape</td>
<td>J. Epstein, 1996</td>
<td>Resource dependence, competition</td>
<td>Simple agent interactions may be used to study a diverse range of (social) phenomena</td>
</tr>
<tr>
<td>Einstein</td>
<td>Ilachinski, 2004</td>
<td>Attrition, expected utility</td>
<td>Battle field situations may be simulated accurately through expected utility</td>
</tr>
<tr>
<td>Trade &amp; Conflict</td>
<td>Bearce &amp; Fisher, 2002, 2003</td>
<td>Trade relations, resources scarcity, interdependence</td>
<td>Trade inhibits war significantly</td>
</tr>
<tr>
<td>Alliance formation</td>
<td>Nakagawa et al., 2010</td>
<td>Competition in bipolarity</td>
<td>Security dilemma in a bipolar world leads to a high degree of polarization</td>
</tr>
<tr>
<td>Alliances and third parties</td>
<td>Warren, 2010</td>
<td>contagion</td>
<td>Changes in alliances may by themselves be sufficient cause for new alliances to form</td>
</tr>
<tr>
<td>Perception of alliances</td>
<td>Oh, Gemelli, &amp; Wright, 2004</td>
<td>perceptual dilemma</td>
<td>Uncertainty in perception of other agents allows for war in the error term</td>
</tr>
<tr>
<td>Cliques</td>
<td>Maoz, 2006</td>
<td>Interdependence</td>
<td>Cliques of states may be formed in addition to alliances</td>
</tr>
<tr>
<td>Civil violence</td>
<td>J. Epstein, 2002</td>
<td>Rebellion, risk averseness</td>
<td>Civil violence may emerge from a very small group of dissatisfied citizens</td>
</tr>
<tr>
<td>Resources and civil violence</td>
<td>Ravi, Miodownik, &amp; Nart, 2008</td>
<td>Resources and conflict</td>
<td>Resources allow for spread of conflict</td>
</tr>
</tbody>
</table>
5. Model narrative

_In this chapter, the model is conceptualized on the basis of the literature review presented in chapter 3 and 4. The contents of this chapter cover step 2 – 4 of the modelling process as outlined in the methodology._

**Initialization** (Cederman, 1994)

During the initialization of the model, agents find themselves located in a virtual landscape. Each agent is called a state and owns at least the province it is located in (the “capital”) and most of the time also several surrounding provinces. The other provinces in the landscape are either owned by other agents or contain water. Water is cannot be owned by any state and thus only serves as a geographical obstacle between states.

When the state looks at the provinces it owns, it will find that each province yields a certain income, possibly contains resources and that each province contains a certain amount of people. When the sum of the income from each province is taken, you get an amount labeled GDP. The sum of the people in all the provinces yields a total population. In addition to the landscape the state is located in, an initial amount of military capabilities is allocated. When combined, the population, provinces, GDP and military capabilities form the power of the state. The sum of the resources contained within the provinces of a state forms the resource allocation of the state. Every state needs the 5 vital resources present in the world and either needs to own it or trade for it. During every time period, the four power aspects will be adjusted according to the growth variables of these variables. These growth variables are composed of stochastic elements and the internal and external conditions of the state. In addition to this endogenous growth, states will experience conflicts with other states which may or may not result in a war and territorial gains.

Conflicts are initiated exogenously on the basis of three factors. First, large and powerful states are more likely to experience conflicts. Second, highly asymmetric dependent relationships are vulnerable to coercion by the less dependent state, which may cause a conflict. Finally, highly dissatisfied states may initiate conflicts with its neighbors. Trade disputes and power transitions may also be endogenous causes of conflict among nations. Once a conflict occurs, a decision whether or not to go to war needs to be made by both states. If both states decide that the utility of going to war is high than the utility of bargaining or submitting, a war is fought. The utility of an option is calculated on the basis of the absolute gains or losses multiplied by weights that are unique to every state. These weights are assigned at the initialization and may change over time. The impact of a war
is a corresponding decrease in military capabilities of both states and a transfer of the spoils of war from the loser to the winner.

Relationships
When the state observes its surroundings, it will find a number of other states that also occupy a number of provinces. For every state, it can perceive the amount of power it has, with a certain standard error. Towards each state, the state potentially has three different types of ties.

1. The first type of ties is the regular or random diplomatic relations (Blainey, 1988). Every agent experiences a certain attitude on a range from 0 – 10 towards other agents. A high attitude indicates friendly relationships, while low attitudes reflect hostile relationships. During every time period, agents act, and by the end of the period, these attitudes are updated on the basis of these actions. Alliances and other positive actions increase attitudes, while conflicts decrease attitudes.

2. The second type of ties is trade relations. Every state exports a certain amount of goods to other states and also imports goods. In addition to these goods, resources are exchanged through these relationships. If a war erupts among states, trade ties will be severed between them. State may choose to break existing trade relationships or forge new trade relationships. If a state chooses to sever a trade relationship, it may need to find a replacement for the resources traded in the old relationship. The volume of goods traded depends on the size and growth of the economy of the importing country.

3. The third type of ties is alliances. If a state is attacked, or feels threatened, it has the option of forging alliances with friendly nations. Agents have the ability to send a request to their allies for military assistance in case they are attacked. Agents commit to alliances when sufficiently friendly nations have a common security threat. These potential allies will perform a utility calculation to determine whether it is in their best interest to join the alliance.

Trade relationships (Bearce & Fisher, 2003)
In every province, one or more types of vital (idiosyncratic) resources are present. In general, every state needs to either possess every type of resource or trade for it. The states are generally willing to sell such resources to other states, and thus trade relationships are established. A trade relationship with a given state allows for access to the resources of the other state. The resources flow from one country to another over the (directed) trade links. Multiple types of resources may be exchanged between countries. When combined with the size of exports and imports, the exchange of resources yields economic and resource dependence among states.
Any state may freely decide where to get its resources, as long as it makes sure that the state has every type of resource. When a state gets its resources from an unfriendly state, it will seek to replace this supplier with another supplier that is friendlier or one that is more dependent on the state. There is however a fixed cost of building a new trade relationship and a cost of maintaining such a relationship. Such costs are distance-dependent. When there is only a limited amount of suppliers for a given resource, states might be a monopoly for such a resource and be tempted to coerce other states. When a state is the sole supplier for a certain resource, states cannot break the trade relationship without occurring huge costs. At this point, provinces containing a certain resource may become subject of war.

**Threats and escalation** (T. Cusack & Stoll, 1990)

At any given point in time, a conflict may erupt among states. As expressed previously, there may be multiple causes of such a conflict. Every conflict is at a certain level of escalation, on a scale from 1 to 5. A higher level of escalation indicates higher stakes in potential losses and gains. Once such a conflict occurs, both parties to the conflict are given 7 options. Each party has to select one of these options to execute. For each option, an equation may be formed using the personality of the state and its risk appetite, leading to absolute utility scores. Based on the chance of winning for the opponent, every state also assesses the likely option to be chosen by the opponent. The utility scores are based on the expected action of the opponent.

- First, every state has to make the choice whether or not it may want to escalate the current conflict or deescalate. De-escalation would be the wisest option if there is at this moment a very low or even negative utility for all options. Escalation would be advisable if the expected gains are fairly high and the risk is considered low. For the remaining scenario’s, keeping the conflict at its current level would make the most sense. This decision is visualized in Figure 4.

- Second, one of five options may be chosen at the current level of conflict. On the basis of the different utilities of these options, one of these options will be executed, as visualized in Figure 4:
  - Attack
  - Build military capabilities
  - Forge alliances
  - Submit
  - Nothing
Once both parties have selected their strategy for execution, interaction occurs among the states. If the attacker backs down, a return to status quo is established, but with a memory of the threat present in the victim’s mind. If the attacker also builds its power, the victim may choose to do nothing, forge additional alliances, or build even more capabilities. At some point in this cycle, both states have to decide whether or not to attack or to back down. If an attack occurs, the victim will ask its allies for help, and depending on such aid and the current power ratio, either give up or retaliate. Giving up means in this case that the victim gives a concession to the aggressor in the form of territory. Retaliation means a war is fought out between the states and their respective allies. The outcomes are determined based on the ratio of military capabilities. The loser then gives a concession to the victor in the form of resources or territory. In addition to losing this concession, the loss of a war may have long-lasting negative effects such as decreased growth.

If both parties select conflicting options (e.g., escalate and de-escalate), the relative power of the states is the deciding factor. Thus, if the larger state chose to escalate, the smaller state’s de-escalatory actions are insufficient to achieve de-escalation. If there is no true differential in power, the actions of the states cancel each other out if they are conflicting. The conflict remains true at its current level.

**Decision-making** (Ilachinski, 2004)

As mentioned during the initialization, conflict among nations will occur on a regular basis. At this point, either party to a conflict may escalate the conflict by threatening the other state. Alternatively, a request may be made to a friendly state for an alliance against the opposing state. A number of
potential options are available at this specific point in time, and assuming a rational actor, an agent needs to make a decision which option best fits its needs. The options available to agents are quite diverse in the real world, but in the model, only a limited amount of these options will be used.

The agent has the ability to make decisions based on the expected utility of the outcomes of the actions. For example, in the decision to escalate a conflict, the agent determines the utility of the various options such as backing down, building capabilities and more. Based on the probability of winning, the cost of fighting, the cost of losing, the benefits of winning, change in security and the potential loss of trade, a utility score can be calculated. When these scores are combined with weights for various factors representing the agent’s personality, this determines the utility of the option. The utility scores for all alternatives are then compared and the highest scoring alternative is chosen. Note that the calculations for the decisions are subject to error in the form of uncertainty regarding the power of opponents (Duffy, 1992). The magnitude of the error in the calculations is decreased by repeated interaction among states, which introduces a learning effect. The magnitude of the error is increased when a state has a large amount of enemies and thus cannot spend as much time observing each enemy.

Alliance formation (Smith, 1996)
Once an agent feels sufficiently threatened to seek allies, it will ask friendly states for aid. An additional requirement for these potential allies is a negative attitude with regard to the aggressor. Such potential allies will need to evaluate the utility of their options. They can choose to forge an alliance, which means they may have to fight a war. Fighting such a war might yield benefits in the form of the loss of a potential threat and spoils that may be gained. Additionally, the relationship with the state it is aiding will improve. On the downside, there is a risk of losing the fight, in addition to the cost of fighting. Also, the attitude regarding the opponent will decrease dramatically. The balance between these two sides will yield a utility score, to be compared with the utility of not joining an alliance. The utility of this option depends on the cost of potentially losing a friendly state, as well as making a potential enemy stronger. Based on these considerations, agents will choose to either forge an alliance or remain neutral.

Waging war
In the case that both parties to a conflict have made the decision to wage war, this war is fought out. Simply put, this means that a winner is selected, both parties lose part of their military forces and the loser is forced to give up some spoils. The winner of the conflict is calculated on the basis of the power ratios on a logarithmic scale. Thus, if the capabilities of both states are very close, the probabilities of winning are roughly 50%. Battle damage is generated on the basis of the Lanchester equations: attrition of own forces are based on the capabilities of the other multiplied by the
effectiveness of its forces. The losers then give up part of their territory to the winner. If there are any bordering territories, these are selected first. Otherwise, the territories closest to the winner are transferred.

**Foreign policy role (Doran, 2012)**
The foreign policy role of a state is the role a state has within the states of the world, as recognized by other states. The foreign policy role is largely based on the relative power a state possess and the development of this power. If a state has been powerful for a long period of time, it is likely this is recognized by other states as powerful. If the power is relatively new, a transition in role is often required over a period of time. Satisfaction of states with the status quo depends on the amount of benefits derived from their role in relation to the relative power of the state. The power and changes therein can be categorized on the basis of inflection points. These inflection points represent changes in the second derivative of the power of a state.

**Various Attributes**
- The technological advancement of a state is measured as it’s GDP per capita divided by the world’s mean GDP per capita
- The fighting strength of a state are the military capabilities multiplied with the technological advancement
- The sense of security of a specific state is the power of itself and friendly states divided by the power of hostile states
- Military spending depends on a constant that changes stochastically, the current size of the military, and the sense of security of the state
- States remember for a set amount of time their level of power, growth thereof and changes in growth
- Interdependence of two states is measured in the total size of goods exchanged between them divided by their combined GDP
- Every state is assigned a string of variables, deemed ideology (based on (Axelrod, 1997)). Ideology is exchanged among friendly nations, and especially among allied nations.
- A power transition is the event where the most powerful state is surpassed in capabilities by another state.
6. Model implementation

_in this chapter a description is given of the implementation of the model as conceptualized in the previous chapter. To this end, the most important formulas and implementation details can be found in section 6.1. The full pseudo code may be found in appendix C. In section 6.2 an overview is presented of the verification as performed. The full verification may be read in appendix D._

6.1. Assumptions and formulas

Power
A state’s power is assigned through the equations as presented in Comprehensive National Power (Chang, 2004):

\[
Power = \frac{Population + Surface area + Economic strength + Military strength}{4}
\]

Equation 1

\[
Population = \left(\frac{population_{state}}{population_{all\ states}}\right) \times number\ of\ states
\]

Equation 1a

\[
Surface\ area = \left(\frac{provinces_{state}}{provinces_{all\ states}}\right) \times number\ of\ states
\]

Equation 1b

\[
Economic\ strength = \left(\frac{GDP_{state}}{GDP_{all\ states}}\right) \times number\ of\ states
\]

Equation 1c

\[
Military\ strength = \left(\frac{military\ capabilities_{state}}{military\ capabilities_{all\ states}}\right) \times number\ of\ states
\]

Equation 1d

Military spending
One of the most commonly used operationalizations of military spending may be found in the arms race model proposed by Richardson in 1960 (Richardson et al., 1960).

\[
\frac{dy}{dx} = Size\ of\ x \times y - Current\ size\ of\ military \times y
\]

\[+\ normal\ level\ of\ spending\]

Equation 2

Hereby is x the military forces of the other state and y the size of one’s own forces.
Chance of winning
The perceived chance of winning of a state y in a conflict with state x may be expressed in the following equation (Weidmann & Cederman, 2007):

\[
\text{Chance of winning } y = \frac{1}{1 + e^{-\left(\frac{\text{total power } y \text{ and allies} - \text{total power } x \text{ and allies}}{\text{total power of all}}\right)}}
\]

Equation 3

The power of state x, state y and potential allies for both sides are subject to both perceptual uncertainty (Howard & Guidère, 2006) and loss of strength gradient (Cederman & Girardin, 2010).

Perceptual uncertainty
States are able to see the capabilities of another state, but only in a bounded fashion, also called perceptual uncertainty. Uncertainty regarding the opponent is based on the amount of previous conflicts, the amount of potential aggressors, and a stochastic function. The amounts of previous conflicts within the memory of state represent the learning effect that may be present (Rosecrance, 1966). Every state has a limited amount of attention that may be paid to a specific (potential) opponent. When there is a multitude of opponents, the state is unlikely to be able to pay enough attention to the opponents to get an accurate picture (Singer & Deutsch, 1964; Waltz, 1979).

\[
\text{Accuracy of perception} = \text{normal}(\mu, \sigma)
\]

Equation 4

In this equation (based on the implementation of (Duffy, 1992)), \(\mu\) is a model input, typically set at 0. Furthermore, \(\sigma\) is a combination of an input, the ratio of hostile to friendly nations and the length of the conflict memory between the two states at hand.

Loss of strength gradient
In the model, this loss of strength gradient, which represents the distance dependent nature of force, was implemented in the following manner, based on (Cederman & Girardin, 2010):

\[
\delta(x, t) = \frac{1}{1 + \left\{\frac{\text{distance}}{\text{technological advancement}}\right\}^{\text{distance-slope}}}
\]

Equation 5

The level of technological advancement is an indicator of a state’s capabilities for projecting its force at a distance. The distance slope is merely a measure of the difficulty of projecting force abroad and is the same for all states, and is implemented as a model input.

\[
\text{Technological advancement} = \frac{\text{GDP}}{\text{Population}} \cdot \frac{\text{Mean GDP}}{\text{Population}}
\]

Equation 6

\[
\text{Fighting strength} = \text{technological advancement} \times \text{military capabilities}
\]

Equation 7
Exploration of paths leading to major power war

Fighting strength compensates for large military forces with very little technology. These forces tend to be far less effective.

Utility
When agents are prompted for a decision, they make such decision on the basis of the expected utility of their actions. The absolute scores of their utility are multiplied by the weights that show the agent’s preferences. The utility of every action is measured through the following variables and their coefficients (Ilachinski, 2004).

- Chance of winning: the agents assessment of the likelihood of winning the confrontation
- Expected spoils: territorial gains to be gained if the confrontation is won
- Expected losses: territorial losses to be sustained if the confrontation is lost
- Military losses: expected loss in military capabilities
- change in chance-winning: the change in chance of winning if the option is chosen
- change in security: the change in sense of security if the option is chosen

The utility of any action thus is calculated:

\[
Utility = w_1 \times chance_{winning} \times expected_{spoils} - \\
w_2 \times expected_{losses} \times (1 - chance_{winning}) - \\
w_3 \times military_{losses} - \\
w_4 \times loss_{of\ trade} + \\
w_5 \times change\ in\ security + \\
w_6 \times change\ in\ chance\ of\ winning
\]  

The expected payoffs of any given action are partly based on the expected action of the opponent.

Agents perform a basic calculation using their perceived properties of the opponent on whether or not the opponent will choose to fight or do nothing. An example of the payoff matrix that could arise is shown in **Fout! Ongeldige bladwijzerwijzing.**

---

*Figure 5: Example payoff matrix*
Exploration of paths leading to major power war

Lanchester equations
The Lanchester equations are a set of equations that describe the development of attacker and defender strength on the basis of the strength of the opponent (Ilachinski, 2004). Various implementations are present, but the most basic implementation is known as the “square law” and was used in the model:

\[
\frac{\partial y}{\partial x} = -K_x y \quad \text{Equation 9}
\]
\[
\frac{\partial x}{\partial y} = -K_y x \quad \text{Equation 10}
\]

\(X\) and \(Y\) are the military capabilities of the two states fighting, while \(K\) describes the attrition rate at which forces may be decimated.

Foreign policy role and inflection points
For every state, a record is kept of the development of its power. As part of this, the growth in power and the change in growth of power are recorded every time step. The growth of power is measured as the difference between the current and the previous step. This allows us to classify where each state is on its power cycle in the following manner, based on a change of direction in the second order derivative of the power, as suggested by Doran (1980).

\[\text{Inflection Point Categories}\]

![Inflection Point Categories](image)

Figure 6: Inflection point categories based on second order derivatives

The foreign policy role (FPR) of a state depends on two aspects: its power and the expectation of what this power should be. The expectation is a linear extrapolation of a state’s previous growth pattern multiplied by its power at a previous state. Please note that this operationalization was not found in literature and was thus created for this model. The formula is designed to account for the
lag in foreign policy role behind the actual power. This represents the unwillingness of other states to recognize newly risen states, or recently declining states.

This is expressed in the following formula:

\[
\text{Expected}_\text{Power} = \text{Power}_{t=0} \ast (1 + \text{mean}\_\text{power}\_\text{growth})^t
\]

\[
\text{FPR}_{\text{dissatisfaction}} = \text{Expected}_\text{Power} - \text{Power}
\]

Figure 7: Power and foreign policy role

Each state is assigned a risk-averseness factor, which is based on the weight the state has assigned to expected losses and expected gains. For dissatisfied states, the risk averseness decreases and for satisfied states, risk averseness increases. Dissatisfied states seek to change the status quo and are more likely to take risks in order to reach their intended goal. Satisfied states will seek to maintain the status quo and will thus seek to avoid risks.

Conflict decision making

If a conflict is present among states A and B, A may find itself in one of three possible scenarios, each with several potential actions. A schematic overview of these actions can be found in Figure 4. The three scenarios are based on the distribution of power among states A and B. A 3 : 1 ratio is the default power distribution for pruning the cases (Davis, 1995; J. Epstein, 1989). A maximum of five potential options for states was taken into account in order to limit computation and implementation time.

- Opponent has a 3 : 1 or better military advantage:
Exploration of paths leading to major power war

- There is hardly any point in building military capabilities due to preponderance in power of the opponent
- An ally would have to be a major power in order to offset the power differential
- Submission is most likely preferential to fighting (and losing)
- Opponent has no decisive military advantage or disadvantage
- Opponent has a 1:3 or worse military disadvantage

Creation of conflict
Conflict is created exogenously by the environment. There may be a lot of reasons why conflict occurs among states, but we postulate that the exact cause of conflict is not of high importance in this research. Thus, three causes of conflict are taken into account:

- Randomized (representing “normal” interactions among states)
  Many different causes, like a spy plane crashing in hostile territory may be represented by a stochastic function. Based on the input likelihood of conflict, an x amount of states is selected and a conflict is created between pairs of such states. Selection is based in part of the rank of a state, with higher ranked states more likely to be selected.
- Asymmetrical trade relations (representing coercion among states).
  Asymmetry in trade relations yields to opportunity for the less dependent state to coerce the other state. Additionally, highly dependent states will seek to sever dependencies. Thus, in the model, a preset percentage of highly asymmetric trade relations experience conflicts.
- Dissatisfied states (representing opportunistic behavior of dissatisfied states)
  Highly dissatisfied states are more likely to experience conflict. Those extremely dissatisfied states will experience conflicts with neighboring states.

Waging wars
When the outcome of the interaction of states is that a war is to be fought, the following rules and assumptions are used. First, all exports between warring nations are terminated (Bearce & Fisher, 2003). Second, attrition of forces is based on Lanchester equations (Davis, 1995; J. Epstein, 1989; Ilachinski, 2004). Battle damage and attrition of forces is based on the capabilities of the opposing forces. If any alliance partners fight on either side, their forces are taken into account. Each state gets battle damage in accordance with the power share it has within the alliance.

Updating
Key variables of states and provinces are updated every time step. Most notably, these variables are the GDP and population, but also other various minor aspects. In general, such variables are updated through Markov chains (Norris, 1998): The value of the variable next step depends only on the value
Exploration of paths leading to major power war

this step and a (randomized) growth variable. Updates occur per patch and are then accumulated into state-wide variables. An example would be GDP:

\[ GDP_{\text{patch}}_{t+1} = GDP_{\text{patch}}_t \times (1 + growth_t) \]

Equation 13

\[ Growth_t = growth_{t-1} + \text{uniform}(0,0.2) - 0.1 \]

Equation 14

Interaction

Interaction among agents (or states) is always local and typically one-on-one. When a conflict occurs, this means that both sides made a decision, which then needs to be executed. Briefly said, if they both took the same decision, e.g., fight, this decision is executed. However, if different options were chosen, a resolution is required. Three possibilities are present at that point, being:

- Execution of the choices made by one of the sides and ignore the other, and vice versa,
- Repeat the process but with more limited options
- Allow the actions to cancel each other out

The choice between these three options is made by the environment on the basis of the power ratios among the two states. If the power differential exceeds a threshold value, the more powerful state’s choice is executed. If neither party exceeds the threshold value, the actions either cancel each other out, if possible, or the process is repeated next time step.

Distributing spoils

If a war has been fought, spoils from the losers are distributed among the victors. The size of the spoils depends on the level the conflict is fought at: a higher level of conflict means more potential spoils.

\[ Total\ spoilsize_{\text{victors}} = \% \ of \ spoils \times total\ provinces_{\text{losers}} \]

Equation 15

If there is more than one victor, the total spoil size is split among the victors. If there is more than one loser, the same formula is used to calculate how many provinces a state is required to give up.

The ratio at which this occurs is strictly based on power share within the alliance:

\[ Spoilsize = \frac{\text{power}_{\text{self}}}{\text{total power}_{\text{alliance}}} \times total\ spoilsize \]

Equation 16

The specific provinces to be transferred are in the first place those provinces that are at the border of the two states. If the states are not bordering, those provinces closest to the winner are transferred. If more provinces are demanded then available, the state dies. Also, when the capital is conquered, the state dies.

Alliance request

One of the options for a state in a conflict is to request another state for an alliance. Thus, in the light of a specific enemy, the state searches for another state that matches the following criteria:
Exploration of paths leading to major power war

- The state has a friendly attitude towards you
- The state has a hostile attitude towards the enemy at hand
- The state has a positive utility score for fighting against this specific enemy

If such a state exists, an alliance may be forged for the duration of the conflict. At the end of the conflict, the alliance remains in place as long as the two states are in a friendly relationship.

Trading relations
States engage in trade with other states. If a state finds another friendly state with whom trade would yield a positive utility, a trade relationship will be forged. If any trade relationship is not beneficial to the state, the relationship is severed if the cost is outweighed by the benefits.

In the model, there are 5 key resources that every state needs in order to fulfil its needs, similar to the model of trade discussed in section 4.2 (Bearce & Fisher, 2003). If a state does not own a resource and none of its current trading partners possess the resource, it will need to find a new trading partner with whom to trade for this resource. If there is only one supplier, this supplier becomes an invaluable trading partner because its resources are desperately needed.

Update attitudes
Attitudes among states are updated per time step. These updates are twofold in the sense that there is a stochastic component and a component based on actions if any interactions occurred among the states. The stochastic interactions represent the “normal” interactions among states. A pair of states experiences a positive interaction with probability of current attitude (i.e., a pair with an attitude of 7 has a 70% chance of a positive interaction). In case of a conflict, alliance, severing or creation of a trade relationship, the attitude is updated accordingly.

\[ p = \frac{\text{Attitude}}{10} \]

\[ x \rightarrow \text{positive with probability } p \]

\[ x \rightarrow \text{negative with probability } 1 - p \]

\[ \text{Attitude}_{t+1} = \frac{\text{Attitude}_t + 9 + x}{10} \]

Various

\[ \text{Interdependence}_{xy} = \frac{\text{Exports}_{xy} + \text{Imports}_{xy}}{\text{GDP}_x + \text{GDP}_y} \]

\[ \text{Sense of security} = \frac{\text{Power}_{\text{hostile states}}}{\text{Power}_{\text{self}} + \text{Power}_{\text{friendly states}}} \]

Equation 17

Equation 18

Equation 19

(Oneal & Russet, 1997)
6.2. Verification & validation

In this section, the validation and verification of the model is discussed as part of the modelling process. The verification involves the evaluation of the model is in agreement with the model design and whether or not any bugs may be present. The validation of a model involves the evaluation of the model is fit for the purpose of the research at hand. If the goal is scientific, this would involve evaluation of the truth-value of the model. However, in this case, the goal of the model is not strictly scientific but rather exploratory.

The validation of any model is generally a tricky effort at best. The mere fact that the model is always a simplification of reality, and is based on certain assumptions that may be faulty, makes validation a difficult task. In case of an exploratory model validation requires that the author provides a reasonable indication that the model is a useful simplification of reality and that the assumptions made lead to useable outcomes. In order to provide such validation results, the steps proposed by Augusiak, et al. are used (Augusiak, Van den Brink, & Grimm, 2014).

6.2.1 Data evaluation

Augusiak, et al. (2014) define the data evaluation step as “the assessment of the quality of numerical and qualitative data used to parameterize the model, both directly and inversely via calibration, and of the observed patterns that were used to design overall model structure, whereby not only the measurement protocols need to be evaluated but conclusions drawn from the data should be challenged as well” (Augusiak et al., 2014). As such, in Table 1, an overview is given for the basis of key categories of data. Please note that very little empirical data forms the basis of the model but rather the patterns from these sources are reused. For a complete overview of similar models that were used for inspiration or sources, please refer to chapter 4. The implementation itself was discussed in section 6.1.

<table>
<thead>
<tr>
<th>Type of data/pattern</th>
<th>Implementation basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landscape characteristics</td>
<td>Data are based on implementation of (Cederman, 1994)</td>
</tr>
<tr>
<td>Decision making on the basis of utility</td>
<td>Data are based on implementation of (Ilachinski, 2004)</td>
</tr>
<tr>
<td>Trading</td>
<td>Data are based on implementation of (Bearce &amp; Fisher, 2003)</td>
</tr>
<tr>
<td>Foreign policy role &amp; inflection points</td>
<td>Data are based on implementation of (Doran, 2000b)</td>
</tr>
<tr>
<td>Perceptual uncertainty</td>
<td>Data are based on implementation of (Duffy, 1992)</td>
</tr>
<tr>
<td>Ideology</td>
<td>Data are based on implementation of (Axelrod, 1997)</td>
</tr>
</tbody>
</table>

As can be observed in Table 1, numerous aspects of the implementation and the data used therein are based on previous implementations. However, a number of implementations were not found in
previous works and therefore were rather uncertain. The second step for the data evaluation consists of a listing of the various types of uncertainties present and the ways they were dealt with. An overview of this is presented in Table 2.

Table 2 Types of uncertainties

<table>
<thead>
<tr>
<th>Type of uncertainty</th>
<th>Method</th>
<th>Uncertainty</th>
</tr>
</thead>
</table>
| **Parameter uncertainty** | Usage of a range of values and testing these in the EMA workbench. Tests included if the model would “break” or would show unexpected behavior that could not be explained. | • Reparations rate  
• give-in-compensation  
• Attrition rate  
• Weights  
• Attitude changes  
• Threshold values for actions |
| **Heterogeneity** | Application of normal and uniform distributions to allow states to initiate in multiple possible initializations | Normal distribution of:  
• Trade size and growth  
• Initial Military capabilities  
• Perceptual uncertainty  
Uniform distribution:  
• Initial population  
• Initial economy  
• Initial trade  
• Water  
• Resources |
| **Structural uncertainty** | Wide range of values to compensate for structural values that cannot be known. Several structures were tested in order to exclude those values that did not confirm to the expectations. | • Memory length  
• Ideology length and change rate  
• Impact of dissatisfaction on risk appetite  
• Probability of conflict |

In Table 2, an overview is presented of the various uncertainties used. One of the most common ways to deal with them has been to apply statistical distributions to variables in order to create heterogeneity. As distributions, the uniform and normal distributions were used to represent unknown distributions and variations around an average respectively.

6.2.2 Conceptual model evaluation

Augusiak, et al. (2014) define the conceptual model evaluation step as “the assessment of the simplifying assumptions underlying a model’s design and forming its building blocks, including an assessment of whether the structure, essential theories, concepts, assumptions, and causal relationships are reasonable to form a logically consistent model”. The conceptual model was used to create the model and if there are inconsistencies in the design, these would need to be removed. During the implementation and design, various conceptualizations were considered. In general, for every aspect of the model, a single conceptualization was eventually chosen. However, as Augusiak et al. mention already, specific testing strategies for such a conceptualization are lacking. The best we can do at this point is therefore to compare the conceptualization here with other models and specific literature. As such, in chapter 4 an overview is given of several comparable models. These
models have heavily influenced the current model in the sense that these models were used where possible to provide conceptual designs. Additionally, when there was no objective way of choosing between multiple conceptual models, multiple implementations were attempted of the various conceptual models. If the implementation proved to be too difficult, the conceptual model was discarded and a more suitable option was chosen. If multiple viable options remained, multiple options were implemented with switches to control them. One of the examples of this is whether or not coercion among states is a possibility, which the literature could not agree on. A switch is thus present in the model to allow for both possibilities.

6.2.3 Implementation verification
Model verification or implementation verification is performed as step 6 in the modelling process. During this step, a check is performed on whether or not the model is built according to specification and no bugs are present. To this effect, model verification is the process of looking at the inputs and outputs of the model, the model behavior and extreme conditions. The data for these tests involve a large amount of runs preformed under varying inputs. A full overview of the tests and setup in verification may be found in appendix D.

First, when running the model a large amount of time, various input errors were found. Most notably, division by zero and empty agent sets were frequently found. A number of safeguards was subsequently built in to allow the model to perform under all (extreme) conditions. These safeguards were in the form of if-statements verifying the inputs for a procedure were valid.

Second, it was found that the model was not complete: several circumstances were not accounted for in the programming logic. For example, not all 49 possible combinations of decisions could be processed and thus certain conflicts remained in place indefinitely. Similar problems were found when certain conflicts would not always get two decisions from the agents participating in the conflict. Extra interaction pairs as well as safeguards were implemented to resolve these issues.

Third, the model and agent behavior were studied. It was found that within the set of decision taken, certain decisions were more prevalent than others. An example of this is that fighting was far more prevalent than building capabilities. A small change in the logic here allowed for a more diverse picture, more representative of the real world. In addition, important aspects of the model were studied, such as foreign policy role and dissatisfaction. It was verified that high dissatisfaction levels are almost always seen when a state approaches its upper inflection point, as predicted. It was also verified that no invaluable trading relationships were severed, no states were missing resources, and no conflicts remained true indefinitely.
Finally, setup was verified to have all values within appropriate range of values. The only remaining thing is that some model runs had no population or economy. These models will not yield any usable results and are therefore excluded from the results.

The combination of these tests and the fixes for the problem found leads me to conclude that the model is now in agreement with the model design. The repetition of the process has made it highly unlikely that errors still remain in the model.

6.2.4 Model output verification

Is the model output suitable for answering the questions posed in this research? Three aspects of this question are explored in this step: (1) is it capable of reproducing specific behaviors? (2) Are historic wars represented in the model outcomes? (3) Are the model outcomes especially sensitive to certain inputs?

Is the model capable of reproducing specific behaviors? The model was specifically designed to explore the pathways to major power wars. The main pathways that may be distilled from the model are presented in chapter 7.2. Seven pathways, found in both the model and the literature, are visualized in this section. However, it must be said that specific elements are not present in the model and can therefore not be found in the outcomes. An example would be rivalries, which are not found as such in the model. Additionally, no clear results were found regarding polarity and the origins in war.

Are historic wars represented in the model outcomes? As may be observed from Table 3, the most recent major power wars are all present in the model outcomes. It was found to be rarer to have multiple major powers fighting on the same side, hence the relative frequency of that type of war. Fairly “simple” wars, like the Franco-Prussian war were more prevalent.

<table>
<thead>
<tr>
<th>War</th>
<th>Key aspects</th>
<th>Presence in model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crimean war (1853)</td>
<td>Multipolar</td>
<td>Rare</td>
</tr>
<tr>
<td></td>
<td>Multiple major powers on one side, fighting 1 other</td>
<td></td>
</tr>
<tr>
<td>Franco-Prussian war</td>
<td>One-on-one war, no allies</td>
<td>Very frequent</td>
</tr>
<tr>
<td>(1870)</td>
<td>Multipolar</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dissatisfied contenders</td>
<td></td>
</tr>
<tr>
<td>Russo-Japanese war</td>
<td>Two dissatisfied contenders</td>
<td>Very frequent</td>
</tr>
<tr>
<td>(1905)</td>
<td>Multipolar</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low interdependence</td>
<td></td>
</tr>
<tr>
<td>WWI &amp; WWII (1914 &amp; 1939)</td>
<td>Multipolar</td>
<td>Rare</td>
</tr>
<tr>
<td></td>
<td>Very dissatisfied challenger</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Multiple major powers on each side</td>
<td></td>
</tr>
<tr>
<td>Korea (1950)</td>
<td>Bipolar</td>
<td>Rare</td>
</tr>
<tr>
<td></td>
<td>High polarization</td>
<td></td>
</tr>
</tbody>
</table>
Are the model outcomes especially sensitive to certain inputs? The relation between specific outputs and specific inputs is analyzed in Appendix F. Here, several scenarios are tested using the PRIM algorithm. Specific inputs are sought that describe groups of outputs. One of the outcomes of the analysis is that the model outcomes are very sensitive to the variable FPR impact. This variable describes the impact of dissatisfaction on risk appetite. Virtually all experiments with large amounts of major power wars saw high values of FPR-impact. To a lesser extent, three other variables were also found to have a large impact on model outcomes. These would be the weights assigned to expected gains and expected losses, as well as the probability of a conflict between two states. The conclusion that can be drawn from these findings is that the outcomes of the model highly depend on these values. Considering these values are unknown, it is hard to draw any conclusions regarding validity.

6.2.5 Model analysis
This step consists of a check of what model behavior is generated and how this may be explained. In table 3, several key behaviors are displayed and an explanation is given for their emergence.

<table>
<thead>
<tr>
<th>Behavior</th>
<th>Explanation of emergence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power law distribution for conflict level</td>
<td>Escalation requires for both parties to strongly desire escalation. Conflict level 1 is there for the most prevalent. For conflict level 5 to be even reached multiple successive rounds of decision-making need to result in this escalatory process, which is rare.</td>
</tr>
<tr>
<td>Bell curve for ideology</td>
<td>At start, all ideology is randomly distributed. As such, there will be very few similar ideologies. As time progresses, the model converges to a single ideology. High values disappear, and if the model is run for a long enough period, the bell curve shifts to the left.</td>
</tr>
<tr>
<td>High dissatisfaction for fighting states</td>
<td>In the model, there is a relation between the risk appetite of a state and its dissatisfaction. Highly dissatisfied states will take more risks, and are therefore more readily represented in the population of major powers fighting.</td>
</tr>
<tr>
<td>Extremely high interdependence</td>
<td>Extremely high levels of interdependence may only be attained when extreme levels of resource dependence are present across all resources. This occurs only when there is a single supplier present for a specific resource.</td>
</tr>
<tr>
<td>Full polarization</td>
<td>As relationships develop over time, wars and conflicts allow for states to lose all friends. This means that it is isolated from other states and may be considered fully polarized.</td>
</tr>
</tbody>
</table>
6.2.6 Model output corroboration
In the method proposed by Augusiak et al. the sixth step consists of comparing the model outcomes to newly available data. In the past six months, no new major power wars have occurred and very few new articles were written concerning the origins of major power wars. This has led us to conclude that this step cannot be performed.

Additionally, the exploratory nature of this model allows for exploration of outcomes not previously seen in history. Such outcomes ought not to be discarded because it cannot be corroborated. Rather, these outcomes warrant further research.

6.2.7 Stochasticity
A final element to the validity of the model is the question regarding the impact of stochasticity on the model outcomes. Specifically, the impact of stochasticity revolves around the question whether or not the outcomes of interest may be caused by specific inputs of the model. Alternatively, certain stochastic elements present in the model may cause a “random” occurrence of certain events. In terms of the model this question revolves whether or not major power wars occur randomly, or if certain inputs significantly determine the occurrence of major power wars.

In order to answer this question, PRIM analyses were used on specific cases, as shown in appendix F. In such a PRIM analysis, clusters with a high concentration of cases are sought that all show a certain attributes. The clusters are formed on the basis of the values of specific input values. If clusters of cases may be found that are determined by specific inputs, the conclusion may be drawn that these cases are not randomly created by the model but are the results of specific inputs. In appendix F, 7 such prim analysis results are shown. Within these cases, the coverage and density of the results are the focal point of this analysis. If a certain cluster contains a high concentration of cases in a large part of outcomes, based on specific inputs, the conclusion is drawn that the outcome of interest is the result of the model rather than stochasticity.

Table 5: Coverage and Density of PRIM analyses

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Coverage</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>80%</td>
<td>80%</td>
</tr>
<tr>
<td>2</td>
<td>80%</td>
<td>50%</td>
</tr>
<tr>
<td>3</td>
<td>50%</td>
<td>90%</td>
</tr>
<tr>
<td>4</td>
<td>67%</td>
<td>92%</td>
</tr>
<tr>
<td>5</td>
<td>65%</td>
<td>57%</td>
</tr>
<tr>
<td>6</td>
<td>75%</td>
<td>50%</td>
</tr>
<tr>
<td>7a</td>
<td>80%</td>
<td>80%</td>
</tr>
</tbody>
</table>

In Table 5, an overview is given of both coverage and density of the PRIM analyses in appendix F. As may be observed, for every scenario, a box with both high coverage and density may be found. For
each of these scenarios a specific combination of inputs may be found that explains high concentrations of cases across all model outcomes.

6.2.8 Conclusions
Seven analyses regarding validity, verification and evaluation of the model have been presented. From these analyses, it may be concluded that the model replicates historic events as well as specific behaviors. These behaviors have a basis in the literature and stem from specific logical model behavior. Stochasticity of the model is relevant, but the outcomes of interest may be explained largely on the basis of a combination of inputs. The data used is mostly stochastic and thus empiric comparison is irrelevant for specific elements. On the basis of all of these analyses, we have drawn the conclusion that the model is fit for the purpose of exploring paths to war.
7. Experimentation and results

This chapter covers the computational experimentation that has been performed as step 7 in the ABM framework. The emphasis here was to explore the behaviors found in the model and to provide the insights into the behavior of states concerning war. In the first section the experimental setup will be described that would be necessary to recreate the results that were obtained. The second section will present the model outcomes in the form of data analysis and visualizations. The third section will explore a series of special cases through scenarios combined with data analysis and visualizations.

7.1 Experimental setup
In the experiments performed with the model, a few basic settings controlled the outcomes. If somebody were to replicate these results, the following setting ought to be used.

Amount of experiments and repetitions
In order to obtain the data from the model, 1,000 experiments were performed with 10 replications each. This total of 10,000 cases could still be obtained in a matter of several days and would not cause major problems in processing power in the data analysis. Even though more experiments and repetitions would be desirable, time and computing constraints made us decide to limit the amount of runs to 10,000. The amount of replications was set at 10 replications per experiments. This number was chosen on the basis of experimentation with the outcomes. This experimentation may be found in appendix E. Here, a comparison is performed between various amounts of replications. It was concluded that performing a larger amount of replications would not weigh up against the extra time required and would not yield new information.

Number of agents
The number of states in the system and the size of the landscape they occupy may be varied as the modeler desires. However, in order to keep the amount of computing resources required within reason, the decision was made to limit the amount of agents to 25 in a landscape of 41 by 41 provinces. The specific number 25 was chosen because it is low enough to allow the model to run swiftly but not too small for multiple major power and multiple minor nations. The landscape size of 41 by 41 (or maximum x and y value of 20, minimum value of -20) was chosen to be large enough to allow a spread in the amount of provinces a state owns, but not so large that larger amounts of computing resources were required. Some testing was performed with more agents in different sized landscapes, but the amount of time required for performing a single run of the model increased exponentially in larger models.
Exploration of paths leading to major power war

Run length
The run length of the model, which is the amount of time steps performed per model run, was set at 500. This specific run length was chosen to take into account the warm-up period of the model. Considering the model starts empty without any conflicts or memory, a certain amount of time is required in order to achieve the conditions under which a major power war is possible. In the initial runs, it was determined that major power wars rarely occurred before time step 100. This was thus the very minimum amount of time for the model to run. The amount of major power wars appears to stabilize itself within this period of 500 time steps. This was there for chosen as the maximum run length. The amount of major power wars is visualized in Figure 8.

7.2 Results: common paths to war
In this section, the results from the model runs and experiments are presented. Major power wars were observed to occur under a variety of circumstances. These major power wars are the emergent behavior that the model was designed to study. As such, the model is capable of generating behaviors such as predicted in various theories that were introduced in chapter 3. Several of these observed behaviors will be discussed in this section. The results shown in this section occur in the vast majority of cases, with only a few exceptions present. These exceptions will be discussed in section 7.3.
The structure of this section is based on the three levels of analysis, as introduced by Waltz (Waltz, 1979). As such, first the structure of the system is addressed. This is followed by changes in this structure to represent the dynamic nature of the world. Finally, aspects of individual fighting major powers are addressed.

7.2.1 System structure

Polarity
The polarity of the states is the very basic structure in which these states may be grouped. The three possible types of polarity (unipolarity, bipolarity, and multipolarity) are a representation of the number of major powers in the world. An extensive introduction into this topic is provided in section 3.1. The various scholars here disagree whether bipolarity or multipolarity is more likely to experience major power war and what may cause such wars. In Figure 9, the model outcomes with respect to the amount of wars that occur under the various amounts of polarity. Please note that unipolarity is not included here because a single major power does not allow for major power war.

![Figure 9: Histogram polarity](image)

In the histogram, both the amount of major power conflicts and the amount of major power wars are represented. Even though the amount of conflicts is roughly similar in both multipolarity and bipolarity, the amount of conflicts that escalate to war differs. In bipolarity, 22% of all conflicts among major powers escalate to major power war, and in multipolarity 36% of conflicts escalate.

Polarization
Polarization describes the nature in which cross cutting ties among states are present, as introduced in section 3.1. The commonly used reference here is the Cold War, in which the world was polarized
into two blocks, among which barely any cross cutting ties were present. At high values of polarization, there are no common ties among the warring major powers. This structure provides fewer restraints for wars in the sense that there are no common friends of the warring states and trade relations are typically also absent. In addition, there are likely to be more potential allies when fighting the conflict. Such potential allies are recruited among friendly states, which will only commit to an alliance if they are to be fighting a hostile state. In a highly polarized system of states, more such states are likely to be available.

Polarization is operationalized in the model as the amount of friends of state A that are enemies of state B, and vice versa. A level of polarization of 1 indicates no cross cutting ties, a level of 0 indicates a large amount of cross cutting ties. The distribution of polarization among warring major powers in the model outcomes is presented in Figure 10.

![Histogram polarization](image)

**Figure 10: Histogram polarization**

The vast majority of all major power wars occur at high levels of polarization (polarization = 1). In the sense that there are fewer restraints to waging war in such a situation, this is accordance with prediction. However, it must be observed that large amounts of wars occur at low levels of polarization. A clear peak may be observed at 0, in which case the warring states are closely tied.

**Interdependence**

Interdependence describes a state of mutual dependence among states, as introduced in section 3.3. Interdependence is based on the tradevolume between the two states and their cumulative GDPs. An additional component is present for resource scarcity when one of the states is the sole supplier for a certain resource. The role interdependence plays is a change in the utility calculation for states...
Exploration of paths leading to major power war

considering fighting wars. A decrease in welfare may be the result of severing relations with the opposing states and may not be desirable. Alternatively, high interdependence may be a source of conflict, as one or both of the parties seek to sever dependencies. The distribution of interdependence among warring major powers in the model outcomes is presented in Figure 11.

Figure 11: Histogram interdependence

Interdependence of major powers fighting is in almost all occurrences 0 or very low. In such a case, no trade is present among the warring major powers. Considering war may sever trade relations, this has important implications. If there are no trade relations to sever, there is no loss in welfare in that regard if war is declared. In these cases of low interdependence, there is also no form of resource dependence present. High values of interdependence indicate at least one key resource is exchanged.

Ideology Dissimilarity
The ideology similarity of states is expressed as the difference in values for specific attributes. These attributes are randomly assigned at the setup and will converge over time to the attributes of friendly states. When the model is ran over long periods of time, it settles eventually at a single center of ideology. Over time, friendly states and especially allies converge and as such, relationships change and states converge to a single ideology. The distribution of ideology similarity among fighting major powers is presented in Figure 12.
As may be observed from the figure presented, most major power wars occur under “medium” ideology similarity. It presents as a bell curve in the sense that very high and very low levels show few wars. An explanation for this may be that high levels are unlikely to exist for long due to convergence of the model. Additionally, the random nature of the initial setup requires time for low values to be present.

7.2.2 Changes in system

Power transitions
Power transitions are those situations where the most powerful state is overtaken in power by a different state. This theory was introduced in section 3.2 as both a potential cause and consequence of major power wars. A power transition leaves a former powerful state that is unlikely to give up its power position as well as a new power that is not given its “rightful” position. The confrontation between these two states may result in major power war. Additionally, the destruction of war will shift the power balance and potential spoils for victors may shift the balance even further. This may cause the power to transition to a different party. The distribution of time regarding power transitions and major power wars is presented in Figure 13 and Figure 14.
Exploration of paths leading to major power war

Two observations may be drawn from Figure 13 and Figure 14. First, major power wars follow power transitions within a few time steps. As displayed on a logarithmic scale, the vast majority of major power wars follow a power transition within a few time steps. Only in rare cases, a major power war is not close to a power transition. Second, most major power wars are followed by a power transition in a few time steps. As displayed on a logarithmic scale, the vast majority of power transitions follow a major power war within a few time steps. In fact, 76% of major power wars are both preceded and followed by a power transition within 5 time steps.
Power parity

Power parity refers to the idea that states fight each other only at roughly equal levels of power. The notion is that states fight only at power parity is present in multiple theories. In section 3.1 (Polarity), the idea is introduced that preponderance of power scares off any potential challengers, because they know they will lose. If a conflict occurs between a minor state and a major power, preponderance is likely to get the minor state to concede. Only when parity is present, both parties may have a reasonable expectation of victory and thus fighting may occur. In Section 3.2 (Power transitions), it is stated that rivals for the position of dominant state will fight at power parity, unless the hegemon attacks preemptively. In section 3.4 (Rivalries) rivalries only exist prolonged if roughly power parity exists. In such a case, both parties are unable to defeat the other party and thus a vicious circle starts. Finally, in section 3.6 (arms races), it is introduced that unless there is a reasonable expectation of being able to defend against the opponent (i.e., power parity or better), there is little sense in an arms race. The distribution of power among warring major powers is presented in Figure 15 and Figure 16.

Figure 15: Scatterplot power with indication of power parity
Figure 15 and Figure 16 indicate a clear tendency for states to fight at approximate equal levels of power. Wars fought at power parity are the most prevalent: 56% of all cases fall in the narrow bandwidth of the red dots in Figure 15. In Figure 16, a large “hot” zone on the bottom left indicates a high prevalence of cases here. However, despite this tendency, there are still quite a few cases at power disparity, and even at extreme disparity.

**Inflection points**
The inflection points are those points at the power curve of a state where the general direction changes. Mathematically speaking, this occurs when the second derivative changes sign. The inflection points were given categories, as displayed in Figure 6.

In the power transition theory, as posed by Doran and reiterated in section 3.2, is it predicted that major power wars occur at a specific stage. The combination of a status quo dominant power just past its peak in power and a newly risen challenger approaching its peak is expected to lead to war. In terms of the operationalization in the model, this means that a dominant power in inflection point 1 or 5 fights against a contender in 4 or 1. The distribution of inflection points among warring major powers is presented in Figure 17. The seven histograms here show the frequency of all 49 possible combinations. On the x-axis, the specific combination is given in the form of a tuple: (inflection state 1, inflection state 2).
Figure 17: Histograms of inflection points and the frequency of combinations

On the basis of the model outcomes, it was found that 3% of major power wars are fought between a rising power and declining hegemon. Major power wars as predicted by Doran appear to be a rare occurrence in the model. Instead, it was found that the vast majority of major power wars are fought between rising powers. In fact, approximately 50% are fought between two rising powers in category 4, of which 75% is between two contenders. A large group of states also fights when they are at stage 2 of their inflection points. Inflection point categories 3 and 6 are rare occurrences in the model in general, and thus also among major power wars. The reason for this is that periods of prolonged rise or decline are unlikely due to the volatile nature of the model.

When considering the dominant state, in 73% of major power wars, the dominant state is not involved at all. These wars are fought among major powers that are competing for the top spot. For the remaining cases, in 13.6% of major power wars, the dominant state wages a preemptive war. In 12.6% of cases, the dominant state is attacked.
7.2.3 State characteristics

**Dissatisfaction**
A state’s satisfaction with its place in the world is based on its actual power, relative to other states, and recognition of said power. Dissatisfaction of states is based on the notion that foreign policy role (i.e., expectation of power) lags power. Satisfaction is the difference between expectation of power and actual power, as displayed in Figure 7.

The dissatisfaction of states impacts the risk appetite of states. When the states make decisions on the basis of utility, the weights of gains are increased and the weights of losses are decreased. The distribution of dissatisfaction among warring major powers is presented in Figure 18.

![Figure 18: Scatterplot of foreign policy role satisfaction](image)

The vast majority of all cases of major power wars involve one or both states with high dissatisfaction. In fact, 89% of major power wars are fought with at least one participant with a dissatisfaction of 7.5 or higher. In contrast, only 38% of MP conflicts have at least one participant with a dissatisfaction of 7.5 or higher.

When taking into account the work of Doran and power transitions, where a satisfied status quo fights a dissatisfied challenger, 21% of cases involve a satisfied state fighting a highly dissatisfied state. Interestingly, both of them may be initiator. 18.7% of cases with only the initiator with high dissatisfaction versus 11% of cases with only defender with high dissatisfaction.

**Perceptual uncertainty**
Is war in the error term or would structural causes explain everything? Considering uncertainty in the perception of the power of an opponent, both parties may overestimate their chances of winning, or
underestimate. Without uncertainty, the assessment of chance of winning for both parties adds up to 1 (or 100%). If both states overestimate, war may be attractive to both parties, even at power disparity. The distribution of assessments among warring major powers is presented in Figure 19.

![Figure 19: Scatterplot of the assessment of the probability of winning](image)

Considering the values in Figure 19, the vast majority of cases perform an approximately “right” assessment in the sense that both assessments add up to 100%. However, there are still significant amounts of major power wars fought where both parties are overly optimistic or pessimistic. This would allow for war in the error term due to perceptual uncertainties.

7.3 Results: scenario exploration

In section 7.2, the general model outcomes have been presented. However, these overall outcomes only cover those cases that cover a large percentage of cases. Provided this preliminary exploration of the model, several special cases of interest may be specified for further exploration. These cases display unusual combinations of events that may conflict with conventional wisdom. These cases will be further explored in this section to determine the pathways to major power war. The complete results of the PRIM analyses for the individual scenarios may be found in Appendix F.

Scenario 1: High interdependence

In this scenario, a major power war occurs at high levels of interdependence. As may be observed from Figure 20, the vast majority of all major power wars in the model occur at low levels of interdependence. A small peak however is found at the very right of the figure, representing major power wars at very high levels of interdependence.
Exploration of paths leading to major power war

April 7, 2015
Roderik Luteijn

Figure 20 Interdependence histogram

Prim
The outcome of the prim analysis was that cases that fall into this category have in common high values on FPR impact. This variable indicates the influence dissatisfaction has on risk appetite.

Outcomes
The case at hand here involves a major power war between two contenders, fighting in a multipolar world. Both of these states are in inflection point category 4 (i.e. declining rise). As such, they are very dissatisfied with their place among states and the lack of recognition of their foreign policy role. Additionally, the relationship between these two major powers is rather close in the sense that the polarization is 0. This means that a large amount of cross cutting ties is present. The warring states are not completely equal in all aspects however. A significant difference in power may be observed with the initiator possessing far more power than the opponent. This situation has resulted in a small conflict, at conflict level 1 among these two major powers. The conflict is directly between the two states, without involvement of allies. It ought to be mentioned that multiple smaller major power wars occurred just before the current conflict.

In the period before the conflict, both states experienced endogenous growth. They sustained high growth rates over a prolonged period of time. As such, they grew from relative obscurity to become major powers. As this rise from obscurity occurred, these states became increasingly powerful, but this was not recognized as such by other states. The recognition tends to lag behind actual power developments. This increased dissatisfaction among these two states, as well as a desire to become top dog, is present. This high dissatisfaction results in an increasing number of conflicts that may be used in a variety of ways. First, they may be used to expand by conquering other states or acquiring parts of other states. This would require fighting to occur, which makes forcing other states into
submissio more attractive. Due to a power difference between these major powers and other states, this will most likely work for most states.

When considering the conflict that lead to this major power war, both states went through a series of considerations in order to arrive at the major power war. First, state 1 has a large chance of winning and can, therefore, reasonably expect the opponent to back down when pressed. If an opponent should be still willing to fight, state 1 has a high risk appetite and will therefore be equally willing to fight. Escalation would not be desirable, as currently the situation is already very favorable. Concretely, state 1 makes the choice between aggression and backing down. Based on the utility of these options, fighting is expected to yield the largest utility, despite a large negative component for the high interdependence among the two states. For state 2 the situation is rather different. A small chance of winning is present and the opponent is likely to fight, as it is in their interest. State 2 also has a rather large risk appetite, but cannot be reasonably expected to win a confrontation. Allies are sought, but no other state sees a positive utility in joining this fight. The choice thus remains between giving in to demands from state 1, and fighting with a high probability of losing. High risk appetite makes choice for fighting more appealing (with a small chance of winning) than a definite loss in case of submission, where some concessions are required.

Fighting is still the likely choice for both states in this scenario, despite the high interdependence. The high risk appetite ensures the weaker state chooses the more risky approach to avoid a definite loss. The stronger state will always press its advantage. The higher risk appetite does depend on the overall impact dissatisfaction has on risk appetite.

Scenario 2: High polarization and medium interdependence
In this scenario, the possibility is explored of a major power war occurring at medium levels of interdependence (between 2 and 8), but also at a high level of polarization (=1). In Figure 21, this situation is indicated by a relatively small amount of cases in the middle of the graph. Please note that this histogram is on a logarithmic scale.
Exploration of paths leading to major power war

Figure 21: Interdependence and Polarization histogram

**Prim**
The Prim analysis revealed that cases of high polarization and medium levels of interdependence share specific high values for the variable that describes the impact of dissatisfaction on risk appetite. The probability of attacks for those relationships with higher than average interdependence was also found to be rather high in these cases.

**Outcomes**
The major power war in this case is a war between a satisfied defender and a dissatisfied initiator. The two states have very similar ideologies and have likely crossed paths before. The defender is the dominant power and thus far more powerful than the initiator. These two states fight a small conflict, without any allies, major power to major power.

In the period before the conflict, state 1 experienced an accelerating growth rate and has just become a major power. The recent nature of this transition means that the foreign policy role lags and high dissatisfaction is present. Several smaller conflicts occurred with state 1 as a participant to reflect this dissatisfaction. State 2 is at the top of the system and is therefore satisfied with the status quo. Even though it is still growing in relative power, this growth is declining.

In the conflict, state 1 has a very high risk appetite, but a rather small chance of winning. In addition, due to the power differential, there are no allies capable of balancing the power between the two sides. High risk appetite means fighting is appealing, despite small chance of winning. State 2 has a much lower risk appetite and almost certainty of winning. The low risks of fighting combined with a preference for maintaining the status quo will make fighting an acceptable option compared to doing...
nothing. Waiting is not very appealing considering the opponent will become relatively stronger. Striking now is advantageous compared to later.

This case involves a preventative war of a hegemon defending against a rising contender. The high risk appetite of the rising state explains its willingness to fight, even though it may objectively not be a smart choice. The hegemon does not want to lose its position and is given a chance to preemptively take out a potential opponent. The high probability of a conflict among interdependent states may be said to provide this opportunity.

Scenario 3: Satisfaction and high interdependence
Scenario 3 involves a major power wars occurring at low levels of dissatisfaction for both fighters and high interdependence. Both of these factors are expected to diminish the odds of a conflict escalating to a major power war, but war did occur. In Figure 22, the red dots indicate the cases major power war with a high level of interdependence. Most of these are located in regions with high dissatisfaction, but a small number is located elsewhere. In Figure 23 a scatterplot is presented with the dissatisfaction of warring states. 89% of all major power wars fall within the red dots, which indicate high levels of dissatisfaction.

![Figure 22 Dissatisfaction scatterplot, under conditions of high interdependence](image)

**Outcomes**
The case at hand here involves a major power war at high interdependence that is very similar to scenario 2. Three crucial differences make this case worth exploring nonetheless. First, this case is at roughly power parity. Second, the participants here are a mature, satisfied, economically developed dominant state 1 and a challenger state 2 that is also satisfied. Third, a power transition is expected within five years due to high growth rates of the challenger and low growth for the defender.
In the conflict that lead to a major power war both states experienced a low risk appetite due to their relatively satisfied condition. State 1 is the stronger state, which for the most part based on its technological development. Even though power parity is present, the technological advancement of state 1 means it may wage war far more effectively and will likely win. Considering this fact, fighting is an attractive option despite low risk appetite. The risks of fighting are limited, with almost certainty of winning and thus the gains will likely outweigh costs. Additionally, doing nothing will allow the opponent to rise further, while state 1 approaches its top. State 2 on the other hand has multiple options, but has to consider that losing a war or even giving concessions to the opponent will be very costly. Fighting is the lesser of two evils in this case and will therefore be chosen.

Figure 23 Dissatisfaction scatterplot

**Prim**
The only variable worth mentioned out of the prim analysis is again the FPR impact, which indicates the influence of dissatisfaction on risk appetite.

**Scenario 4: Power disparity**
Even though the vast majority of cases is fought at approximately power parity, there is a certain amount of major power wars that occurs at extreme disparity in power. As may be observed in Figure 24, there are quite a few major power wars where one of the parties has a small amount of power in the range 3 to 6, while the other party has a power of 10 or higher.
Exploration of paths leading to major power war

Prim
The prim analysis revealed that cases that fall into this category share two inputs. First, once again, FPR impact is a factor. Second, the weight assigned to potential losses suffered in a conflict also is high for these cases.

Outcomes
The major power war at hand is one where the difference in power between the two participants is 10. This extreme power disparity did lead to a major power war, despite high deterrence caused by power preponderance. In addition to this power disparity, the two parties experienced an interdependence of 0 and a polarization of 1. These figures indicate no trade was present, nor any exchange of resources, and that there were no friends in common. State 1 was the initiator of this war and was also the weaker party. A high risk appetite was present, despite very low chances of winning. State 2 has a low risk appetite combined with near certainty of winning. The large difference in power means that the potential gains for state 1 are far larger than the potential losses. This difference means that when a high risk appetite is present, the option to fight may be more attractive in rare cases, especially when combined with low weights for potential losses.
Exploration of paths leading to major power war

Scenario 5: Conflict levels

In Figure 25, the conflict levels are indicated at which major powers have been fought in the model. The vast majority of cases is fought at a level of 1, which is the equivalent of a small border clash. Major power war at conflict level 5 is an all-out war, and does not occur very often.

Prim
Four inputs were revealed in the prim analysis to be of specific importance. First, the weights assigned to potential gains and losses. Second, the impact of dissatisfaction on the mean values of these weights. Finally, the threshold for when fighting is considered ineffective due to the power differential, is also relevant here.

Outcomes
The major power war at high conflict level under review here is a war between a dominant state and a challenger. A power transition among these two is expected in a short time span. Among these two states there is low polarization and medium interdependence. Both are neither risk averse or risk seekers, but are rather tempered in their preferences. A small power differential is present, not quite power parity among the two states. The challenger recently became major power and the dominant state is not very much stronger.

In order to escalate, one or both parties must select escalation as its preferred option. This option is chosen if the utility of fighting at a high level is preferred to the current level. Seeing as neither party is convincingly stronger than the other, both parties must select escalation. High conflict levels indicate higher potential gains, and high potential losses. When combined with the threshold for
escalation, both parties have repeatedly selected this option. The combination of specific outputs may facilitate higher conflict escalation.

**Scenario 6: Assessment**
States perceive the power of their opponent, as well as their own power, with a certain amount of uncertainty. On the basis of these perceptions, an assessment is made for the probability of winning. These combined assessments ought to add up to a value of 1 without any uncertainty. However, as may be observed from Figure 26, major power war occurs when both parties strongly overestimate.

![Figure 26 Assessment of winning scatterplot](image)

**Prim**
Unsurprisingly, the standard deviation of the perception comes out strong in the PRIM. Additionally, the standard deviation of GDP growth also does well. Final, the FPR impact once more is a strong indicator.

**Outcomes**
The major power war in this instance occurs at approximate power parity. The interesting parts here are the assessments of both states. State 1 assesses the probability of winning at 76%, while state 2 assesses it at 90%. Both parties severely overestimate their probability of winning. This war occurs in a bipolar world that recently became bipolar from a situation without any major powers. Both of these states are very dissatisfied and share similar ideologies. Additionally, a high amount of polarization and a low amount of interdependence is present.

The assessment of power is influenced by a learning effect and how hostile the environment is. Both states only recently became major powers and previously no major powers were present. As such,
they had very little interaction with each other and no previous conflicts that would have allowed for a learning effect. Additionally, the high polarization of the system is an indication of a relatively large amount of hostile states for both states. Limited attention may be paid to each such hostile state, decreasing knowledge regarding capabilities. When these assessments are used by both states in their utility calculations, war appears very attractive due to expected certainty of winning.

Scenario 7: Inflection points
The final group of scenarios involves the power curve of states and where on their respective power curves are when they fight. A large amount of conflicts was recorded as being between two states that were at point 4, which is declining growth. However, there are more possibilities than that, albeit these possibilities are rarer.

Scenario 7A
For every conflict, a record is maintained who made the final aggressive move. This state is denoted as the aggressor and typically assigned “state 1”. In a small percentage of cases, the hegemon was found to be this initiator, which will now be further explored.

Prim
Once again, the FPR impact is a common trait for the cases at hand. Additionally, the weights assigned to potential losses also are relevant.

Outcomes
In the major power war at hand, the warring states find themselves in a bipolar world and are roughly at power parity. The nature of their power is vastly different however in the sense that the challenger is a technological advanced major power while the dominant power is a very large, but not very advanced state. Militarily, there is an advantage for the dominant state, as the challenger’s power is mostly economic based. The challenger is expected to overtake the dominant state imminently, due to the fact that the economic strength allows for military buildup. It should be mentioned that both states are dissatisfied.

For the challenger, fighting the dominant state may bring a twofold gain in the sense that it would allow for it to become the new dominant state as well as acquire additional population and lands that may further fuel growth. For the dominant state, fighting now is preferable to fighting in the future due to the expected changes in power, especially military power. Both parties therefor see benefit in fighting. The risk appetite of both states is not as relevant here, as both states have clear motives for fighting now.

Scenario 7B
The final case involves a major power war among declining major powers in a multipolar world.
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**Prim**
No results were obtained from the prim analysis, considering there were too few cases among the major power wars in the dataset to run the analysis.

**Outcomes**
The specific case here involves two major powers in accelerating decline, or inflection point category 5. War is initiated by the contender, which is declining in power slower than the dominant state. Among these two states, the power balance is shifting in the favor of the challenger. Considering both states are past their top and had been a major power for quite a while, both are fairly satisfied and risk averse. Low interdependence is present, and more importantly, neither state has any friendly states. There are almost no constraints present for waging wars. The assessment therefor comes down to the expectation of winning and the amount of gains and losses present. Both parties will seek to wage war and thereby stop their own declining and gain or maintain the top ranking.
8. Conclusions

This research has been aimed at exploring the pathways to major power wars using the generative approach. Rather than applying data analytics to macroeconomic data, this study replicated the behavior of states in a simulation model. The central notion here was to generate paths leading to major power wars and compare the outcomes against claims made in literature. The simulation model was implemented as an agent based model in Netlogo. A large amount of experiments was then performed, which included uncertainty of inputs. Using the EMA workbench and scenarios discovery, the results in chapter 7 were obtained. In this chapter, conclusions are drawn on the basis on chapter 7.

8.1 Conclusions

The following question has been at the center of this research:

What pathways can be identified in the interactions among nations that lead to a major power war?

In the model outcomes, a number of pathways were discussed in sections 7.2 and 7.3. Every one of these pathways is a potential explanation of how major power war may develop on the basis of a certain aspect in the interaction of states.

First and foremost, the risk appetite of states as well as their dissatisfaction plays a central role in a large amount of major power wars. In the literature it was found that the thesis is that dissatisfaction will contribute to aggressive behavior. In the model it was concluded that dissatisfaction appears to be one of the main drivers of major power war. This is, however, not the entire story, as major power wars do occur at low levels of dissatisfaction. In those cases, the perceived benefits of war are already present without high levels of dissatisfaction.

Second, power transitions appeared adjacent to major power wars in a vast majority of all cases. The literature reviewed often predicted that a major power war is either the cause of a transition or the result of a transition. In the model outcomes it was found that power transition occurs both before and after major power wars. In such cases, the power transition caused stress among the fighting nations and the destruction resulted in a power transition.

Third, the interdependence of states on the basis of trade and resources was found to be in almost all cases very low among warring states. This is in accordance with the literature, in which the liberal
thesis states that interdependence decreases conflict; highly interdependent states do not fight. In the model outcomes, highly interdependent states rarely fought and most wars occur when there is little to no interdependence. If war does occur under high interdependence, it is accompanied by extreme risk appetite of both states. This risk appetite must be severe enough to offset the restraining effect of interdependence.

Fourth, the polarization of the relationships between states was found to be rather high for most model outcomes. In the literature, high polarization and its decreased constraints provide the stage for the events that may lead to war. In the model outcomes, this tendency was also found. However, it should be noted that a large group of major power wars did occur at lower and intermediate values. In addition, the polarity of the system showed that a multipolar system is more prone to major power wars due to the possibility of contenders fighting among each other.

Fifth, wars are expected to be fought at approximate power parity, considering this may provide both parties the assessment they are able to win. In the model outcomes, wars are fought at power parity in overwhelming majority of cases. However, wars may be fought at power disparity when the weaker party has very large potential gains and an extremely high risk appetite.

Sixth, the ideology similarity of major powers fighting was found to be moderately different. In the literature, fighting parties most often possess dissimilar ideology. In the model however, the ideology similarity is in the shape of a bell curve. This means that most wars are fought at different ideologies, but not extremely different.

Seventh, the uncertainty in the perception of other states allows for wars to be fought where both sides are convinced they are able to win the military confrontation. In the literature, this is often referred to as: “war occurs in the error term” (Gartzke, 1999). In the model outcomes, a number of cases were indeed found that allow for both states to over or under estimate their chances. However, the vast majority of major power wars occur under approximate correct assessments.

However, the most interesting conclusions may lie in the situation where two contenders fight against each other. In this case, it is not the number one fighting against the number two for dominance over the other states, but rather the numbers two and three fighting. Even though this case was not found in an extensive literature review, it was expressively found in the model outcomes. The explanation for this case may be found in the extreme risk appetite and dissatisfaction of contenders, especially compared to satisfied dominant states. When two extremely dissatisfied states are pitted against each other, both may see merit in fighting due to their respective risk appetites. The dominant state does not have such a risk appetite and will seek to
avoid war in a large number of cases. It must be mentioned however that this outcome does depend on the impact of dissatisfaction on the risk appetite. If this impact is very strong, the urge for contenders to fight becomes more present.

In the next section, the implications of these conclusions will be discussed in the light of policy makers seeking to prevent the outbreak of major power wars.

### 8.2 Policy implications
The remaining question is then what these conclusions mean for policy makers seeking to prevent the outbreak of major power wars. To this end, the specific conclusions drawn will be discussed and an indication is given of what the impact of these conclusions is on policies.

As a first implication, when the prevention of major power war is set as a goal, barriers to such wars may be relevant. Three such barriers were found to be present in the model as well as the literature. First, interdependence in the form of trade and resources may limit the outbreak of major power wars. If trade relations are present among states, and especially when the volume of trade forms a significant part of the economy of the states, this provides a serious incentive not to wage wars. Severing trade relations or using trade sanctions thus does not provide the right incentive in a conflict, and increasing trade may provide more of an incentive not to wage wars. Second, high polarization may set the stage for major power wars. The implication here is that there is a benefit in mutual friendships among major powers. Such states may be able to temper the drive for war. Forging friendly relations with the friends of potential adversaries in the future may decrease polarization and thereby provide a barrier to major power war. The third barrier may be found in accurate and objective information regarding the capabilities of your own state and potential opponents. Especially underestimations of the opponent or overestimation of your own forces may lead to situations where both parties see a great advantage to waging war. In such a case, the balance of force is wrongly estimated and thus more accurate information may lead to different decisions. The gathering of intelligence, sharing intelligence and similar measures may therefore limit the possibility for major power war.

A second implication may be found in those situations that may be classified as high risk situations. Certain aspects of states may make them more prone to waging wars and thus may warrant caution. First and foremost, the most extreme outcome of the model is the impact of risk appetite and dissatisfaction on the propensity for states to wage war. Highly dissatisfied states will ignore mitigating factors such as interdependence and may choose to wage war. If the lag between power and recognition thereof is to be decreased, the dissatisfaction of such states may not become so
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Extreme that war becomes an attractive opportunity. This lag may be for example decreased if in international institutions this balance becomes more effectively represented. A second outcome is the adjacent nature of power transitions to major power war. If a power transition is expected, this may be a high risk situation for major power wars. At this point, power parity is likely to be present, or will soon be present. A power transition is expected between China and the US over the coming decades if growth rates are to be considered. Creating barriers to major power wars at these high risks situations may prove beneficial in preventing the outbreak in major power wars.

Finally, what does this mean for actions commonly taken by policy makers? First, in the short term, interdependence may be used to leverage states to back down from a conflict. This may be done in the form of sanctions and thus a temporary decrease in interdependence. In the long term, decreases in interdependence increase the risk of major power wars because of a decrease in constraints to major power wars. Second, alliances may be forged with other states. If such an alliance decreases the polarization of the states in the world, this may provide an additional barrier to major power wars. Conflicting alliance obligations, such as seen in the balancing among states in the concert of Europe, may be effectively used to prevent major power wars. If such alliances increase polarization however, this may promote wars. This choice in different alliances types may also be classified as to balance or to bandwagon. Third, the use of alliances and interest to enlarge existing wars through joining conflicts ought to be limited. A part of major power wars may originate from minor conflicts that escalate. Final, the buildup of military forces may lead to arms races, or provide a deterrent to war. Key question here is the risk appetite of the states involved and whether or not military forces may offset potential gains.

8.3 Future research
This research has been done in the context of an MSc graduation and is, therefore, limited in time and scope. The very nature (i.e. exploratory) of this research and the limitations of this project allow for a host of future work to be done.

First, the model may be expanded to include additional or different implementations of concepts. The first expansion may be in the population and economical dynamics. Currently, the updates in population and economy are modeled as relatively simple Markov chains. The interactions of these variables with each other and the rest of the model may be more advanced and thus more realistic. As a second aspect to be expanded upon, the conflict escalation dynamics come to mind. This is highly debated upon aspect within the International Relations, but not modeled in a very advanced fashion in this model. The third expansion is in the agent decision-making process. Currently, this is
modeled as a utility maximization process where agents base their decisions on six aspects. However, agents may seek to utilize different strategies, other than just maximization of utility. In the model framework constructed by Cederman and others, this was established by constructing and expansion called Geocontest. This allowed for comparison of various strategies, as well as a learning effect in the strategies of agents. The various strategies may be also linked to the real world strategies followed by policy makers.

Second, specific outcomes have been rather unexpected and thus warrant further exploration. Despite the fact that the majority of outcomes have been predicted by at least part of the literature, some of the outcomes have not been found in comparable literature. These outcomes may require further investigation in order to establish if these were model anomalies, or may indeed be found in the real world as well. The most surprising outcome definitely is the possibility of major power wars among contenders rather than dominant states. This outcome can be explained by the large risk appetite and high dissatisfaction of these states. However, this relationship would need to be further explored. The nature of the impact of dissatisfaction on risk appetite is a question that is highly relevant for this path. Further analysis of literature to find other references of the fighting among contenders may also yield some results. However, what may be most promising is to analyze existing International Relations theories in the light of contenders fighting and the implications of such a different view.

Third, the methods and tools used may be expanded to provide new insights. The first and foremost expansion lies in the agents themselves. Currently, the agents are not quite as smart as we may like them to be. They are able to make bounded rational decisions, but are not able to adapt or learn and improve their decision making. The ability to recognize trends is not possible either, as well as the ability to deal with emotional aspects such as fear. A specific solution to this problem has been advocated by Epstein in a recent publication (J. Epstein, 2013). He suggests the inclusion of emotional responses as a vector with the rational decisions of agents. In tandem with the inclusion of smart agents, the ABM framework may be expanded as well. The rationale of agents is rather simple, often in the form of Beliefs-Desires-Intentions. More advanced rationales are being developed and may allow for more suitable models in the future. Final, the possibilities to analyze behavior of agents may be improved as well. Such behavior is most often not a single event, but rather a process involving multiple events over a given period of time. For example, in the model, the escalation to a major power war is a process of decisions and events. What may be measured is however the occurrence of a major power war. Tools or methods for capturing such processes may allow for a better analysis of model outcomes.
8.4 Limitations

Despite the efforts that have been put in analyzing, conceptualizing and implementing the model, several limitations remain the reader ought to be aware of. The first limitation stems from choices made in which theories to implement in the model. A scoping was needed to select a reasonable amount of concepts from the IR literature to be included. In this process, certain simplifications were made in order to improve our ability to model the system at hand. One such simplification is the choice the model states as unitary actors. Despite the fact that this is often done within realist literature, this is an obvious simplification and may have caused us to overlook certain dynamics. More such simplifications are present and thus the model is not complete. The interactions among states are however such a complex process that simplified is required. Only a limited amount of interactions could be taken into account. Considering the generative perspective, it is likely that not all possible paths to major power war could be implemented and even more paths may exist.

The highly stochastic nature of the model with the many uncertainties also limits the applicability of the model. Despite efforts to deal with these uncertainties in a highly structured manner, the fact remains that certain values are unknown and may therefore be simply wrong. The increased amount of runs to deal with the outcome space is also limited by the availability of computing resources and time. These problems stem of course from the lack of real world data. One of the reasons this research was desired is that such data is often hard to find. The data that is available is often in the form of small samples or highly biased data. This research is there for mainly theory driven, and not data driven. Further exploration of the problem with as much empirical input as possible would be desirable.

Other limitations may be found in the validation of models in general, and ABM specifically. Several options are present for validation; with expert validation and comparison to empirical data the most commonly used types. However, it remains hard for anyone to compare the features of the model directly to the real world in order to validate the model. The result is that the outcomes of the model should not be read as absolutes truths but rather possible outcomes. For ABM in particular, many ABM practitioners have recognized this difficulty, such as (B. Epstein, 2012). The emergent nature of many of the outcomes rather than linear translation of inputs makes a validation even more difficult. In the model at hand here, which is based on theories and stochastic elements, the validation is even more limited due to a lack of empirical data available for comparison.
9. Reflection

This chapter provides the author with a final opportunity to look back on this research project and reflect on what happened, how it could have been improved and what lessons should be taken away.

9.1 Reflection on the model
Reflecting on the model, I am rather pleased with the outcomes of the model. When I first started with this project, I did not have a full understanding of what would be involved in creating such a model. Only after performing a very extensive literature study, I could grasp the full scale of the conceptual model to be created, and thus the model itself. In fact, a lot of scoping needed to be done at this point in order to limit the model to a manageable size. Despite these difficulties, I am pleased that I was able to build a model that showed a large part of the behaviors indicated by the literature.

The model ended up being completely exploratory as point of departure: no policy options were implemented and tested. The analyses performed were aimed at distilling relations from the model and generalizing these to the “real world”. The problems modeled here are likely too complex to apply policy options to, but nonetheless this may provide useful insights for policy makers. One example would be whether or not sanctions would help prevent war. This is essentially a measure of whether decreasing interdependence achieves peace. In order to increase the relevance of this study to practitioners, policy options ought to be testable in models, especially concerning newly discovered results such as the option of contenders fighting.

9.2 Reflection on methodology
In this work, agent-based modelling has been the methodology that was used, implemented in Netlogo in conjecture with the EMA workbench. Generally speaking, the choice for ABM as a methodology has been satisfactory. I am certain this has provided a different point of view than other simulation methods or analyses that have been performed. I highly doubt that the same types of emergent aspects may have been found in for example statistical analysis of history.

Even though the choice for ABM may have been a satisfactory one; Netlogo, however, did show its limitations when a long time was spent working in it. The attractiveness of simplicity of programming in Netlogo for initial use is offset by the increased difficulty of programming more complicated code. The way in which programming is implemented in Netlogo did make me choose not to implement
certain code for purely practical and time saving reasons. Other programming languages or tools may provide easier ways of implementing for example differential equations.

The link with the EMA workbench did work well, after some initial hiccups. Considering previous experience with the built in Behaviorspace module of Netlogo, the workbench has delivered a far more compelling experience. The only downside for me was my personal lack of experience with Python, which forced me to spend time on doing a bit of a crash course in python. This did cost me quite a bit of time to get right, but in the grand scheme of things the impact was limited. Personally, I would think a limited graphical user interface for the workbench would make it much more appealing to a larger crowd.

9.3 Reflection on Process
The process of performing this research and writing my thesis was experienced as a rather fluent process, with very few large problems that were encountered. My initial challenge was to understand enough of IR literature in order to understand what I would be modelling. After initial efforts to get caught up with IR literature had been performed, I was able to understand much of what the model would include. When I also studied previous efforts of other studies in reproducing interactions of states, I was able to conceptualize the model in more concrete terms, using their implementations. The only problem encountered here was the lack of operationalizations of variables within IR. Even though many papers would for example discuss foreign policy role, no papers were found that would provide concrete measures that may be used to model this aspect. This presented me with the challenge of determining an operationalization that would be in agreement with the prevalent literature and I would be able to implement in the limited time given.

It may be said that when I started out with this project, I did not fully comprehend the full scope of the project. This resulted in an overly ambitious start of the project and a need for several sessions in defining the scope. Due to my lack of initial IR knowledge, I was not able to do such a scoping until later on in the process. My initial, rather ambitious, for also including policy options and testing these was therefore scrapped at a later point in time. Even though I would like to do such a thing, a more complex model may be required and a large amount of time. The results as presented now do encourage policy makers to account for several possibilities that have not been considered previously.

Throughout the process, weekly meeting with my supervisors helped me stick to my time schedule and forced me to have results every week to show my supervisors. Additional discussions with analysts at HCSS gave me new ideas on a regular basis, which made my time spent working at HCSS
very valuable. One additional challenge I picked up here is translating my model and my (engineering) ideas to those with completely different backgrounds (e.g. social sciences). Certain aspects I considered trivial, I discovered needed a lot of explaining.
References


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Appendix A: Modelling steps

Step 1: Problem formulation and actor identification
The first step in modeling a system is gaining an understanding of what the problem is and to whom it is a relevant problem. This step typically involves reading relevant scientific literature and stakeholder interviews. The outcome of this step would be a definition of the problem as well as a scope within which the research is to be conducted.

Step 2: System identification and decomposition
Provided the problem definition and scope of the system to be studied, relevant modelling aspects are identified in this step. Specifically, the modeler decomposes the system of interest into the following five aspects:

1. Agents:
   The objects to be studied
2. Properties:
   The relevant properties of the agents to be included.
3. Behaviors:
   Those behaviors shown by the agents that may impact the system of interest.
4. Interactions:
   The actions taken by the agents and how these influence the other agents and the environment
5. Environment:
   The environment includes everything that is relevant to the model but not included in the agents.

Step 3: Concept formalization
In this step the aspects of the system identified in step 2 are translated into more formalized concepts. The goal here is to produce usable concepts that may be implemented in the model to be built. Often, an ontology of the concepts is created along with a UML class diagram to serve as the basis for implementation of the model in a programming environment (BRON).

Step 4: Model formalization
In step 4 the modelling process is formally kicked off with the creation of two documents that describe what the model will do. First, a narrative is an informal description that describes what the model “world” will look like. The specific focus of the narrative is to describe what agents will take which actions at what point in time. The informal nature of this document means that may still be shared widely with stakeholders that do not have a programming/modelling background.

Even though the narrative may be informal and easily understood, the model implementation itself may not be so readily available. In order to facilitate this transition, pseudo code is often created as a step in between. This pseudo code contains all the logic, calculations, parameters, and conditions.
that are to be implemented in the model. However, the pseudo code is not quite programmable code and still allows for interpretation. In the implementation, this pseudo code may be quite literally translated into a programming language of choice.

**Step 5: Software implementation**
Implementation of the model formalization into a software environment, for which in this study Netlogo will be used. More on the use of Netlogo in section 2.4.

**Step 6: Model verification**
Once the model has been implemented in the software, verification needs to be performed in order to make sure that the model corresponds with the design. This is a highly iterative process of finding bugs and repairing these. In addition to bug fixing, actions and relations described in the model design are to be checked if they are performed in accordance with the logic set, and if the logic is correct. This process does not check whether or not the model corresponds with the “real world”, which is done in step 9, but rather whether the model and the design agree.

**Step 7: Experimentation**
If the model is declared to be in accordance with the design, experimentation with the model may be in order. By varying input parameters, the model outcomes may be explored. In this study this will be done through the combination of Netlogo and the EMA workbench, which will be discussed in section 2.4 and 2.5 respectively.

**Step 8: Data analysis**
The experimentation performed in step 7 is likely to yield large amounts of data. This data is to be analyzed by using for example statistical analysis or data mining. This data analysis aims to provide those answers that the problem owners are looking for.

**Step 9: Model validation**
Is the model suitable for answering the questions posed in this research project? This question is to be answered in the validation of the model. Most models are however fairly complex and do not allow for a direct comparison with the real world. A commonly used proxy is the use of expert validation. If an expert in the field of study considers the model behavior to be within the expected values, the model is often considered valid. Another proxy may be historic examples of past events for which data is available. However, the exploratory nature of this study means that the focus has been on expanding insights and knowledge rather than exactly replicate the world. This admittedly makes validation difficult.
In an effort to still perform validation, the methods proposed by Augusiak et al. (2014) are used. In their six step validation, verification and validation process, number of model aspects are analyzed in order to provide feedback regarding validity of the model.

**Step 10: Model use**
The final step in the modelling process is the interpretation of the results obtained from step 7 and 8 and thereby generating the conclusions of the study. An important aspect here is the usefulness of the model and whether or not it is capable of answering the research questions.
Appendix B: Model conceptualization

Entities, state variables, and scales

Agents have

- A set of provinces: List
- Power, based on (Chang, 2004): Integer >= 0
  - Population size of all provinces owned: Integer >= 0
  - GDP of all provinces owned: Integer >= 0
  - Military capabilities: Integer >= 0
- Resource presence: List
- Hostile states: List
- Friendly States: List
- Trade relations: List
- Invaluable trading partners: List
- Allies: List
- Export size: Integer >= 0
- Import size: Integer >= 0
- Utility Preferences: List
- Power Memory: List
- Power growth memory: List
- Power growth change memory: List
- Ideology: List
- Memory of conflicts: List

Relevant conditions

- Sense of security: Integer >= 0
- Foreign policy role satisfaction (Doran, 1989)
  - Relative rank among states: Integer >= 1 and <= number of states
  - Benefits received from foreign policy: Integer >= 0
  - Satisfaction with foreign policy role: Integer
- Major-power: Boolean
- Ranking: Integer
- Interdependence: integer
- Technological advancement: Integer
- Inflection point category: Integer

Agent behavior

- Degree of uncertainty: Integer >= 0
- Probability of success: Integer >= 0 and <= 1
- Expected cost of performing the action
  - Direct (i.e., loss of military capabilities): Integer >= 0
  - Indirect (i.e., loss of trading partner): Integer >= 0
- Expected benefits of expected outcome: Integer >= 0
- Cost of failure: Integer >= 0

Interactions with environment

- Growth of Population: Integer
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- Growth of GDP: Integer
- Growth of Military Capabilities: Integer

Environment/Provinces have:
- Population per square: Integer >= 0
- GDP per square: Integer >= 0
- Resources within squares: List
- Province is capital?: Boolean
- Owner of Province: List

Environment:
- MeanGDPgrowth: Integer
- MeanMilitaryGrowth: Integer
- MeanPopulationGrowth: Integer
- SDGDPgrowth: Integer
- SDMilitaryGrowth: Integer
- CreateConflict
- CreateWater
- Setup
- RankStates
- RedistributeSpoils

TradeRelations:
- Members: List
- Tradevolume: Integer
- Interdependence: Integer
- Forge():
- Break()

Provinces:
- Capital: Boolean
- My-State: List
- Population: Integer
- GDP: Integer
- Resources: Integer
- Water?: Boolean

States:
- Power: Integer
- Population: Integer
- GDP: Integer
- MilitaryCapabilities: Integer
- ResourcePresence: List
- Imports: Integer
- Exports: Integer
- TradeRelations: List
- My-provinces: List
- Allies: List
- Possibilities: List
- FriendsStates: List
- SatisfactionPPR: Integer
- MajorPower: Boolean
- SharedSecurity: Integer
- Ideology: List
- TechnologicalAdvancement: Integer
- Power-memory: List

DiplomaticRelations:
- Attribute: Floating point
- Ideology-similarity: Integer
- Conflict-memory: List
- UpdateAttributes(): Floating point

ForeignPolicyRole:
- RelativeRanking
- Satisfaction

Alliance:
- Members: List
- Forge()
- Break()

Figure 27 UML class diagram of model
Appendix C: pseudo-code

In this appendix, the model conceptualization out of appendix B is translated into pseudo code as part of step 4 of the modelling process. For each of the methods that have been implemented in the model itself, pseudo code is written and presented here. Please note that this has not been directly implemented but rather translated again into appropriate syntax for Netlogo.

A) Decision-making for state A in militarizing conflict

If (at time T, conflict between A and B is true)
    Determine all states with whom conflict = true
    Foreach opponent:
        Perform decision procedure on militarizing conflict:
            Determine reparations factor and attrition rate, based on the level of conflict
            Determine chance of winning
            Find potential allies
            Determine how the sense of security might change from fighting, submission or doing nothing

If conflict has been true for longer than maximum duration:
    Both sides decide to fight or do nothing, no other options possible.

Escalation variable = (w1 * expected-spoils) / (w2 * expected-losses)
If (Escalation variable > threshold escalation) ➔ escalate
If (Escalation variable < threshold de-escalation) ➔ deescalate

If (threshold escalation > Escalation variable > threshold de-escalation) ➔ continue

Find likely action by opponent by:
Choice = ((1 - chance-winning) * uw1 * actual-reparations-factor * count my-provinces) - (chance-winning * uw2 * actual-reparations-factor * (count [my-provinces] of enemy))

If (choice < 0) Opponent is unlikely to fight and will likely submit or build capabilities
If (choice > 0) Opponent is likely to fight

Calculate expected gains and losses based on attrition rates, reparations factors and the likely action of the opponent.

If: opponent is a hostile state, A has three possible scenarios, each with several potential actions
1. Opponent has a 3 : 1 or better military advantage, there is no point in building military capabilities due to preponderance in power
   a. Finding an ally that is powerful enough to offset advantage of opponent
      i. If unsuccessful, decide between options b or c
      ii. If an ally is found, move to 2 or 3, based on the new military situation
   b. Fight
      i. Fight war
      ii. Structural change
   c. Giving in to demands
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i. Structural change occurs through bargaining

2. Opponent has no decisive military advantage or disadvantage
   a. Build military capabilities
      i. Military spending is increased
   b. Find allies
      i. Alliance is forged
   c. Give in to demands
      i. Structural change occurs through bargaining
   d. Fight
      i. Structural change occurs through war

3. Opponent has a 1:3 or worse military disadvantage
   a. Fight
      i. Structural change occurs through war
   b. Do nothing
      i. No change in structural aspects, but a memory of conflict remains

The utility of every action is measured through the following variables and their coefficients

1. Advantage B
   a. utility-fight = w1 * chance-winning * expected-spoils - w2 * expected-losses * (1 - chance-winning) - w3 * military-losses - w4 * loss-of-trade + w5 * change in security
   b. utility-submit = w5 * change in security + w2 * (reparations-factor – give in compensation) * amount of provinces

2. No advantage
   a. Utility-build = w6 * change in chance-winning + w7 * cost of additional units + w5 * change in security
   b. Utility = w6 * change in chance-winning + w8 * cost of alliance + w5 * change in sense of security
   c. utility-fight = w1 * chance-winning * expected-spoils - w2 * expected-losses * (1 - chance-winning) - w3 * military-losses - w4 * loss-of-trade + w5 * change in security
   d. utility-submit = w5 * change in security + w2 * (reparations-factor – give in compensation) * amount of provinces

3. Advantage A
   a. utility-fight = w1 * chance-winning * expected-spoils - w2 * expected-losses * (1 - chance-winning) - w3 * military-losses - w4 * loss-of-trade + w5 * change in security
   b. Utility-nothing = 0

Change in sense of security = Recalculation of sense of security based on changed power and changed set of hostile/friendly states

B) Changes in attitude

If (at time T, conflict between A and B is true) and (an action was chosen by both actors)

If (A acted aggressive versus B )
  Increase attitude of B's hostile states and A
  Decrease attitude of B's friendly states and A
  Decrease attitude of B and A

If (A showed restraint )
  Increase attitude of B's friendly states and A
  Increase attitude of B and A

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If (alliance was formed between B and C)
  Increase attitude of B and C
  Decrease attitude of A and C

If no conflict occurred,
  A positive interaction occurs with probability attitude
  a negative interaction occurs with probability attitude

C) Alliance request

If (alliance request is received from A in conflict against B)
If else (attitude self-B is friendly)
  [Reject proposal]
  [calculate pWinning A + Self, B
calculate:
utility-fight = w1 * chance-winning * expected-spoils - w2 * expected-losses * (1 - chance-winning) - w3 * military-losses - w4 * loss-of-trade + w5 * change in security
Do nothing:
decrease in attitude (and potential change in sense of security and trade relations)]
Decision = max utility

D) Interact

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<th>State 2</th>
<th>Interaction</th>
</tr>
</thead>
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E) wage war
If there are any trade relations between A and B, terminate these

if (chance-winning of A > chance-winning of B) → declare A winner, B loser
if there any allies involved →
set total power A = sum of power of A and allies
set total power B = sum of power of B and allies
set total power A = total power a – attritionrate * total power B
set total power B = total power B – attritionrate * total power A
based on original power ratio’s and the new total power, assign new military capabilities to all states
else:
set (military capabilities of A) (military capabilities of A)
– attritionrate * military capabilities of B
set (military capabilities of B) (military capabilities of B)
– attritionrate * military capabilities of A

F) Structural change
set spoils reparations factor * provinces of losing alliance/state
based on power ratio’s of victors, distribute these spoils across the victors.
For each victor, ask every loser to give up resources until you have matched the spoils

Provinces are chosen on the following basis:
Find any provinces that border the victor and are owned by the loser.
If there are any, assign these to the victor
If there aren’t, find a random patch that is closest to the victor.
From that random patch, find neighboring patches that also belong to the loser and assign these to the victor.
If the spoils equal or exceed the total amount of provinces a state has left, it dies

G) Change trade relations
For every state:
Find out which resources are produced by the provinces owned
If (not all resources owned) → see what resources are owned by current trading partners and thus can be traded. If there is just one supplier for a specific resource, this becomes an invaluable tradingpartner
If (not all resources owned & not owned by current trading partners) → find new tradingpartner(s) that do own the specific resource
For potential new tradingpartner(s), select the best one that has the lowest cost and highest attitude

For current trades, find which ones are highly assymetrical and with hostile nations, but not with invaluable tradingpartners, and break these trades, if the cost aren’t too high.

H) set power

set critical-mass ( (population / total-population) + (count-provinces / total-area) ) * current-amount-of-states
set economic-strength (GDP / total-GDP) * current-amount-of-states
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set military-strength (MilitaryCapabilities / total-Militarycapabilities) * current-amount-of-states
set power (critical-mass + economic-strength + military-strength) / 4

I) chance of winning

Perceive military capabilities of A with a degree of uncertainty
Perceive military capabilities of B with a degree of uncertainty
Perceive military capabilities of allies A with a degree of uncertainty
Perceive military capabilities of allies B with a degree of uncertainty

Chance of winning A = \frac{1}{1 + e^{-\frac{(\text{total power } A \text{ and allies} - \text{total power } B \text{ and allies})}{\text{total power of all}}}}

J) Create conflict

Let amount of conflict be the probability of conflict * the total amount of diplomatic relations
Let amount of conflict regarding trade be the probability of conflict of interdependence* the total amount of trade relations

Repeat for amount of conflict times:
Select two states, each with probability (number of states – rank) / total amount of ranks
If no conflict is present yet, create a conflict

Repeat for amount of conflict regarding trade times
Select the diplomatic relation with the highest interdependence and conflict false, then set conflict true

Select a preset number of very dissatisfied states, if any, and create a conflict between these states and a neighboring minor state.

K) Foreign Policy Role (FPR)

Set expected benefits = (current rank/ total ranks) * total benefits
Set received benefits = (foreign policy rank / total ranks) * total benefits

Set satisfaction (expected benefits - received benefits) * power

L) Update attributes

Update provinces
GDP (t+1) = GDP (t) * Economic growth (t)
Economic growth (t) = Economic growth (t-1) + Change
Change = normal ( mean = 0, SD = input )

Population (t+1) = Population (t) * population growth (t)
population growth (t) = population growth (t-1) * change population growth
change population growth = Weight * Economic growth (t)

Update States
exportsize = sum of all exports
importsize = sum of all imports
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GDP = sum of all provinces
Population = sum of all provinces

Technological advancement = (GDP/capita) / mean GDP/capita
Fighting strength = Military Capabilities * Technological advancement
Military capabilities (t) = Military capabilities (t-1) * military growth
Military growth = random variable + Increased spending + Change
Change = size of threat – compensation for current size of military

Power = Set Power
Store power in Power memory

Change in power = (new power - old power) / old power
Store change in power in Power growth memory

Change in power growth = (new growth – old growth ) / old growth
Store Change in power growth in power growth growth memory

Determine inflection point

Resources = sum resources of all provinces

If (Power > threshold for major power) [major power = true ]

W1 = universal W1 + FPR-impact * (FPR-satisfaction - mean-FPR)
W2 = universal W2 - FPR-impact * (FPR-satisfaction - mean-FPR)

If (attitude among alliance partners = hostile ) [ break alliance ]

Update relationships
Size of exports (t)= Size of exports (t - 1) * economic growth of trade partner
Size of imports (t)= Size of imports (t - 1) * economic growth of yourself

M) Determine inflection point

If (growth = 0) [ category = 1 ]
If (growth = positive) [
If (change in growth = positive) [ category = 2]
If (change in growth = 0) [category = 3]
If (change in growth = negative) [category = 4]
]
If (growth = negative) [
If (change in growth = positive) [category = 7]
If (change in growth = 0) [category = 6]
If (change in growth = negative) [category = 5]
]

N) Ideology

Create a list with length n with ideology values [ x1 x2 x3 ... xn]
Choose one of the variables in the ideology
Choose a friendly state

If (variable = same) [ do nothing]
If (variable = bigger than friend) [ set variable -1]
If (variable = smaller than friend) [ set variable +1]

Determine similarity:
Similarity = ideology – ideology of other state →
Similarity = [ x1 x2 x3 ... xn] - [ y1 y2 y3 ... yn]

O) Find sense of security
Sense of security = total friendly power / total hostile power
Total friendly power = own power * uncertainty + sum power of friendly states * uncertainties
Total hostile power = sum power of hostile states * uncertainties

Change in sense of security = new sense of security - old sense of security
New sense of security → update own and opponent’s power with expected losses and gains, recalculate
Appendix D: Verification

The iterative process of verification was performed after the model implementation was mostly finished. For specific parts of the model, tests were performed to verify whether or not the model design corresponds with the model implementation. For every aspect of the model, the following questions were asked:

- Does the model “break” under certain inputs?
- Are there any emergent behaviors that may “break” the model?
- Is the observed behavior in disagreement with common sense?

The model was run a 1000 times over a length of 500 ticks in the workbench. The input values were varied in a range and any errors were recorded, as well as various output variables per test.

Model setup

Observations
- The landscape is created in accordance with the design
- All agents are assigned initial values for all variables
- States can vary in size in the range of 1 – 250 patches
- The system may initiate with zero or multiple major powers

Issues
- Various divide by zero errors were raised in the model
- Lists were on occasion empty, which prompted errors
- Agents were non-existent on occasion, which prompted errors
- Very high percentages of water would cause errors in landscape setup
- Specifically, “Islands” were created within bodies of water that could not be assigned to any state. The result was patches that weren’t assigned to any state and also weren’t water.
- It is possible for a run to be set up without any population in any of the states or without any GDP.

Fixes
- If statements verifying parameters would not be zero were placed before relevant code.
- If statements verifying the relevant list or agent set does exist were placed before the relevant code.
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- Additional, in the model code, several “Carefully” methods were implemented. This code allows the model to run even though an error is encountered. If an error is encountered, alternative code is run.

- When the states were done growing, any unassigned patches would be designated water.

- No more than 50% of the landscape may be designated water.

Conflicts

Observations
- No clear link was shown between power and the amount of conflicts present: all states experienced conflicts and fought wars
  - Possible explanation: Lower levels of power are more abundant and thus even though these states fight less wars, the total amount of wars is similar

- Several outliers were found in FPR dissatisfaction that experienced high levels of conflict and high levels of dissatisfaction

- Several outliers were found in Interdependence that experienced high levels of conflict and high levels of interdependence

Issues
- Several conflicts did not receive two decisions

- Some conflicts remained true indefinitely

Fixes
- A failsafe was built to ensure every conflict would receive two decisions

- A maximum duration was set for conflicts after which states must either fight or the conflict ends

Utility in decision making

Observations
- All seven options for decisions are used

- The maximum utility option was always correctly chosen

- Every conflict received two decisions every time step

Issues
- Not all pairs of interactions were accounted for

- Even though all seven options for decisions are used, some were significantly more prevalent than others:
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<td>0</td>
</tr>
<tr>
<td>De-escalate</td>
<td>327</td>
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</table>

Fixes

- Several additional pairs of interactions were defined
- Additional code was written to allow for the stronger party in a conflict to have a stronger say in which interaction occurs. This allowed de-escalation to occur more often and fighting/escalation less frequently.

Trade relations

Observations

- No trade relations are ever severed if it involves an invaluable trading partner
- Every state possessed every resource unless a certain resource was not present in the model.
- Agents correctly identify missing resources and do not exit this method until they are able to trade for it

Issues

- Low levels of interdependence among major powers were found

Fixes

- A bug was found in the code calculating interdependence

Foreign Policy Role

Observations

- High values for dissatisfaction were witnessed for states approaching the top of their power before overtaking the hegemon.
- States with a stable amount of power were neutral, only rapidly declining states were extremely satisfied

Issues

- Several extreme spikes were found in foreign policy role

Fixes

- The order in which code was executed was changed in order to prevent such spikes from happening
- A maximum dissatisfaction of 10 was set
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Waging war and division of spoils

Observations

- Spoils are transferred from losers to winners
- Correct amount of total spoils is transferred
- Correct amount from each loser to each winner
- Correct winner determined and battle damage was generated
- The probability of winning converges to the mean value after a small number of trials, which is approximately the actual chance of winning

Issues

- Battle damage could cause military capabilities to turn negative

Fixes

- Minimum amount of military capabilities was introduced

Minimum model

A minimum model is the model run with only 2 agents.

Observations

- The model did not yield any errors
- Conflicts occurred and several wars were fought
- Obviously, no alliances were formed

Issues

- No power transitions occurred: the bigger state remained on top

Fixes

- This issue was not “fixed” because the large power differential between the two states would almost always make it unlikely that a power transition occurred.

Maximum model

A maximum model is the model run with 130 agents.

Observations

- Model becomes incredibly slow, even when run on brand new hardware
- Small power differential among states because every state got a few provinces, and then none were left
- Large amount of conflicts
- Landscape does not change significantly

Issues

No problems were found

Fixes

No issues needed fixing
Exploration of paths leading to major power war

Sanity checks

Observations
- Long values for memory length showed extreme spikes in several variables
- High or low threshold values would freeze the system in a specific configuration
- The amount of conflicts and thus wars is very highly dependent on the probability of conflict initiated randomly.

Fixes
- Very long memory lengths were excluded
- Other problems were accepted, as they are modeling choices/uncertainties
Appendix E: Stochasticity

In the model, various elements of stochasticity as present. Example of this would be:

- The order of execution among agents
- The model setup and especially the landscape is done through various stochastic functions
- Perception of power of states depends on a normal distribution

Considering the goal of this project is exploratory, a question looms here. How many replications with the same set of inputs is required in order to get satisfactory results? It would be desirable to do as few runs as possible considering computational requirements of large amounts of runs. However, enough runs are desired so all possible behaviours may be witnessed.

Method
In order to determine the number of replications to run, a test was performed. Using a single operationalization (set of variables), a 100 runs were performed. The results of these runs will be compared to just the first 10, 30, and 50 results. If results are not very different for a higher amount of runs, a higher amount of runs is not required.

Comparisons
In Figure 28, the range of values witnessed for the ideology similarity remains roughly the same for all replications, with the exception of 100 replications. There does not seem to be much of a need to increase the amount of replications unless a 100 or more is feasible.

Figure 28: Boxplots of ideology similarity at various amounts of replications
For Figure 29, the range of values goes slightly up as more replications are used. The differences are fairly small however.

Figure 29: Boxplots of dissatisfaction at various amounts of replications

For Figure 30, the bulk of values remain in the same range of values. The range of outliers however increases, especially at a 100 replications.

Figure 30: Boxplots of the amount of states at various amounts of replications
For Figure 31, the range of values seen for all amounts of replications is within the same range of values. 10 replications appear sufficient to provide all possible combinations.

Figure 31: Boxplots of the amount of MPW at various amounts of replications
Appendix F: Data analytics/PRIM

In this appendix, the outcomes of the prim analysis are located that have been performed as part of the results in section 7.3. For each of the 7 scenarios in that section, a prim analysis was performed to find out if any of the inputs would be able to provide predictions regarding the clustering of specific outcomes.

For each of the scenarios used, the same process was used to identify those combinations of inputs that would accurately identify the cases of interest. This process consisted of first identifying those experiments, and inputs, that lead to a specific scenario. Once these cases had been identified, a trade-off diagram was made, as shown in Figure 32. In this diagram, those boxes are identified that score on both the coverage and density of cases above 50%. The ideal box has 100% density and 100% coverage. This is however very unlikely, so for every scenario, two boxes were identified that score either very high on density and coverage above 50%, or where both coverage and density are at their maximum. In addition, the peeling and pasting trajectories of the PRIM analysis were used to identify the range of boxes that formed a stable plateau with regard to restricted dimensions. Finally, the individual boxes were analysed and the Qp values of the inputs are hand were studied. These cases are similar to the significance of a variable in statistical analysis: values below 0.05 were considered usable.

Scenario 1: High interdependence

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<tr>
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<th>Coverage</th>
<th>Density</th>
<th>Variables</th>
<th>Reasoning</th>
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Figure 32: Trade-off scenario 1
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Figure 33: Peeling and pasting trajectory scenario 1

**Statistics**

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<tr>
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**Conclusion**

For both boxes, the variables FPR impact is the only adequate descriptor for the boxes.

**Scenario 2: High polarization and medium interdependence**

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Figure 34: Trade-off scenario 2

Figure 35: Peeling and pasting trajectory scenario 2

Statistics

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SD-tradevolume-growth 0.000002 0.094038 2.935178e-01
uW3 1.006319 9.534081 3.078153e-01
uW2 1.482406 9.997366 3.316690e-01
reparations-5 0.400275 0.686470 3.418461e-01
attitude-decrease-war 0.000005 0.752342 3.468565e-01

Conclusion
For both boxes, both FPR impact and Interdependence-pAttack are adequate descriptors.

Scenario 3: Satisfaction and high interdependence

<table>
<thead>
<tr>
<th>Box</th>
<th>Coverage</th>
<th>Density</th>
<th>Variables</th>
<th>Reasoning</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>0.5</td>
<td>0.9</td>
<td>5</td>
<td>Maximum density</td>
</tr>
</tbody>
</table>

- Choice for box 17
  - Coverage > 0.5
  - Density > 0.9

Figure 36: Trade-off scenario 3
Exploration of paths leading to major power war

Figure 37: Peeling and pasting trajectory scenario 3

Statistics

<table>
<thead>
<tr>
<th></th>
<th>min</th>
<th>max</th>
<th>qp values</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPR-impact</td>
<td>0.471252</td>
<td>0.999180</td>
<td>2.452350e-18</td>
</tr>
<tr>
<td>SD-perception</td>
<td>0.036141</td>
<td>0.299786</td>
<td>1.422178e-01</td>
</tr>
<tr>
<td>amount_of_ideology_change</td>
<td>0.011982</td>
<td>0.299773</td>
<td>3.107906e-01</td>
</tr>
<tr>
<td>attitude-decrease-bargain</td>
<td>0.023745</td>
<td>0.499615</td>
<td>3.654370e-01</td>
</tr>
<tr>
<td>reparations-4</td>
<td>0.215013</td>
<td>0.499862</td>
<td>3.703685e-01</td>
</tr>
</tbody>
</table>

Conclusion

For this box, FPR-impact was once again the only adequate predictor. Other boxes were evaluated, but also showed FPR impact to be the only relevant variable.

Scenario 4: Power disparity

<table>
<thead>
<tr>
<th>Box</th>
<th>Coverage</th>
<th>Density</th>
<th>Variables</th>
<th>Reasoning</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>0.67</td>
<td>0.92</td>
<td>3</td>
<td>Maximum coverage and density</td>
</tr>
<tr>
<td>24</td>
<td>0.43</td>
<td>0.98</td>
<td>8</td>
<td>Maximum density</td>
</tr>
</tbody>
</table>
Exploration of paths leading to major power war

Figure 38: Trade-off scenario 4

Figure 39: Peeling and pasting trajectory scenario 4

Statistics

<table>
<thead>
<tr>
<th></th>
<th>min</th>
<th>max</th>
<th>qp values</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPR-impact</td>
<td>0.463992</td>
<td>0.999180</td>
<td>2.870912e-42</td>
</tr>
<tr>
<td>uW2</td>
<td>1.459261</td>
<td>9.997366</td>
<td>2.040694e-01</td>
</tr>
<tr>
<td>amount_of_ideology_change</td>
<td>0.012576</td>
<td>0.299773</td>
<td>2.451459e-01</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>min</th>
<th>max</th>
<th>qp values</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPR-impact</td>
<td>0.463992</td>
<td>0.971076</td>
<td>4.596771e-38</td>
</tr>
<tr>
<td>uW2</td>
<td>2.745747</td>
<td>9.997366</td>
<td>2.232221e-04</td>
</tr>
<tr>
<td>SD-perception</td>
<td>0.046183</td>
<td>0.299786</td>
<td>6.968888e-02</td>
</tr>
<tr>
<td>amount_of_ideology_change</td>
<td>0.012576</td>
<td>0.299773</td>
<td>9.777096e-02</td>
</tr>
</tbody>
</table>
Exploration of paths leading to major power war

reparations-5 0.400275 0.682575 1.751899e-01
SD-military-spending 0.000063 0.094593 2.921244e-01
cost-per-distance 0.000925 9.478211 2.921244e-01
attitude-decrease-submitted 0.022925 0.499536 4.696468e-01

Conclusion
If high coverage is considered to be relevant, FPR impact is the only variable of concern. However, if just density is considered, three more variables are relevant. These variables are UW2 (weight of losses), SD perception and the amount by which ideology changes every time step.

Scenario 5: Conflict levels

<table>
<thead>
<tr>
<th>Box</th>
<th>Coverage</th>
<th>Density</th>
<th>Variables</th>
<th>Reasoning</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.65</td>
<td>0.57</td>
<td>2</td>
<td>Maximum coverage and density</td>
</tr>
<tr>
<td>40</td>
<td>0.3</td>
<td>0.8</td>
<td>8</td>
<td>Maximum density</td>
</tr>
</tbody>
</table>

Figure 40: Trade-off scenario 5
Exploration of paths leading to major power war

Figure 41: Peeling and pasting trajectory scenario 5

Statistics

box 20

<table>
<thead>
<tr>
<th></th>
<th>min</th>
<th>max</th>
<th>qp values</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPR-impact</td>
<td>0.463992</td>
<td>0.999180</td>
<td>3.442558e-43</td>
</tr>
<tr>
<td>uW2</td>
<td>2.745747</td>
<td>9.997366</td>
<td>2.268447e-03</td>
</tr>
<tr>
<td>amount_of_ideology_change</td>
<td>0.012576</td>
<td>0.299773</td>
<td>2.405844e-01</td>
</tr>
<tr>
<td>cost-per-distance</td>
<td>0.000925</td>
<td>9.478211</td>
<td>3.203748e-01</td>
</tr>
<tr>
<td>SD-military-spending</td>
<td>0.000063</td>
<td>0.094593</td>
<td>3.240630e-01</td>
</tr>
<tr>
<td>reparations-5</td>
<td>0.400275</td>
<td>0.682575</td>
<td>3.314499e-01</td>
</tr>
</tbody>
</table>

box 40

<table>
<thead>
<tr>
<th></th>
<th>min</th>
<th>max</th>
<th>qp values</th>
</tr>
</thead>
<tbody>
<tr>
<td>uW1</td>
<td>4.321403</td>
<td>9.998518</td>
<td>0.000003</td>
</tr>
<tr>
<td>FPR-impact</td>
<td>0.162820</td>
<td>0.826093</td>
<td>0.000022</td>
</tr>
<tr>
<td>pWinning-factor</td>
<td>0.511571</td>
<td>0.678124</td>
<td>0.037696</td>
</tr>
<tr>
<td>uW2</td>
<td>1.007703</td>
<td>8.678527</td>
<td>0.063654</td>
</tr>
<tr>
<td>SD-GDP-growth</td>
<td>0.002641</td>
<td>0.048336</td>
<td>0.105861</td>
</tr>
<tr>
<td>likelihoodofresourcespresent</td>
<td>0.000192</td>
<td>0.183461</td>
<td>0.123497</td>
</tr>
<tr>
<td>SD-military-spending</td>
<td>0.000063</td>
<td>0.094508</td>
<td>0.212149</td>
</tr>
<tr>
<td>reparations-2</td>
<td>1.006319</td>
<td>9.463801</td>
<td>0.225431</td>
</tr>
<tr>
<td>water-percentage</td>
<td>0.034383</td>
<td>0.299865</td>
<td>0.266944</td>
</tr>
<tr>
<td>attrition-4</td>
<td>0.100237</td>
<td>0.477471</td>
<td>0.275608</td>
</tr>
<tr>
<td>cost-of-new-trade</td>
<td>0.100237</td>
<td>0.477471</td>
<td>0.275608</td>
</tr>
<tr>
<td>mean-Perception</td>
<td>0.219881</td>
<td>0.499878</td>
<td>0.284996</td>
</tr>
<tr>
<td>interdependence-pAttack</td>
<td>0.007283</td>
<td>9.395558</td>
<td>0.316442</td>
</tr>
<tr>
<td>attitude-decrease-submitted</td>
<td>0.000034</td>
<td>0.091408</td>
<td>0.332405</td>
</tr>
<tr>
<td>uW4</td>
<td>1.330474</td>
<td>9.999405</td>
<td>0.378367</td>
</tr>
<tr>
<td>cost-per-distance</td>
<td>0.461324</td>
<td>9.998353</td>
<td>0.378367</td>
</tr>
</tbody>
</table>
Conclusion
The variable of FPR impact scored high in both boxes, as did UW2. However, in the second box, also UW1 (weight of gains) and the ratio of preponderance were included.

Scenario 6: Assessment

<table>
<thead>
<tr>
<th>Box</th>
<th>Coverage</th>
<th>Density</th>
<th>Variables</th>
<th>Reasoning</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>0.75</td>
<td>0.5</td>
<td>3</td>
<td>Maximum coverage</td>
</tr>
<tr>
<td>32</td>
<td>0.5</td>
<td>0.7</td>
<td>15</td>
<td>Maximum density</td>
</tr>
</tbody>
</table>

Figure 42: Trade-off scenario 6

Figure 43: Peeling and pasting trajectory scenario 6

Statistics

box 17

<table>
<thead>
<tr>
<th></th>
<th>min</th>
<th>max</th>
<th>qp values</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPR-impact</td>
<td>0.358203</td>
<td>0.999180</td>
<td>0.00000</td>
</tr>
</tbody>
</table>
Exploration of paths leading to major power war

SD-perception 0.101125 0.299786 0.00000
likelihoodofresourcespresent 0.000192 0.190429 0.31373

box 32

<table>
<thead>
<tr>
<th>Variables</th>
<th>min</th>
<th>max</th>
<th>qp values</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD-perception</td>
<td>0.108898</td>
<td>0.299786</td>
<td>4.399946e-09</td>
</tr>
<tr>
<td>FPR-impact</td>
<td>0.358203</td>
<td>0.999180</td>
<td>7.237249e-09</td>
</tr>
<tr>
<td>random-pAttack</td>
<td>0.032157</td>
<td>0.199837</td>
<td>1.597406e-01</td>
</tr>
<tr>
<td>reparations-l</td>
<td>0.000104</td>
<td>0.282022</td>
<td>1.960719e-01</td>
</tr>
<tr>
<td>likelihoodofresourcespresent</td>
<td>0.000192</td>
<td>0.190429</td>
<td>2.550992e-01</td>
</tr>
<tr>
<td>attitude-decrease-war</td>
<td>0.040129</td>
<td>0.742472</td>
<td>2.678085e-01</td>
</tr>
<tr>
<td>attrition-3</td>
<td>0.100053</td>
<td>0.388442</td>
<td>2.706634e-01</td>
</tr>
<tr>
<td>attitude-decrease-bargain</td>
<td>0.032269</td>
<td>0.499615</td>
<td>2.883365e-01</td>
</tr>
<tr>
<td>SD-military-spending</td>
<td>0.004401</td>
<td>0.099998</td>
<td>2.883365e-01</td>
</tr>
<tr>
<td>mean-tradevolume-growth</td>
<td>0.910661</td>
<td>1.099823</td>
<td>2.901819e-01</td>
</tr>
<tr>
<td>amount_of_ideology_change</td>
<td>0.015006</td>
<td>0.299773</td>
<td>3.215423e-01</td>
</tr>
<tr>
<td>increased-mil-spending</td>
<td>0.000993</td>
<td>0.960181</td>
<td>3.412581e-01</td>
</tr>
<tr>
<td>distance-slope</td>
<td>0.119331</td>
<td>0.499644</td>
<td>3.412581e-01</td>
</tr>
<tr>
<td>uW2</td>
<td>1.421178</td>
<td>9.997366</td>
<td>3.441080e-01</td>
</tr>
<tr>
<td>threshold-dissatisfaction</td>
<td>3.001186</td>
<td>6.838361</td>
<td>3.587155e-01</td>
</tr>
</tbody>
</table>

Conclusion
In both boxes, the same variables had appropriate qp values: SD perception and FPR impact.

Scenario 7A

<table>
<thead>
<tr>
<th>Box</th>
<th>Coverage</th>
<th>Density</th>
<th>Variables</th>
<th>Reasoning</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>0.8</td>
<td>0.8</td>
<td>1</td>
<td>Maximum coverage and density</td>
</tr>
<tr>
<td>16</td>
<td>0.5</td>
<td>0.95</td>
<td>4</td>
<td>Maximum density</td>
</tr>
</tbody>
</table>

Figure 44: Trade-off scenario 7A
Exploration of paths leading to major power war

Figure 45: Peeling and pasting trajectory scenario 7A

Statistics

<table>
<thead>
<tr>
<th>variable</th>
<th>min</th>
<th>max</th>
<th>q.p values</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPR-impact</td>
<td>0.304004</td>
<td>0.999180</td>
<td>1.362430e-22</td>
</tr>
<tr>
<td>box 16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FPR-impact</td>
<td>0.338570</td>
<td>0.999180</td>
<td>2.401823e-20</td>
</tr>
<tr>
<td>uW2</td>
<td>1.007703</td>
<td>8.280565</td>
<td>1.528095e-04</td>
</tr>
<tr>
<td>SD-perception</td>
<td>0.032785</td>
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</tr>
<tr>
<td>population-GDP-factor</td>
<td>0.018317</td>
<td>0.199912</td>
<td>2.714853e-01</td>
</tr>
</tbody>
</table>

Conclusion

Once more, FPR impact and UW2 are shown to be adequate descriptors.

Scenario 7B

Scenario 7B did not meet the minimum amount of cases for which a PRIM analysis may be performed and was therefore excluded.