Understanding Arms Races for Autonomous Military Capabilities Using a System Dynamics Simulation Model

Laura Wilmes and Rob van Waas
TNO
The Hague
NETHERLAND

laura@wilmes.lu, rob.vanwaas@tno.nl

ABSTRACT

Militaries around the world are expanding their use of autonomous systems. Advancements in artificial intelligence make these systems increasingly effective, possibly leading to arms races. Having fully autonomous robots could change a nation's way of defending itself and achieving its strategic objectives. The need to develop strategies for defence and deterrence is crucial in the face of such technological investments. This paper investigates the arms race dynamics of two hypothetical nations (a hegemon and a rising nation). A System Dynamics simulation model was built using literature and subject matter experts. The model includes potential strategies for each nation. Exploratory Modelling and Analysis was applied to cluster patterns of behaviour. The model produces findings that suggest that most simulation runs lead to arms races, except if the hegemon maintains a strong economy, and the rising nation is not capable of developing high-tech systems. If a race occurs, the hegemon loses its advantage in most of the scenarios produced by the simulation model. The hegemon can try to prevent this outcome by hindering the rising nation in its technological development, which is an effective strategy under most conditions. However, if values and ethical standards of the hegemon require more human control of its autonomous systems, it risks losing. Our research can give insight into which decisions alliance nations can take towards different goals – either preventing arms races, keeping their advantage in an arms race, or preventing an opponent from overtaking them.

Keywords: System Dynamics, Arms Race, Autonomous Military Systems, Exploratory Modelling and Analysis

1.0 INTRODUCTION

The Cold War was characterized by both nuclear and conventional arms races. The two main powers of that time, namely the United States (US) and the Soviet Union, were amassing nuclear weapons in response to the other side ramping up nuclear capabilities. This is called a security dilemma. It refers to the self-perpetuating dynamics of one country increasing their security (e.g., by increasing military capabilities) leading to less perceived security for another state, prompting it to respond by increasing its security, which starts the cycle again [1], [2]. The cumulative number of weapons that each power builds deters the other from attacking it, thus leading to a state of armed peace [3]. Each party knows that by attacking its opponent it would ensure its own destruction. During this period, this was referred to as Mutually Assured Destruction. At the same time, an arms race can potentially have a stabilizing effect as the nations focus on acquiring arms or technology and not on fighting [4].

In the post-Cold-War world, US hegemony has been supported by economic strength, military might, and cultural dominance. However, in recent years, China is challenging it in nearly all aspects [1]. China, with its huge population, industrial strength, and rising military strength, is very likely to further increase its power [5].

According to the international relations theory of "structural realism," the appearance or rise of a new power potentially leads to tensions with the current hegemon, and possibly a security dilemma [6]. For our study we use conditions set forth by Caspary in response to early arms race modelling by Richardson [7]. Caspary considers a build-up of capabilities as an arms race, if three conditions are met: 1) Perceived military insecurity; 2) The arming being a burden on the economy; and 3) Perceived grievances. Perceived military insecurity relates to the security dilemma and links build-up of capabilities to adversary build up. It being a burden on the economy sets a threshold for the costs of the arms race. Finally, the perceived grievances act as a key driver of conflict. The grievances can be fueled by rivalries over status, competing agendas, territorial claims, ideology, or a combination of factors.

Currently, strategic competition among large powers provides some impetus for the outbreak of new arms races. One possible characteristic of this situation is the rapid and widespread acquisition of autonomous systems, such as Unmanned Aerial Systems (UAS) or Unmanned Ground Vehicles (UGV). While the US has been widely using UAS in the past, other countries are now following its example. It is estimated that in 2020, at least 102 countries, as well as some terrorist groups, have active military drone programs [8], [9]. In the six-week war in 2020 in the Nagorno-Karabakh region between Armenia and Azerbaijan, UAS were used extensively, leading some scholars to call it the first “Drone War” [10]. In the ongoing war of aggression of Russia against Ukraine (2023), “kamikaze drones” (also known as loitering munitions) have been used in great numbers against Ukraine [11].

Autonomous / unmanned systems have a wide range of applications. Depending on their size and specifications, they can be used for reconnaissance, target acquisition, swarming, or as loitering munitions [12]. In these applications they have several advantages over manned systems, as they can take faster decisions and are less prone to fatigue. Still, while full autonomy is technologically feasible, meaningful human control is an important element in autonomous military capabilities [13]. In addition, the ethical implications of using autonomous military systems can also affect their level of autonomy. Authoritarian states such as China might face less (regulatory) pressure in reducing the element of human control, while in the West, campaigns such as “Slaughterbots” are calling for a ban on autonomous military systems [14].

The effect of autonomous military systems on deterrence and on international stability is highly uncertain [15]. Some argue that emerging technologies alone cannot increase the risk of conflict escalation [16]. Others argue that autonomous military capabilities such as UAS could be the military revolution of the 21st century [14], [17], [18]. Three combined factors underscore this argument:

1) The fact that autonomous military systems are available at cheaper prices;
2) They can blur the line between defensive and offensive purposes (which can increase the perceived military insecurity of a nation); and
3) These systems potentially reduce risks to the operator.

The first condition is given by the fact that a big part of innovation and development is conducted by the private sector, resulting in dual-use technology that may reach both the civilian and military markets, thereby lowering per-unit production costs. The second factor is the subject of debate by various analysts who argue for or against the proposition that UAS are able to shift the offensive-defensive balance to the offensive side [15]. The third factor postulates that the use of unmanned systems could lower the threshold of war. As the risk of losing lives may be perceived to be lower in the case of completely remote warfare, this potentially removes a disincentive to the initiation of armed conflict [19].

Thus, it is imperative to investigate how a power competition between two states can escalate into an arms race via the acquisition of autonomous military systems. At the same time, it is important to look at different strategies that nations would employ to address this competition. Arms races have been studied mostly in the context of nuclear weapons and the Cold War. Most of these models are of a qualitative nature as opposed to being quantitative models. With autonomous military capabilities being a relatively new phenomenon, there is scant research of this nature to be found.

This study therefore aims to answer the following research question:

> *How can the development of autonomous military capabilities of two states evolve and a potential arms race be influenced?*

The study can be broken down into the following parts:

1) Which considerations should influence a nation's decision to develop its autonomous military capabilities?
2) What is the role of technological developments such as autonomy and other factors in escalating or de-escalating the development of autonomous capabilities into a potential arms race?
3) What is the effect of two example strategies on the frequency with which an arms race will occur?

After introducing the methods we use to address these research questions, we present the results of the model simulations. This is followed by a discussion of the implications of these results, concluding with limitations of the model and recommendations for further research.

2.0 METHODS

The dynamics involving an arms race between two nations can be seen through the lens of a complex system. Complex systems are characterized by multiple interacting components, non-linearity, and emergent behaviour, meaning the system's overall behaviour cannot be easily predicted from the behaviour of its individual components. To study the dynamic behaviour of this complex system over time, a combination of system dynamics (SD) and exploratory model analysis (EMA) is used in this study. System dynamics is particularly well-suited to model systems with a high dynamic complexity, feedbacks, and delays [20], as is the case for the system of this investigation. An SD model consists of interacting feedback loops, accumulations, flows, and delays. An early application of SD for military capabilities was the implementation of Richardson's arms race equations done by Forrester in 1984. The model represents the US and the Soviet Union building up nuclear capabilities during the Cold War [21]. This model captures some, but not all, of the dynamics of interest for an arms race via autonomous military capabilities as a result of two nations entangled in a security dilemma. Therefore, it is used as a starting point for this study. This model was then expanded to be applicable for this research, based on literature research and expert interviews.

The SD simulation model is analyzed using techniques from EMA to overcome the uncertainty of the parameters and understand the behaviour of the system. The EMA workbench [21] is used to conduct computational experiments on the SD model to understand under which circumstances (i.e., combination of uncertainties and policy levers) arms races occur and to explore possible outcomes under using uncertainty ranges [22]. Parameter uncertainty ranges are determined and simulation runs conducted over combinations of these ranges. Then, we search for parameter combinations leading to outcomes of interest. Those parameter combinations represent the conditions for futures in which the arms race escalates and both states accumulate autonomous military capabilities.

Thus, we can identify factors that escalate or de-escalate the build-up of autonomous military capabilities. From this, and inference can be made as to which parameter range and parameter combination cause this outcome to happen and form the discovered scenario of interest. From this we can finally conclude under which technological advancements and other factors in the model an escalation of the build up of autonomous military capabilities into an arms race takes place and in which it does not [24].

3.0 IMPLEMENTATION INTO MODEL

In this section, we report on the implementation of the model, based on the literature that was studied and the experts that were consulted. These experts are all based in the Netherlands and all affiliated to the defence domain. Most of the interviewees work at the Dutch research institute TNO in its Defence, Safety and Security (DSS) unit, at which we conducted this research. TNO is the Netherlands Organization for Applied Scientific Research and its DSS unit works on projects that concern defence and national security. Hence, the people working there generally have a background and experience in the security and defence domain. There are the defence modellers and the strategic defence analysts who, based on their experience with modelling different defence-related topics, could give insight into the potential structures of an arms race model. They explained which archetypes are to be expected and which dynamics could be expected. Academics from the research centre for military technology in the faculty of military sciences at the Netherlands Defence Academy were also interviewed, as well as practitioners from the robotics and autonomous systems (RAS) unit of the Dutch Army, which is developing concepts to employ unmanned robots with varying degrees of autonomy. Finally, we gained insight into how the industry and the business of autonomous military capabilities works, by interviewing entrepreneurs that develop said systems.

The scope of the model, as well as the implementation of the nations' strategies is defined below. This is followed by a description of the parameter ranges and process of validating and verifying the model. A more detailed model description and documentation can be found in the repository of the Technical University of Delft [38].

3.1 Model Scope

The model should capture the tensions between hegemon nation A and rising nation B, as well as the security dilemma [6] that can result in an arms race for high-technology military capabilities [7] (see Figure 1). This is a causal loop diagram in which an arrow indicates a causal relationship that includes a cause (origin of the arrow), effect (end of the arrow), and a polarity (indicated by a plus or minus sign). The effect is influenced in the same direction (increase or decrease) as the cause for a relation with a positive polarity and moves in the opposite direction for a relation with a negative polarity. We modelled three subsystems endogenously: capability planning, capability build-up, and technological development (see Figure 2 to Figure 4, which are screenshots of the system dynamics model as developed in the Vensim software).

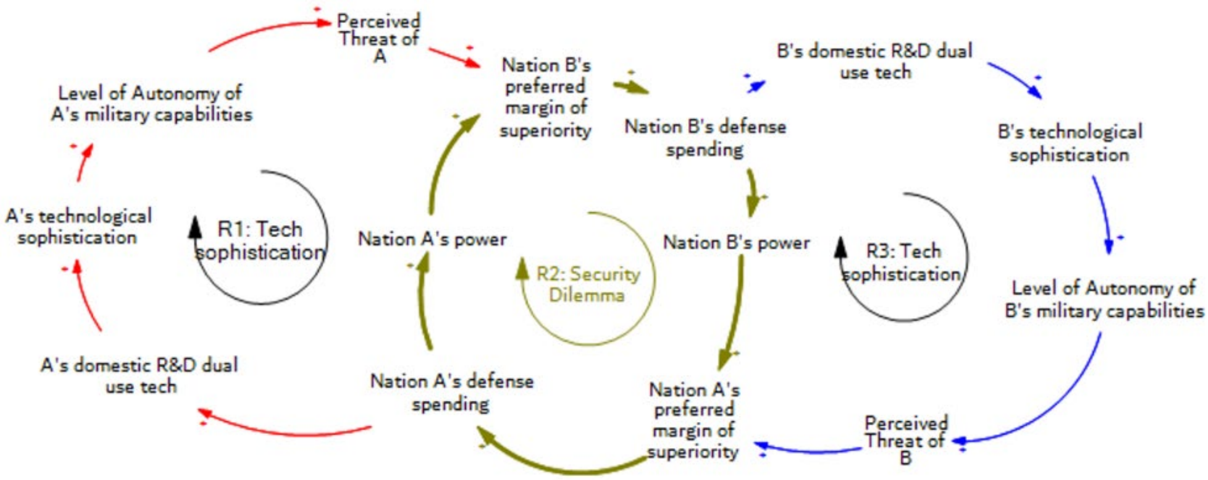

Figure 1: Causal loop diagram giving an overview of the security dilemma in the context of an arms race for autonomous military systems.

The capability planning subsystem captures the needed investments and funding. Figure 2 represents this subsystem for nation A, while it looks the same for nation B. There are two stocks in the subsystem, these being "GDP A" and "Autonomous systems budget A." The flow "GDP growth A" increases the first stock. "Increase in autonomous systems budget A" increases the second stock and represents how much budget is spent on autonomous capabilities, depending on the perceived need for these systems.

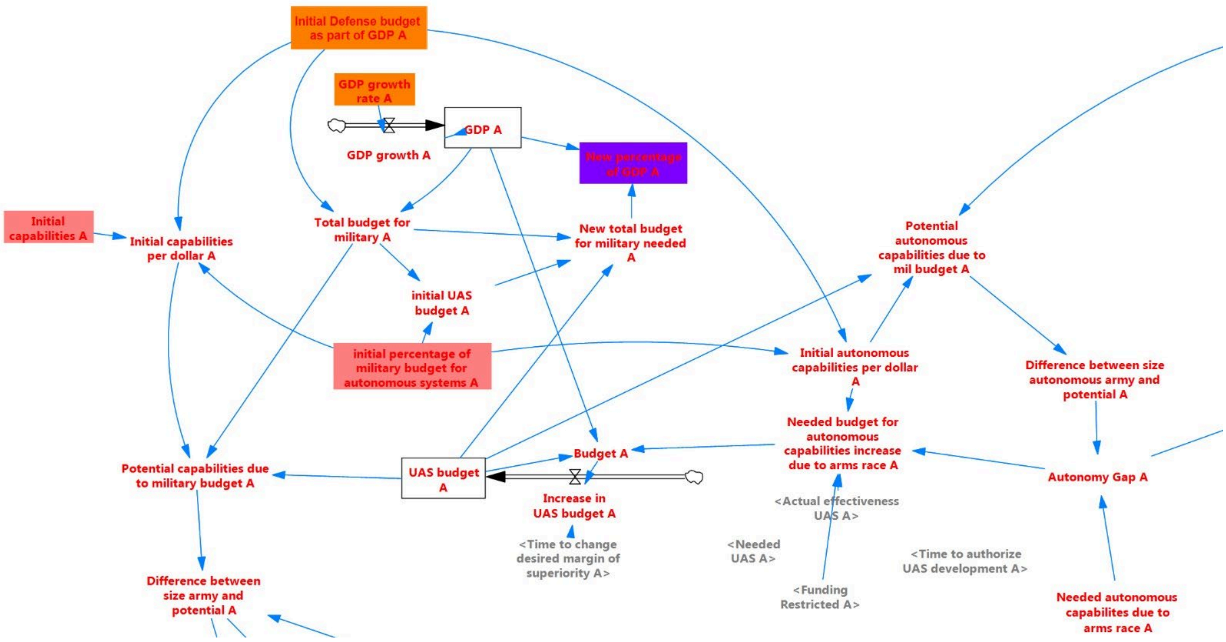

Figure 2: The subsystem "Capability planning" of nation A. The budget that is available for autonomous systems depends on the budget used for other capabilities and for personnel.

The capability build-up subsystem includes perception of the strength of the opponent's autonomous capabilities, as is present in a security dilemma. Figure 3 shows this subsystem for nation A, while it has the same structure for nation B. There is an aging chain with the two stocks "Autonomous systems under development A" and "Autonomous systems stock A," which vary with the flow of autonomous systems that are being produced and are phasing out. New systems are produced in relation with the factor "Desired margin of superiority A," which is calculated based on three variables from other subsystems.

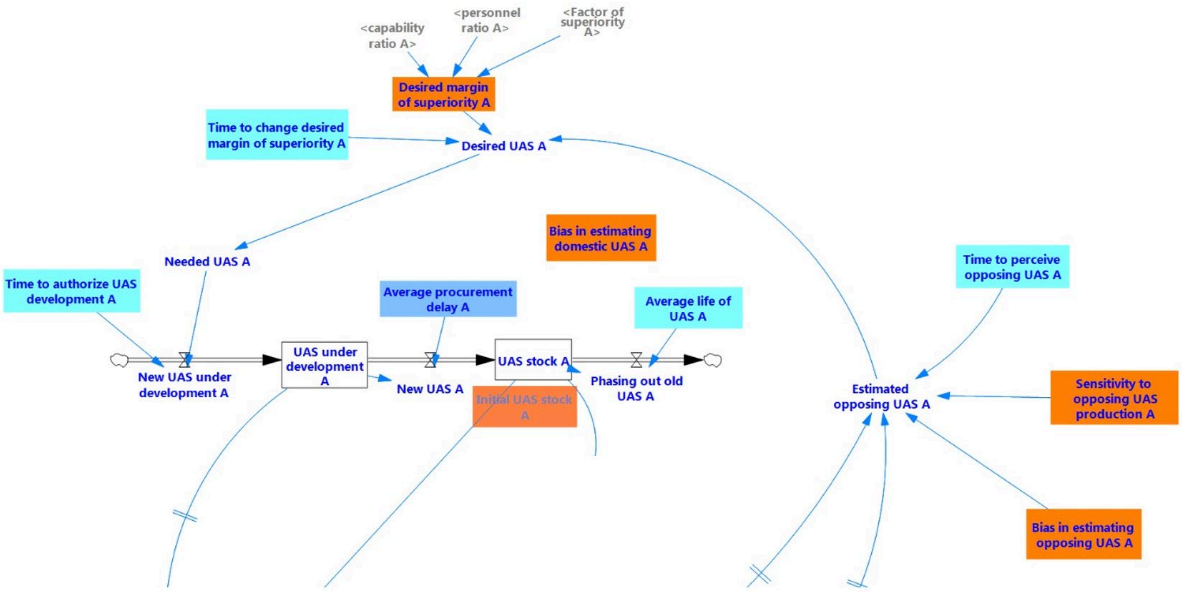

Figure 3: The subsystem "Capability build-up" of nation A. Nation B's subsystem is structurally identical. Nation A determines its desired number of autonomous systems based on its perception of the opposing nation B.

The technology subsystem in Figure 4 includes the technological development of high quality autonomous military systems, which is represented by two co-flows of the aging chain in the autonomous systems in the capability build-up subsystem. On one hand, this is based on developing artificial intelligence and the availability of skilled scientists to enable this research. It also includes the level of access to critical components, allowing for greater technological sophistication of the autonomous systems, such as semiconductors and sensors [25], [26]. For a more comprehensive view and to see how different sub-models are interrelated, we refer to the detailed model description and documentation [38].

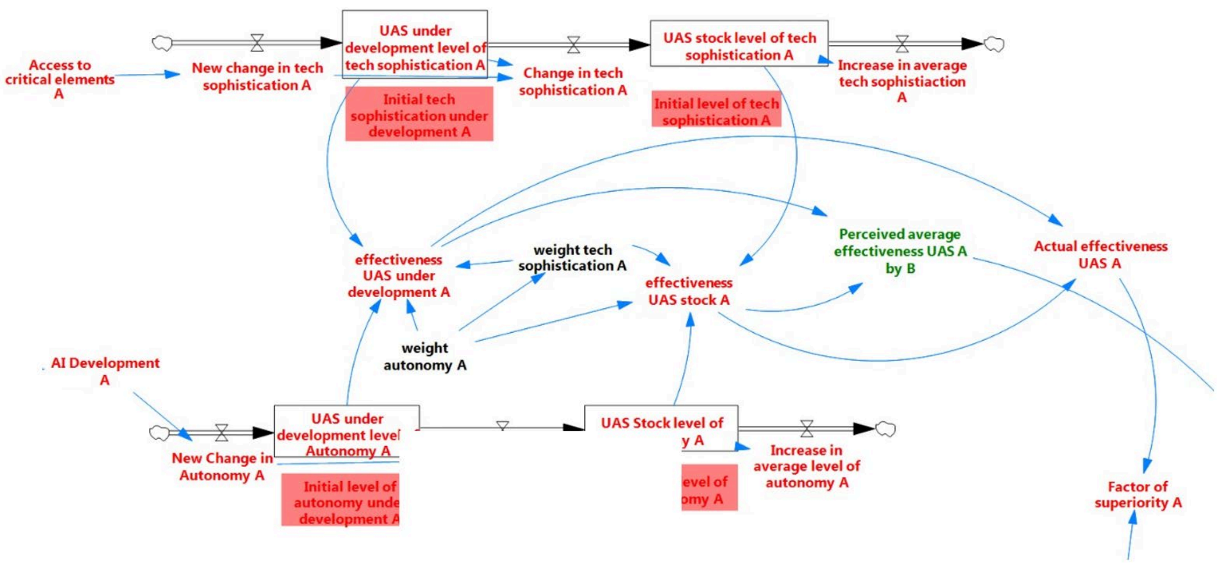

Figure 4: The subsystem "Technological development" of nation A. The flows of technological sophistication and the level of autonomy are co-flows of the flow of autonomous systems in the "Capability build-up" subsystem.

Certain important aspects were not studied and included in the model scope. These include military engagements or outright war between the nations; the influence of other nations on the arms race dynamics; cultural differences between the two nations; national internal stability; and other disruptive technologies.

Further, diplomatic channels, trading relations, and other ways of conducting foreign policy between nation A and B were also omitted. Economic growth is considered exogenous, and the GDP of the two nations is assumed to continue growing at a set pace. The same goes for scientific research; we assume the level of technological sophistication and of Artificial Intelligence (AI) to increase regardless of the potential escalation. This is partially supported, as this is not only driven by military demand, but largely by the private sector for civilian purposes.

In the simulation model, nation A is the initially stronger nation. It has a stronger economy and, as a result, a higher GDP and therefore a higher defence spending. Nation B, on the contrary, has a smaller GDP but is assigned a faster GDP growth, as an analogy to B being a rising nation. In addition, nation A is the more efficient nation in terms of its military planning. It has faster acquisition cycles, with higher quality capabilities, and as such have a longer lifetime before they will be replaced. Nation A has different ethical standards than nation B. These ethical standards are implemented by varying the required number of operating personnel for autonomous systems and their required training. This means that nation A needs a greater number of personnel for its autonomous systems than nation B and it also trains its personnel longer. We reflect on this implementation later in the study.

3.2 Implementation of Strategies

An arms race could be driven by the quantitative growth of each nation's UAS holdings and the qualitative improvement of the UAS in their possession.[27] These factors enable different possible points for a nation to prevent the occurrence of an arms race. The first set of strategies we chose corresponds to regulating the level of autonomy. The second set of strategies corresponds to targeting strategies, with which a nation aims at undermining the opposing nation's development of autonomous capabilities.

3.2.1 Regulation Strategies

Nations can restrain themselves by using regulation strategies for addressing the qualitative dimension of arms races – for example, by bilaterally agreeing on a maximum level of autonomy of their autonomous military capabilities. This is implemented in the simulation model by putting a ceiling on the level of autonomy corresponding to level five. Capping the level of autonomy at level five, according to Sheridan and Verplank's measuring scale for autonomy, [28] means that the system is able to make and execute its own suggestions after human approval. This is generally consistent with the meaning of "meaningful human control" [13]. During the simulations, the cap on autonomy can be implemented at different points in time to see whether the timing of introduction of the cap influences its effect.

3.2.2 Targeting Strategies

A nation can aim to retain the upper hand in an arms race by targeting the opposing nation's capability development. These strategies incorporate elements to target the opposing quantity and quality of systems. One strategy nation A can employ is to attempt to limit the quantity of autonomous capabilities that nation B can acquire. It does so by preventing nation B access to funding to build autonomous capabilities. This could be done, for instance, by focusing on information operations campaigns that undermine rising nation B's ethical integrity. Nation A could spread news that nation B's military is developing "killer robots" that will randomly kill civilians. Nation A, then, may realize its goals by shaping public opinion in nation B to alter that nation's behaviour. (A real-world example of such social media campaigns are the Russian troll factories seeking to influence voter behaviour in the 2016 US presidential elections [28].) In this case, the objective would be for the government of nation B to change its behaviour and restrict the development of these kind of capabilities. The effect of an information campaign does depend on the ability of nation A to reach citizens in nation B. Censorship could be successful in preventing the campaign to be successful. In this case, third countries could be persuaded to limit the export of relevant technologies to nation B and eventually, thereby restricting its access to autonomous capabilities.

Hegemon nation A can also target the quality of rising nation B's autonomous capabilities. For this, on the one hand, nation A restricts nation B's access to highly-skilled personnel. Without skilled personnel, nation B will not be able to achieve the level of autonomy that it desires for its autonomous capabilities. One method of doing so would be to target lead scientists. There are recent, real-world examples of this, such as the assassination of rocket scientist Gerald Bull in 1990 [39] and Iranian nuclear scientist Mohsen Fakhrizadeh (ironically, with autonomous systems) in 2021 [30]. Another way of doing so would be to lure scientists away and to assure them work in hegemon nation A at higher wages and better working conditions, such as the US did with German scientists (see Operation Paperclip) to build their rocket and missile capabilities after the second world war [31]. Then, it needs to be assured that rising nation B's workforce is not too patriotic and is willing to sell its knowledge.

Nation A can also apply restrictions to nation B's access to the critical components it needs for building high-quality autonomous capabilities. These include technologies like semiconductors that the autonomous capabilities need for computational power, and sensors that they need for operating autonomously. This can be done via sanctions and trade embargoes, thereby forbidding third countries from exporting these components to nation B. The effectiveness of such export sanctions is debatable, as can be observed today with Dutch microchips ending up in Iranian UAS used by Russia for its war in Ukraine [32]. These policies can be enacted at a moment in time or can be triggered when the model reaches a certain level of technological maturity, such as when nation A perceives that nation B has achieved the same quantity of autonomous systems as itself.

3.3 Parameter Ranges

We derived the parameter ranges for the defence budgets, training costs, GDP, and initial stocks of military capabilities based on data from the defence spending of nations with varying GDP sizes. To parameterize the technological developments, we adapted a sigmoid function and compared outcomes to expected behaviour until it produced acceptable results. Time delays, procurement delays, training times, lifetimes of capabilities and personnel needed per autonomous system are based on estimations. Biases and sensitivities in perceiving the other nation are included in the model: for this we assumed that a nation either under- or over-estimates its opponent by around 25%. In the parameter settings, hegemon nation A is characterized as the initially stronger nation in quantity and quality of autonomous military capabilities. The opposite goes for rising nation B.

3.4 Verification and Validation

We conducted structure verification tests and model behaviour verification tests [33] on the simulation model and its output. The SD model is constructed in Vensim, and runs are simulated using the EMA workbench. We used the Euler integration method with a time step of 0.00390625 years. This was determined by lowering the time step until the integration error was negligible. We performed 5,000 experiments using Latin Hypercube sampling over the uncertainty space.

To determine whether the SD model represents the problem in a valid manner and whether the model reflects what can be observed in the real world, we used available literature together with expert interviews. Arms races in the model world happen under similar conditions as real-world arms races, as defined by Caspary [7]: 1) Perceived military insecurity; 2) The arming being a burden on the economy; and 3) Perceived grievances. The first and the third condition of arms races are also met by the factors that were identified to lead to arms races.

We find the model to have an acceptable validity for its purpose. The model does produce outliers where the autonomous capabilities and defence spending for both nations rise to very unlikely levels. The underlying parameter combinations for these model runs do, however, seem themselves to be unrealistic. Knowing this, we will explore the issue under many different parameter combinations. It should be noted that there are differences in likelihood for each run and each individual run should be approached with caution. Nevertheless, we still deem the model valid and fit for purpose. This purpose is not to accurately predict arms races, but to investigate the conditions under which the dynamics of arms races between a hegemon nation A and a rising nation B occur.

4.0 RESULTS

This section presents simulation runs with interpretations to answer the research question. For this, arms races as produced by the model are characterized and the winning and losing nations identified. Then, the results of applying any of the implemented strategies are described.

4.1 Characterizing Arms Races

We define arms races as scenarios where the defence spending of a nation increases by more than 50% over a period of 5 years [34]. This reflects our second condition for characterizing an arms race, namely, that the arming is a burden on the economy.

Around 40% of the experiments result in arms races. Most races (about 79%) are bilateral ones, meaning that they are driven by both countries increasing their defence spending at the same time. There are also some unilateral races, where either only hegemon nation A increases its defence spending by more than 50% over a period of 5 years (about 9%), or only rising nation B does (about 13%).

The parameter ranges describing experiments resulting in arms races can be seen in Figure 5. These scenarios could be described as nation B perceiving a gap in military power, with fewer personnel and fewer (autonomous) military capabilities. Hence, nation B invests heavily to catch up and bridge the gap. Nation A, however, wants to maintain its lead and invests as well. At this point, rising nation B can advance more quickly, since it is investing in capabilities with the latest level of technological development. Nation A is less agile, due to its larger initial stock of autonomous capabilities.

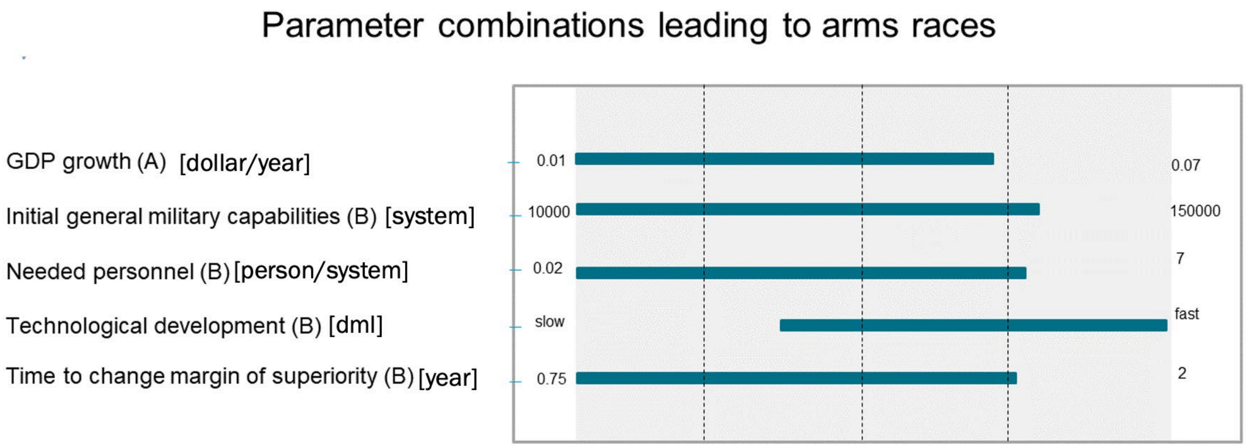

Figure 5: Parameter combination ranges that lead to arms race scenarios.

Another characteristic that is shared among arms races is both nations having relatively short periods of time to change their desired margin of superiority. In this case, the nations are quick to react to their opponent's actions. As soon as one nation perceives another is increasing its stock of autonomous military capabilities, it swiftly decides to invest more into autonomous capabilities. This high sense of urgency to build autonomous capabilities is larger when the nation's bias in estimating the opposing autonomous military capabilities is larger. Thus, when the rising nation B is highly reactive to nation A's capability build-up, arms races are more likely to occur.

The arms race intensifies in cases where rising nation B gets closer or even attains an advantage over hegemon nation A, in terms of the quality of its systems. On these occasions, nation A responds by heavily increasing its capabilities. This causes faster growth of its defence spending. This can result in nation A narrowly maintaining its superiority. At this point, defence spending will plateau, showing S-shaped growth. In scenarios where the nations are not reactive to each other, and the rising nation is not able to produce high-quality systems while needing a lot of personnel to operates its systems, then, in general, no arms races occur.

4.2 Arms Race Winners and Losers

To evaluate which nation wins the arms race, a nation's weighted quantity is computed. We chose to do this at the end of the simulation's run time, corresponding to 30 years. The winner is the nation with the most effective autonomous fleet, by multiplying the number of systems with their average effectiveness.

In the case of no arms race occurring, hegemon nation A maintains its lead and, according to our metrics, wins over nation B in 50% of the experiments. However, as soon as an arms race takes place, the number of experiments in which nation A wins is lower; in only 26% of the experiments, it wins over nation B. The scenarios in which nation A does win the arms race are all characterized by nation A having a faster procurement for autonomous systems than nation B.

In scenarios in which nation B wins, nation A needs more people to operate its autonomous capabilities compared to nation B. This parameter is included in the simulation model to reflect the differences in ethical standards between the two nations.

4.3 Impact of Strategies on Outcomes

Two types of strategies are implemented and tested, namely the regulation strategy and the influencing strategy.

4.3.1 Regulation Strategy

In the regulation strategy, both nations agree to have a maximum level of five on Sheridan and Verplank's measuring scale for autonomy [28]. The frequency with which arms races occur decreases from 40% to 29% (see

Table 1). However, for this strategy, we find undesirable simulation outcomes for hegemon nation A. The frequency of arms races that hegemon nation A wins decreases from 26% to 12%, no matter at which time during the simulation time this regulation is implemented. In fact, the worst simulation outcomes for hegemon nation A occur in simulation runs where the regulation is applied after a nation exceeds autonomy level five. In other words, when nations are not allowed to compete on the level of autonomy of their systems, nation A loses the race more often than not. In cases where there are no arms races, the number of runs in which nation A or B wins is distributed almost equally.

Table 1: Number of scenarios, depending on the different policies.

Policy	Fraction of Arms Races	A Wins Race (B Wins)	No Race: A Wins (B Wins)
None	40%	26% (74%)	50% (50%)
Regulation	29%	12% (88%)	49% (51%)
Influencing	10%	87% (13%)	85% (15%)

4.3.2 Influencing Strategies

For the influencing strategies, we find the number of simulation runs resulting in arms races to decrease to 10% (see

Table 1). This applies to the cases in which only nation A is using influencing strategies against nation B, while nation B implements no influencing strategies against nation A. The number of arms races is three times lower compared to 40% without a strategy implemented. Also, nation A wins in 87% of the scenarios that lead to arms races as well as in 85% of the scenarios where the competition between nations A and B does not end in an arms race.

In the simulation runs in which rising nation B can strike back with influencing strategies aimed at nation A, we find no more arms races (see Table 2). In all runs, neither nation increases their defence spending by more than 50% over 5 years. This is caused by both nations hindering each other from doing so. In 97% of these runs, nation A can win the competition. This corresponds to the prior observation that nation A mostly wins when no arms race takes place. Looking at the remaining 3%, in which nation B can win the competition, we see the number of operators required for nation A is higher, which represents the ethical representations the nations take. Table 2 shows that the chances for nation A to win are different for each type of arms race.

Table 2: Percentage of runs resulting in arms races that hegemon nation A wins, depending on the different types of arms races.

Type of Race	No Influencing Strategy by A	Influencing Strategy by A	Nation B Strikes Back
Bilateral	22%	100%	-
A driven	24%	100%	-
B driven	32%	71%	-
No arms race	50%	85%	97%

5.0 DISCUSSION

This section discusses what the simulation results of arms race dynamics for autonomous capabilities over the parameter ranges mean considering the research question and the objectives for this study.

The concept of balance-of-power in international relations [6] suggests that a relative military power parity leads to stability and peace, while a large power imbalance can result in perceived insecurity, which in turn may result in intense arms races. We see this reflected in our model results – if nation B is significantly weaker than nation A, the risk of escalating tensions and arms races is heightened, as well as the intensity of arms races. The concept of power transition [6] seems to apply as well. Power transition theory states that when a nation's power increases or decreases, the risk of tensions escalating is greater. In the race for autonomy, if nation B demonstrates significant growth in its technological capabilities while nation A experiences a lower GDP growth rate (which can be interpreted as a power transition), the model results show the most extreme cases of arms races.

5.1 Development of Autonomous Military Capabilities

Each nation has different motives for engaging or not engaging in an arms race. Nation A, with a head start in technological development and high-quality systems, may opt to avoid engaging in arms races to retain its advantage in non-racing scenarios. The model results show that when no race occurs, nation A does retain its advantage in most model runs. On the other hand, nation B, knowing its difference in ethical standards, can exploit this by focusing on quantity over personnel training costs and may actively engage in arms races as a means to achieve its strategic goals. The model results show nation B being able to overtake and win the arms race with nation A in most model runs.

Arms races are driven in part by differing ethical characteristics guiding the pursuit of autonomous military capabilities. Nation B, with different ethical standards, can allocate relatively more funding towards acquiring autonomous systems compared to nation A, which requires more personnel for its autonomous systems. This dynamic creates a competitive environment where both nations are motivated to increase their autonomous capabilities.

This presents a difficult consideration for nation A as to whether it should adapt its ethical standards and allow for less human control of its autonomous systems. If nation A's ethical standards significantly impede its ability to compete against nation B, which has fewer ethical constraints, a reconsideration of those standards may be advisable. This strategic decision should be carefully weighed against the potential consequences and implications for international reputation and the overall arms race dynamics.

5.2 The Role of Technological Developments in Arms Races

Regulating autonomy in military capabilities poses challenges. Unlike nuclear weapons that can be counted, autonomy is difficult to measure and control. During the Cold War, treaties such as the Intermediate-Range Nuclear Forces Treaty were signed by the US and the Soviet Union to ban all intermediate-range ballistic missiles and thus de-escalate the dangers posed by the nuclear arms race [36]. Treaties and agreements aimed at limiting autonomy and retaining an amount of meaningful human control may face compliance issues, especially considering the dual-use nature of autonomous systems and the rapid adoption of civilian products for military purposes.

Regardless, restricting the level of autonomy in military capabilities may even be counterproductive, as it limits the qualitative dimension of the arms race. If one nation has superior quality autonomous systems, and can accurately assess this, they do not need to increase the quantity to the same extent. Removing the option to compete on quality forces nations to focus solely on quantity, which in the model results exacerbates arms races.

5.3 The Effect of the Strategies on the Arising of Potential Arms Races

When adopting a strategy that encompasses both the number of systems and their level of autonomy, nation A gains an advantage in most racing and non-racing scenarios, even in the face of reciprocal action from nation B. However, this approach is not without its shortcomings and can result in arms races. Notably, nation B can still achieve a higher level of quality of systems compared to nation A by permitting a lower level of human control in its autonomous systems. Nation B prevails in model runs where nation A requires a relatively high degree of human control for its autonomous systems.

A third-party intervention could help mitigate arms races by easing tensions between the nations and therewith reducing their reactivity to each other’s actions. The model results indicate that by extending the reaction time before responding with increased autonomous military systems, the likelihood of arms races could be decreased. Additionally, aligning nation B’s ethical standards for human control of its autonomous capabilities may help in reducing the intensity of arms races.

It can be argued that, through a third party, nations could mutually agree on a quantity of autonomous capabilities. However, this kind of non-proliferation agreement is unlikely to work in practice. The application of autonomous systems is too broad; due to their dual-use nature, any off-the-shelf product can be very quickly adopted for military purposes, as can be seen in the war in Ukraine [35].

5.4 Limitations

The quantitative nature of the simulation model enables a different line of thinking compared to the often qualitative nature of methods in strategic anticipation. Concepts need to be translated into measurable variables in our model so that the model outcomes will also be measurable. This then enables the exploration of a wide parameter space and the use of data-analysis tools to analyze the results generated by the model.

The study is limited in its scope and did not consider several aspects that are likely to be influential in determining arms race dynamics. Many different means of addressing perceived threats between nations are not considered, such as diplomacy, negotiation, confidence-building measures, alliances and collective security, economic cooperation, or even cultural exchanges. Also, the costs of implementing the two strategies outlined here have not been considered. There could, for example, be economic consequences caused by disrupting trade relations. To some extent, the funding of these strategies could be seen as an increase in defence spending. Taking that approach is unlikely to change the conditions for an occurrence of arms races. However, it could change an arms race that was earlier defined as a unilateral arms race (meaning only one country fulfills the arms race conditions) to a bilateral arms race. Another aspect that is not included in the model is the success rate of the influencing strategies. The potential fallout of the influencing strategies in international trade, or losing face in the international community due to perceived meddling, is not considered. Finally, in our current model we did not implement or test whether the offensive versus defensive posture of the investments into autonomous capabilities influences the arms race dynamics.

6.0 CONCLUSION

The ongoing tensions in today's world can create a security dilemma between two nations that are potentially undergoing a power transition. This can lead to an arms race via the acquisition of autonomous military capabilities. As ongoing research and development makes these systems more and more autonomous, the need for human control diminishes. Since these autonomous capabilities can be used for a plethora of applications, from target acquisition to swarming, many militaries are already experimenting with concepts for their deployment.

In this study, we constructed a system dynamics model to capture the dynamics of a build-up of autonomous military systems between two nations caught in a security dilemma. In the model, we incorporated several considerations that nations consider when developing autonomous capabilities, as well as potential strategies to influence the other nation and prevent arms races.

In our simulation results, we identified certain characteristics for arms races. In general, a hegemonic nation starts by having an advantage on both quantity and quality of autonomous systems. The rising nation will develop its capabilities and the arms race intensifies as soon as the rising nation gains a perceived edge in developing high-quality autonomous systems. This can partially be achieved if the rising nation is less constrained by ethical standards. To the hegemon, it initially matters little how many military systems the rising nation possesses, if it perceives itself to have a large enough advantage in quality of systems. However, when the hegemon loses this perceived advantage in quality of systems it begins accumulating autonomous military systems, regardless of whether its systems are of better quality. This prompts the rising nation to respond in kind. Thus, the model characterizes arms races as situations resembling great-power transitions with an uneven balance-of-power between two nations. Hence, international relations theories such as structural realism do apply in the model.

We explored the considerations nations take, or conditions for arms races, and the role of technological developments, and evaluated the performance of strategies in research questions one to three. The choice of the most effective strategy for influencing an arms race depends on the objectives, which can either be winning the arms race or preventing its occurrence. We identified the most effective strategies for each nation, considering a range of parameters and potential counter-strategies. By effective, we mean having the fewest undesirable outcomes over the wider model uncertainty space.

For the hegemon nation to maximize its chances for favorable outcomes we found that combining strategies of regulation and influencing to be most effective. This strategy aims to hinder the rising nation in both developing high quantity and quality of autonomous capabilities. However, it does not prevent the rising nation from winning in all scenarios. Two types of scenarios exist in which the hegemon loses despite employing the regulation or the influencing strategy. The first is when the hegemon requires more human control of its autonomous military capabilities relative to the rising nation. The second is when the rising nation is highly reactive to the hegemon nation's capability build-up. In such cases, a third party could play a role in facilitating a relaxation of the tensions between the two nations to create conditions for the rising nation to be less reactive. Additionally, a third party could encourage a dialogue on bridging ethical gaps between the nations regarding autonomous capabilities.

The rising nation, on the contrary, can maximize its chances by engaging in an arms race, since we found it winning most instances in which an arms race takes place. This is mainly due to the rising nation being less constrained by requiring less human control of its systems. The rising nation can also choose to strive for implementing regulations – for example, a maximum agreed level of autonomy, since this shifts the race to a race for quantity, which the rising nation wins even more frequently.

To reduce the overall occurrence of arms races, both nations should aim to disrupt each other's race for autonomy. In our simulation model, this effectively prevents arms races. It should be noted that the consequences of these disruptions fall outside of the scope of the model, even though they could outweigh the benefits of avoiding an arms race. It is worth investigating whether cooperative mechanisms can achieve similar results with fewer negative side effects.

For future research, we recommend further improving the simulation model by introducing balancing effects, such as trade relations, implementing more realistic mechanisms for both nations to disrupt each other's autonomous capability development, and taking a closer look at the actual effectiveness of autonomous military systems given their application and integration into a nation's armed forces.

ACKNOWLEDGMENTS

The authors would like to thank TNO and the faculty for Technology, Policy and Management at the Technical University of Delft, where this research was partly conducted in the context of the author's master thesis. Special thanks also go to Prof.dr.ir. Mark Voskujil and Lt Col Martijn Hädicke for their guidance during this research.

7.0 REFERENCES

[1] Mearsheimer, J.J., "China's unpeaceful rise," in Realism Reader. Routledge, 2014, 464-467. [Online]. Available: https://www.taylorfrancis.com/chapters/edit/10.4324/9781315858579-72/china-unpeaceful-rise-john-mearsheimer

[2] Kirshner, J., "The tragedy of offensive realism: Classical realism and the rise of China," European Journal of International Relations, 18(1), 53-75, 2012.

[3] Freedman, L., "Introduction – the evolution of deterrence strategy and research," in NL ARMS Netherlands Annual Review of Military Studies 2020. Springer, 2021, 1-10. [Online]. Available: https://link.springer.com/chapter/10.1007/978-94-6265-419-8 1

[4] Gray, C.S., "The arms race phenomenon," World Politics, 24(1), 39-79, 1971.

[5] Shambaugh, D., "US-China rivalry in Southeast Asia: Power shift or competitive coexistence?" International Security, 1;42(4), 85-127, 2018. [Online]. Available: https://direct.mit.edu/isec/article-abstract/42/4/85/12193/U-S-China-Rivalry-in-Southeast-Asia-Power-Shift-or

[6] Wohlforth, W.C., "The stability of a unipolar world," in Realism Reader. Routledge, 2014, pp. 383-395. [Online]. Available: https://api.taylorfrancis.com/content/chapters/edit/download?identifierName=doi&identifierValue=10.4324/9781315858579-61&type=chapterpdf

[7] Caspary, W.R., "Richardson's model of arms races: Description, critique, and an alternative model," International Studies Quarterly, 11;(1), 63-88, 1967. [Online]. Available: https://www.jstor.org/stable/3013990

[8] Gettinger, D., "Drone databook update: March 2020," Center for the Study of the Drone at Bard College, 2020.

[9] Voskuijl, M., Dekkers, T., Savelsberg, R., "Flight performance analysis of the Samad attack drones operated by Houthi armed forces," Science & Global Security, 28(3), 113-134, 2020.

[10] Welt, C., Bowen, A.S., "Azerbaijan and Armenia: The Nagorno-Karabakh conflict," Library of Congress, Washington DC, 2021.

[11] Eslami, M., "Iran's drone supply to Russia and changing dynamics of the Ukraine war," Journal for Peace and Nuclear Disarmament, 5(2), 507-518, 2022.

[12] Michel, A.H., Unarmed and Dangerous: Lethal Applications of Non-Weaponized Drones. Center for the Study of the Drone at Bard College, 2020.

[13] Ekelhof, M.A., "Lifting the fog of targeting," Naval War College Review, 71(3), 61-95, 2018.

[14] Altmann, J., Sauer, F., "Autonomous weapon systems and strategic stability," Survival, 59(5), 117-142, 2017.

[15] Calcara, A., Gilli, A., Gilli, M., Marchetti, R., Zaccagnini, I., "Why drones have not revolutionized war: The enduring hider-finder competition in air warfare," International Security, 46(4), 130-171, 2022.

[16] Sechser T.S., Narang N., Talmadge C., "Emerging technologies and strategic stability in peacetime, crisis, and war," Journal of Strategic Studies, Sep 19;42(6), 727-35, 2019.

[17] Horowitz, M.C., "When speed kills: Lethal autonomous weapon systems, deterrence and stability," Journal of Strategic Studies, 42(6), 764-788, 2019.

[18] Sweijs, T., Osinga, F., "Conclusion: Insights from theory and practice," NL ARMS, p. 503, 2021. [Online]. Available: https://library.oapen.org/bitstream/handle/20.500.12657/47298/9789462654198.pdf?sequence=1#page=511

[19] McKay, A., Watson, A., Karlshøj-Pedersen, M., "Remote warfare: Interdisciplinary perspectives," E-International Relations Publishing, 2021.

[20] Sterman, J., "System dynamics: systems thinking and modeling for a complex world," 2002. [Online]. Available: http://hdl.handle.net/1721.1/102741

[21] Kreutzer, D.P., "A microcomputer workshop for exploring the dynamics of arms races," in Proceedings of the System Dynamics Group International Conference, Keystone Colorado, 1985. [Online]. Available: https://proceedings.systemdynamics.org/1985/proceed/kreut463.pdf

[22] Kwakkel, J.H., "EMA workbench docs," 2022. [Online]. Available: https://emaworkbench.readthedocs.io/en/latest/

[23] Walker, W.E., Marchau, V.A., Kwakkel, J.H., "Uncertainty in the framework of policy analysis," in Public Policy Analysis. Springer, 215-261, 2013. [Online]. Available: https://link.springer.com/chapter/10.1007/978-1-4614-4602-6 9

[24] Groves, D.G., Lempert, R.J., "A new analytic method for finding policy-relevant scenarios," Global Environmental Change, 17(1), 73-85, 2007.

[25] MoD, Concepts and Doctrine Centre, "Human-machine teaming (JCN 1/18)," 2018 [Online]. Available: https://www.gov.uk/government/publications/human-machine-teaming-jcn-118f

[26] Scharre, P., Four Battlegrounds: Power in the Age of Artificial Intelligence, New York W.W. Norton & Company, 2023.

[27] Intriligator, M.D., Brito, D.L., "Can arms races lead to the outbreak of war?" Journal of Conflict Resolution, 28(1), 63-84, 1984.

[28] Sheridan, T.B., Verplank, W.L., "Human and computer control of undersea teleoperators," Massachusetts Inst of Tech Cambridge Man-Machine Systems Lab, Tech. Rep., 1978.

[29] MacFarquhar, N., "Inside the Russian troll factory: Zombies and a breakneck pace," 2018. [Online]. Available: https://www.nytimes.com/2018/02/18/world/europe/russia-troll-factory.html

[30] Bergman, R., Fassihi, F., "The scientist and the AI-assisted, remote-control killing machine," 2021. [Online]. Available: https://www.nytimes.com/2021/09/18/world/middleeast/iran-nuclear-fakhrizadeh-assassination-israel.html

[31] Golinkin, L., "Why do Stanford, Harvard and NASA still honor a Nazi past?" 2021 [Online]. Available: https://www.nytimes.com/2022/12/13/opinion/stanford-harvard-nasa-nazi-scientists.html

[32] NOS, "Nederlandse chips in iraanse drones van russisch leger,'" 2022. [Online]. Available: https://nos.nl/artikel/2455866-nederlandse-chips-in-iraanse-drones-van-russisch-leger

[33] Senge, P.M., Forrester, J.W., "Tests for building confidence in system dynamics models," System dynamics, TIMS studies in management sciences, 14, 209-228, 1980.

[34] Diehl, P.F., "Arms races to war: Testing some empirical linkages," The Sociological Quarterly, 26(3), 331-349, 1985.

[35] Kramer, A.E., "From the workshop to the war: Creative use of drones lifts Ukraine," 2022. [Online]. Available: https://www.nytimes.com/2022/08/10/world/europe/ukraine-drones.html

[36] Kühn, U., Péczeli, A., "Russia, NATO, and the INF treaty," Strategic Studies Quarterly, 11(1), 66-99, 2017.

[37] Meadows, D.H., Thinking in Systems: A Primer. Chelsea Green Publishing, 2008.

[38] Lonardo, L., "Power to the people. How open technological innovation is arming tomorrow's terrorists," 2021.

[39] Wilmes, L., Modelling a Race for Autonomy. 2023. [Online]. Available: http://resolver.tudelft.nl/uuid:f05094ff-9f6e-4a9c-b509-b4fd22e1d154

[40] Joseph P. Fried, "Gerald Bull, 62, shot in Belgium; scientist who violated arms law," 1990. [Online]. Available: https://www.nytimes.com/1990/03/25/obituaries/gerald-bull-62-shot-in-belgium-scientist-who-violated-arms-law.html