Agent-Based Model for Proportionality Assessment in Military Operations

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Abstract: The proportionality assessment is a fundamental principle and a critical consideration in military operations. It involves weighing the anticipated military advantage of a military action against the potential for collateral damage, ensuring that the harm inflicted on civilians and civilian objects is not excessive in relation to the intended military gains. This process is inherently complex, requiring decision-makers to navigate uncertain and dynamic operational environments while integrating diverse variables, such as the operational context, available intelligence, and the evolving nature of conflict. To explore and better understand this decision-making process, this research introduces a novel Agent-Based Model (ABM) designed specifically to model and simulate proportionality assessment in military operations. The model proposed captures the interactions between decision-makers, environmental variables, and operational factors, providing a dynamic platform for analysing complex proportionality scenarios. By modelling these interactions and the underlying behaviour of this assessment process, this Artificial Intelligence (AI) model enables the simulation of diverse operational contexts, offering valuable insights into the decision-making process. Through this approach, this research contributes to the ongoing development of responsible and trustworthy AI models that enhance the understanding and evaluation of proportionality in military operations, supporting the creation of more informed and ethical operational strategies.

Keywords: Targeting, Proportionality, Military operations, Agent model, Agent-Based modelling, Artificial Intelligence

1. Introduction

> *"The art of war is of vital importance to the state. It is a matter of life and death, a road either to safety or to ruin. Hence it is a subject of inquiry which can on no account be neglected."*
>
> *(Sun Tzu)*

At the heart of the International Humanitarian Law (IHL) is found the principle of proportionality, a fundamental measure aimed at balancing military objectives with the protection of civilians and civilian infrastructure during armed conflict. This principle prohibits attacks where the anticipated collateral damage would be excessive in relation to the direct and concrete military advantage sought. These two components are also referred to as the positive and negative components of the proportionality assessment (Rosen, 2023).

Based on the legal foundations set by the Geneva Conventions, particularly Article 51(5)(b), the principle of proportionality reflects a humanitarian commitment to minimize suffering while maintaining military effectiveness. Sassòli, Bouvier & Quintin (2011) emphasize the principle's role in creating a framework for ethical targeting decisions, ensuring that the destruction caused by military actions does not exceed the bounds of necessity. At the same time, Wright (2012) and Fenrick (2009) further highlight the principle's preventative scope, which mandates that military decision-makers to take active measures to mitigate harm and reassess proportionality as operational circumstances evolve. Moreover, the application of proportionality in military operations is a dynamic and multifaceted process that involves all levels of command. From planning to execution, commanders must evaluate the potential collateral impact of an attack by considering up-to-date reliable intelligence, the nature of the target, available weapons, and operational urgency. This assessment is a continuous process, as new information may necessitate the suspension or cancellation of planned actions if the collateral damage is deemed excessive. As Wright (2012) notes, proportionality also obliges military planners to adopt precautionary measures, including weapon and tactic selection and the issuance of warnings where feasible, to reduce harm to civilians. Despite its critical role, applying proportionality remains challenging due to the difficulty of comparing military advantages with civilian harm in quantifiable terms, as stressed by Fenrick (2009, Maathuis & Chockalingam, 2023). By embedding proportionality into decision-making processes and building corresponding models for intelligent support, military forces ensure compliance with international norms while upholding the dual imperatives of necessity and humanity.

An important set of tools that is increasingly used in the military domain is based on various Artificial Intelligence (AI) techniques given their decision-making support capabilities and adaptability to various complex, dynamic, and uncertain scenarios (Gunneflo & Noll, 2023). In this respect, Rosen (2023) emphasizes the role of machine learning algorithms in simulating various scenarios to predict collateral impacts under different operational parameters. By integrating AI-driven predictive models, military planners can evaluate proportionality dynamically, taking into account changes in the operational environment. Furthermore, AI systems have the potential to enhance transparency and consistency of decisions made, by providing evidence-based recommendations, reducing the subjectivity traditionally associated with proportionality judgments. Nevertheless, as Rosen (2023) highlights, the reliance on AI in such sensitive judgments raises ethical concerns, particularly regarding the accountability for decisions informed by automated systems. Despite these challenges, the potential of AI to augment human judgment in complex, critical scenarios is valuable, marking a significant step toward more informed and legally compliant military operations.

Recent advancements in the AI domain have reignited interest in agentic models as powerful tools for decision-making support, particularly in complex and dynamic systems. Accordingly, agent-based models (ABM) simulate interactions between individual entities (agents) within a system to uncover emergent patterns, making them particularly valuable for military and operational decision-making. Furthermore, the offer a unique combination of flexibility and adaptability, allowing for the modelling of large systems of interacting components, such as troop movements or supply chain logistics, under varied scenarios Daly et al. (2022). Unlike traditional top-down modelling approaches, ABM adopts a bottom-up perspective, emphasizing the interactions among agents to reveal emergent system-level behaviours (Bonabeau, 2002, Siebers, 2016). Agents themselves are autonomous software modules capable of perceiving and responding to their surroundings (Maathuis, 2024a). They range in complexity from simple "if-then" reactive units to sophisticated entities capable of reasoning, learning, and adapting through frameworks like the Belief-Desire-Intention (BDI) model, which imbues agents with goals, plans, and situational awareness (Abar et al., 2015). In military contexts, agents are often designed to simulate the behavior of combatants or systems, enabling the exploration of scenarios such as troop movements, target engagement, and logistical decision-making (Cil & Mala, 2010).

Nevertheless, given the extensive literature review conducted in this research, to the best of our knowledge, agentic solutions have not been yet designed and proposed to tackle and model the proportionality assessment tin military operations. This represents the aim of this this research. To accomplish this goal, an agent-based model is developed and proposed under the guidance of the principles of the Design Science Research methodology (Peffers et al., 2007; Gregor & Hevner, 2013).

The remainder of this article is structured as follows. Section 2 presents the background and relevant research studies conducted in this domain. Section 3 discusses the research methodology used to achieve the goal of this research. Section 4 presents the model proposed together with evaluation considerations. At the end, Section 5 provides reflections, concluding remarks, and future research perspectives on this topic.

2. Research Background

Agent-based modelling is a computational method used to simulate the behaviour, interactions, and dynamics that surround autonomous agents in a defined environment. An agent is generally understood as an autonomous entity capable of processing information, interacting with its environment and other agents, and making independent decisions. The autonomy of agents allows for decentralized control, enabling them to function independently while still contributing to the overall system's dynamics. Moreover, the agents are often heterogeneous, meaning they have unique characteristics or behaviours, and their collective actions give rise to emergent system properties from the bottom up. ABMs are characterized by their capacity to model agents with active behaviours such as being goal-directed, reactive to their environment, and capable of bounded rationality, learning, and adaptation. These features make ABM a robust tool for studying complex systems, particularly those involving human decision-making, social systems, and military operations (Crooks & Heppenstall, 2013). At the same time, the agents are active in that they are goal-directed, reactive to their surroundings, and capable of interacting with other agents and their environment. This interaction is enriched by their bounded rationality, enabling agents to make decisions based on incomplete or imperfect information, mimicking human decision-making in uncertain and dynamic conditions. Moreover, the agents can learn and adapt over time, either individually or collectively, allowing the simulation to evolve and reflect changes in the system (Chaudhary, 2015).

In particular, an agent-model was proposed for exploring strategies that allow the reduction of casualties in active shooter scenarios, focusing on the potential impact of unarmed resistance by victims prior to the arrival of law enforcement officers (LEOs). This approach was inspired by real-life examples, such as the train attack from Amsterdam to Paris in 2015, where passengers successfully subdued a gunman. The model simulates scenarios where a small proportion of potential victims swarm an active shooter, analysing outcomes in terms of casualties and risks to the fighters. Results indicate that even a minuscule probability of overcoming the shooter can significantly reduce overall casualties, albeit at increased risk to the individuals resisting (Briggs & Kennedy, 2016). From a different perspective, Peng et al. (2022) developed a multi-agent system that combines system dynamics and intelligent-agent simulations to predict total attritions, their temporal and spatial distribution, and the composition of the wounded. The model integrates combat damage assessments with specific mission parameters to generate attrition data, which is further decomposed into individual combatants and assigned injury details. This approach transforms attrition flows into casualty flows, providing a scientific basis for medical resource allocation, injury treatment, and logistical planning. By simulating individual combatants' injuries, the model enables tailored medical support strategies, enhancing the effectiveness of battlefield healthcare operations.

Going into the military domain, the U.S. Army and DoD (Department of Defense) have long sought methods to quantify the value of information systems on the battlefield, particularly in enhancing combat effectiveness. To this end, (Kewley & Larimer, 2003) propose a robust agent-based framework for evaluating the impact of such systems by simulating decision-making processes within a combat force equipped with advanced information systems, such as Future Battle Command Brigade and Below (FBCB2). The methodology involves a three-step process: running simulations using a dynamic scenario, transferring operational details to an ABM with intelligent agents to refine unit behaviours, and integrating the refined course of action back into the scenario for further simulations. Moreover, the decision agents contain battlefield information on enemy positions, friendly forces, and terrain to adjust strategies dynamically, resulting in more effective and adaptive operations. Comparative analyses demonstrate the enhanced performance of forces agent-based generated behaviours versus those without updated information (Kewley & Larimer, 2003). (Yun, Moon & Lee, 2015) design a model that integrates operational details as discrete event models and incorporates soldier behaviours through behavioural models, creating a comprehensive simulation of the C2 (Command and Control) at the company level. Then the model enables an analysis of the most critical tasks faced by company commanders, offering insights into how operational environments influence task priorities. The results inform commanders on how to allocate their efforts to the most impactful activities, enhancing overall operational effectiveness. Further, an agent-based model is proposed to enhance decision-making for threat evaluation in air defense simulations. The model integrates C2 architectures with agent-based programming, representing tasks as ordered action sets shared across C2 units. By combining first-order logic with analytic methods, this agent-based design introduces a dynamic aspect management framework for evaluating and engaging targets Hocaoğlu (2022). Anghinolfi et al. (2013) proposed an agent-based framework, Operative Evaluator, for analyzing ship efficiency in naval tasks. The study began by evaluating existing simulation environments such as MANA, NetLogo, and Stage to identify their strengths and limitations. Building on this analysis, the Operative Evaluator was developed in collaboration with Orizzonte Sistemi Navali, incorporating features to better assess operational effectiveness in reference tasks. This new framework supports the early-stage design of naval vessels by simulating task performance and efficiency, offering valuable insights for optimizing ship designs and ensuring mission readiness in complex maritime operations. At the same time, Miller & Lunday (2016) uses an agent-based approach to simulate the potential key performance parameters (KPPs) of the SACM, substituting unclassified data from Lockheed Martin's Cuda prototype. The authors examined the tactical advantages of the missile in an air combat scenario, demonstrating how different factors influence operational outcomes. By applying experimental methods, the study evaluated the missile's capabilities, interactions, and battlefield dynamics, providing critical insights to inform acquisition decisions.

Christensen and Salmon (2022) proposed an agent-based model that integrates established infantry small-unit tactics with sUAS capabilities for surveillance and indirect fire targeting. The model simulates engagements between defending forces with sUAS capabilities and superior attacking forces without such capabilities. Through six experimental cases, defenders deploy a single sUAS in various patrol patterns to evaluate their impact on engagement outcomes. The analysis reveals that sUAS deployment significantly enhances defender survival odds and increases indirect fire opportunities, particularly with short-range and concentrated patrol patterns. In the area of effectiveness assessment, Brooks et al. (2004) demonstrated the U.S. Air Force’s Systems Effectiveness Analysis Simulation (SEAS) tool's ability to model collateral damage through an agent-based approach. By simulating two scenarios under varying rules of engagement, the model illustrates the trade-off between mission effectiveness and collateral damage. Unlike traditional models, SEAS incorporates interactive factors such as crowd dynamics, information operations, and communication infrastructure effects, providing a more nuanced understanding of battlefield performance and long-term attitudes toward military actions.

The increasing complexity and tempo of modern asymmetric warfare demand rapid and precise information dissemination and adaptive operational strategies. Cil and Mala (2010) developed a two-layer hybrid agent-based architecture to address these challenges, combining cognitive and reactive agent layers to simulate and evaluate planning outcomes. This architecture models land combat as a nonlinear dynamical system composed of semi-autonomous agents that adapt to changing battlefield conditions. By simulating multi-dimensional warfare scenarios, the model demonstrates its capability to effectively analyze and validate small unit combat strategies. Agent-based modeling has also been applied to simulate small-unit combat scenarios in the context of military operations other than war (MOOTW). Woodaman (2000) proposed an agent-based model that focuses on the unique challenges of MOOTW, including peacekeeping, disaster response, and humanitarian aid. The model evaluates the behavior and interactions of small units operating in non-traditional combat environments, highlighting the importance of coordination, adaptability, and decision-making under uncertainty.

At the same time, information warfare is a critical component of modern military strategy, involving actions to achieve information superiority by targeting adversary information systems while safeguarding one's own. Chaturvedi et al. (2000) proposed an agent-based model to analyse the behaviours of key actors in information warfare: governments, firms, and perpetrators. The study employs the Synthetic Environment for Analysis and Simulation (SEAS) Lab at Purdue University to experimentally model the interactions among these agents. The experiments explore how agents employ tools such as computers, modems, and software to achieve their objectives, reflecting the tactics used by hackers and cybercriminals. This model provides insights into the strategic dynamics of information warfare, enabling a better understanding of the interplay between offensive and defensive information operations. And going further in the cyberspace domain, Kotenko (2005) developed an agent-based model to simulate cyber warfare engagements, specifically focusing on Distributed Denial of Service (DDoS) attacks and their countermeasures. The model involves teams of software agents deployed across various network hosts, with each team pursuing antagonistic objectives while cooperating within their group to achieve shared goals. The study defines ontologies for DDoS attack mechanisms and defence strategies, describing the hierarchical action plans, team structures, and interaction mechanisms among agents. By modelling these interactions, the research provides valuable insights into the dynamics of cyber conflicts, enabling the evaluation of protection mechanisms and team strategies. The model demonstrates the effectiveness of agent-based modelling for analysing complex cyber warfare scenarios and supporting the development of robust defensive strategies. Furthermore, Dobson and Carley (2017) introduced the Cyber-Forces Interactions Terrain (Cyber-FIT) Simulation Framework, an agent-based model designed for virtual experiments in cyber warfare. The framework allows military planners to evaluate cyber force projections across varying terrains and against diverse adversarial forces. The model simulates engagements at a granular level, assessing vulnerabilities, asset degradation, and mission capability rates. Specifically, by predicting the outcomes of cyber warfare scenarios, Cyber-FIT provides a decision-support tool for military planners to reason about strategic cyber operations. This framework marks a significant advancement in the simulation of cyber warfare, offering an environment for evaluating the effectiveness of cyber tactics and enhancing operational readiness.

3. Research Methodology

Proportionality assessment is one of the most important principles in military operations, requiring decision-makers to weigh the anticipated military advantage of an action against the potential harm to civilians and civilian infrastructure. This process is complex and uncertain, demanding a nuanced evaluation of diverse variables such as operational objectives, intelligence quality, and the evolving dynamics of conflict environments. Furthermore, the uncertainty and time-critical nature of military operations add layers of complexity and subjectivity, as decision-makers must operate within fluid and often ambiguous scenarios. To address these challenges, this research adopts the Design Science Research (DSR) methodology (Peffers et al., 2007; Gregor & Hevner, 2013; Fard & Maathuis, 2021) to systematically design and develop a novel agent-based model for simulating the proportionality assessment in military operations. The model proposed is the primary artefact in this methodology, encapsulating the interactions between decision-makers, environmental factors, and operational variables. By employing the DSR approach, the model development follows an iterative process that integrates design, testing, and evaluation phases, to assure that the model embeds both knowledge and data captures from a comprehensive literature review, relevant activities, and field expertise.

Furthermore, the proposed model provides a dynamic and adaptive simulation platform that models the behaviours and interactions underlying proportionality assessments, providing insights into the ethical and strategic trade-offs faced by military planners. The model integrates diverse operational variables, including mission objectives, environmental conditions, and intelligence data, to reflect the multifaceted nature of real-world scenarios. Through this approach, the model captures not only the immediate impacts of military actions but also the broader contextual factors that influence decision-making. A key emphasis during development was placed on ensuring the artefact's adaptability, interpretability, and transparency, aligning with the principles of responsible and trustworthy AI (Maathuis, 2022). The iterative design process involved simulating multiple scenarios to refine the model's performance, ensuring robustness and reliability under varying conditions. By employing the DSR methodology, this research advances the theoretical understanding of proportionality assessment while also contributing with an AI-model that supports military planners in navigating the complexities of operational environments.

4. Model

Traditional physics-based models, which are well-suited for representing mechanical systems like tanks and aircraft, fall short in depicting the nuanced and dynamic nature of human actions on the battlefield. As an alternative, Middleton (2010) stresses the necessity of transitioning from a mechanistic view to one that portrays humans as decision-making entities, capable of processing information, adapting to environmental and operational stressors, and being influenced by psychological and physiological factors. This approach builds models as rational entities that operate with incomplete and sometimes inconsistent data, requiring inference and autonomy to represent and reason in complex scenarios. Accordingly, the proposed model integrates interdisciplinary rules and behaviours to simulate how the agent evaluates battlefield dynamic and make proportionality judgments. By implementing rules rooted in theories of Complex Adaptive Systems (CAS), the model captures emergent behaviours and interactions that are vital for assessing proportionality in diverse (complex) combat scenarios. This human-centric ABM approach allows building an intelligent adaptive model that captures both the complexity of human behaviour and battlefield dynamics, and integrates both collateral damage and military advantage components. The model is formally defined as follows:

$$A_i = \{S_i, R_i, D_i\}$$

where

Si represents the state of the agent,

Ri represents the set of rules governing the agent's decision making,

Di represents the data perceived by the agent.

The collateral damage component is a function *CD(x)* that quantifies the unintended effects caused by a military action *x*, as further defined:

$$CD(x) = \sum_{j=1}^{n} (H_j \cdot P_j(x))$$

where

Hj is the potential collateral damage to a civlian person or entity *j* (e.g., human lives, infrastructure),

Pj(x) is the probablity of collateral damage to *j* caused by action *x*.

The military advantage component is a function *MA(x)* that quantifies the intended effects or operational gain achieved by a mlitary action *x*, as follows:

$$MA(x) = \sum_{k=1}^{m} (G_k \cdot W_k(x))$$

where

Gk represents the (strategic) importance of objective *k*,

Wk(x) is the probability of achieving objective *k* through conducting action *x*.

Then the proportionality assessment of an action x is assessed as the function P(x):

$$P(x) = \begin{cases} 1, & \text{if } MA(x) \geq \alpha \cdot CD(x) \\ 0, & \text{if } CD(x) \gg MA(x) \text{ (i.e., } CD(x) > \beta \cdot MA(x)) \end{cases}$$

where

the action is Proportional (*P(x) = 1*) in case that the anticipated *MA(x)* is greater or equal than the expected *CD(x)*, within an acceptable threshold α,

or otherwise Disproportional (*P(x) = 0*) in case that the expected CD(x) is excessively greater than the anticipated MA(x) with the threshold β. This implies that the action *x* is disproportionate due to the excessive collateral damage (i.e., harm to people and/or damage to objects) produced relative to the gain.

Furthermore, a series of rules are provided:

∀x((I(x)=LOW∧D(x)=LOW∧O(x)=YES∧A(x)=HIGH)⟹E(x)=Proportional Engagement)

where if

I(x)=LOW which implies that the injury level caused by the action is low.

D(x)=LOWD(x) = LOWD(x) = LOW which implies that the death level caused by the action is low.

O(x)=YESO(x) = YESO(x) = YES which implies that the object destruction is a factor.

A(x)=HIGHA(x) = HIGHA(x) = HIGH which implies that the military advantage of the action is high.

then E(x)=Proportional Engagement which means that in this action, the engagement is proportional.

∀x((I(x)=MEDIUM∧D(x)=HIGH∧O(x)=NO∧A(x)=LOW)⟹E(x)=Disproportional Engagement)

where if

I(x)=MEDIUM which implies that the injury level caused by the action is medium.

D(x)=HIGHD(x) = HIGHD(x) = HIGH which implies that the death level caused by the action is high.

O(x)=NOO(x) = NOO(x) = NO which implies that object destruction is not a factor to be accounted.

A(x)=LOWA(x) = LOWA(x) = LOW which implies that the military advantage of the action is low.

then E(x)=Disproportional Engagement which means that in this action, the engagement is disproportional.

For evaluation purposes, the model is demonstrated through execution in a simulated environment with 1,000 autonomous agents. These agents were tasked with evaluating a diverse set of scenarios, representing varying levels of civilian injury, death, civilian object destruction, and military advantage. The simulation results revealed that out of the 1,000 scenarios, 630 engagements were assessed as proportional, while 370 were classified as disproportional. This distribution indicates that in approximately 63% of cases, the military advantage sufficiently justified the collateral damage under the proportionality thresholds (MA(x)≥α·CD(x)MA(x). At the same time, in 37% of scenarios, the collateral damage significantly exceeded the military advantage (CD(x)>β·MA(x)CD(x), leading to a determination of disproportionality, and 0 cases when the simulation failed, as depicted in Figure 1.

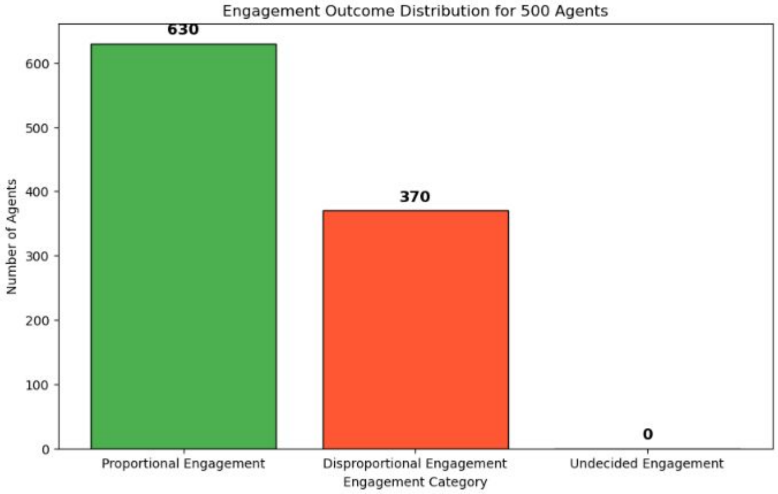

Figure 1: Simulation

These results show the model's capability to systematically distinguish between acceptable and excessive engagements, providing valuable insights into how specific combinations of variables influence decision outcomes. Moreover, the findings show the importance of building such models when analysing complex military decision-making processes that account relevant legal and ethical perspectives when conducting the proportionality assessment in a responsible way in military operations.

As exemplification, in a Cyber Operation scenario, the model would need to weigh a Distributed Denial of Service (DDoS) attack targeting an adversarial command-and-control (C2) server against potential collateral effects on civilian infrastructure. Specifically, through the rules it is assessed the probability of neutralizing the adversarial server (with the defined military advantage function, MA(x)) relative to the likelihood of unintended disruptions to civilian networks (quantified by CD(x)). If critical civilian resources such as hospital systems or public utilities share the targeted network, then the probability of substantial collateral damage increases, potentially tipping the proportionality assessment to Disproportional (P(x) = 0) if CD(x) significantly exceeds MA(x) beyond threshold β. At the same time, if the targeted server is sufficiently isolated from civilian networks and the anticipated operational gain (e.g., severing enemy communications) is high, the model would consider a proportional engagement (P(x) = 1). Hence, using simulation runs across varied network topologies and operational conditions, allows a systematic investigation on how different assumptions regarding connectivity, collateral disruption probabilities, and operational gain thresholds shape the agent's proportionality judgments.

5. Conclusions

The proportionality assessment is a core principle in the planning and execution of military operations, requiring decision-makers to balance the anticipated military advantage of an action against the enemy against the potential harm and damage to civilians and civilian objects. This process involves capturing and dealing with the uncertain and dynamic operational environments while integrating variables such as the operational context, available intelligence, and the evolving nature of conflict. To address the complexity of this assessment, this research introduces an agent-based model designed to simulate proportionality assessments in military operations. The proposed model captures interactions between decision-makers, environmental variables, and operational factors, creating a dynamic framework for analysing diverse proportionality scenarios. By modelling these interactions and simulating various operational contexts, this AI model provides valuable insights into the proportionality decision-making process and serves as a design mechanism for further AI-based system that could be built upon it making use of both actual data and expert knowledge. At the same time, this research contributes to the ongoing development of responsible and trustworthy AI systems that enhance ethical and strategic military decision-making (Maathuis, 2024b).

Building on this development, the research opens several future directions. Firstly, integrating real-time data streams, such as battlefield intelligence and operational updates, into the model could improve its responsiveness and realism, enabling more accurate simulations of dynamic operational contexts. Secondly, considering multidisciplinary collaboration by incorporating perspectives from ethics, international law, and cognitive science would expand the model's capacity to address complex legal, social, and moral dimensions of proportionality assessments. Thirdly, integrating game-theoretic and graph-theoretic principles into the model by incorporating weighted directed graph structures and the strategic equilibrium concepts of game theory, it may be possible to capture both system-wide network dynamics and the adaptive decision-making that unfolds at the agent level to be able to capture real-time complexities of military, legal, and ethical constraints. And fourthly, developing robust evaluation frameworks with comprehensive metrics to validate the model's reliability, transparency, and ethical alignment in diverse scenarios would enhance its applicability in real-world military decision-making (Maathuis, 2023). Together, these research directions provide a series of pathways to strengthen the adoption of AI-driven tools for more informed, intelligent, accountable, and ethically prepared operational strategies.

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