An agent-based model of military mechanization

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1 Introduction

This paper presents an agent-based model of military mechanization. First, it provides a theoretical discussion of military mechanization, states the research hypothesis, and explains why agent-based modeling is an appropriate research strategy. Then, it details an original agent-based model; presents results; and discusses their implications for the academic debate on military mechanization.

In summary, the orthodox view of military mechanization is that it is a reflexive process: states choose their mechanization posture largely based on that neighbors, enemies, and recent military experiences (e.g. defeat in counter-insurgency). This paper argues that this view—based on traditional longitudinal data analysis—is ripe for agentization. It implicitly argues for autonomous agents (states) that have cognition regarding mechanization that takes into account other agents (e.g. enemies), spatiality (e.g. neighbors), and learning from experience. This paper builds such a model and validates it against the empirical record, using the National Mechanization Index of Sechser and Saunders 2010. It finds that the orthodox view of mechanization does not stand up to agentization. A positive feedback loop exists causes states to mechanize much faster and to a greater degree than occurs in the real-world. This implies the existence of some countervailing factor (possibly a negative feedback loop) that mitigates the extent of mechanization. Candidates for what this could be mostly center on "internal" factors—e.g., culture, economy, and so on—as opposed to the "external", security environment-centric orthodox view.

2 Background

2.1 Military mechanization

States differ in the composition of their military ground forces.[1] One notable axis of comparison is *mechanization*: the degree to which an army consists of infantry vs. combat vehicles. Treating mechanization as a continuous variable, one extreme is an army consisting exclusively of dismounted, small arms-wielding infantry units; the other extreme is an army consisting solely of tank units, armored personnel carriers, artillery, and the like. Clearly, no modern state embodies either extreme, but the 1970s-era Vietcong are a good example of a low-mechanization army and the 1980s-era Israeli army of high mechanization.

The consequences of mechanization are large. There is academic consensus that defense policy—including but not limited to mechanization—conditions battlefield effectiveness. Lyall and Wilson 2009 finds that highly mechanized militaries are less effective at counterinsurgency, while Biddle 2004 argues that mechanization-enabled mobility aids conventional warfighting. It thus pays to have an army that is designed to win the kinds of conflicts that a state is likely to face. Lacking a crystal ball, however, leaders cannot always forecast conflict, and armies are large, complex organizations that typically are held to change only infrequently and slowly (Murray and Millett 1998, Locher 2004, Zegart 2000). A state suddenly faced with a war for which its mechanization posture is ill-suited can either concede or pay a cost in blood and treasure; what it cannot do is quickly overcome the constraints imposed by past mechanization decisions. A quote from then-Secretary of Defense Donald Rumsfeld—made in 2004, when the U.S. military was confronted in Iraq with the consequences of past choices regarding mechanization—emphasizes the point: "you go to war with the army you have" (Schmitt 2004).

The causes of military mechanization are disputed. *Realists* believe that mechanization choices are driven by security environment. States choose mechanization policies that they believe will allow them to prevail against potential adversaries, or to send a signal of deterrence, or to learn from the perceived mistakes of the last war (Mearsheimer 1983; Huth 1988; Murray 2011). The other school of thought is more diverse and so harder to name, but may be termed *institutionalists*. They believe that factors other than strategic calculation determine military mechanization. Domestic political institutions—e.g., democracy vs. autocracy, politically stable vs. coup-prone, the state of civil-military relations, and so on—may influence force structure (Reiter and Stam 2002; Quinlivan 1999; Talmadge 2015; Brooks 2008). Economic factor endowments may play a role: e.g., capital-rich states may mechanize more than labor-rich states (Gartzke 2001). Lastly, ideology (Van Evera 1984) and culture (e.g., Pollack 2004) are hard-to-measure but perhaps influential. Consider Ireland: between the 1920s and 1940s, it expended a large portion of its defense budget

[1] States may have multiple organizations that conduct ground combat operations: e.g., the United States operates both an Army and a Marine Corps as independent services. Henceforth, this paper uses the terms "army" and "ground forces" interchangeably.

on building a small number of tanks. They were wholly insufficient to repel a British invasion (their ostensible purpose), and Ireland would have been better-served to pursue a low-mechanization guerrilla defense strategy, but tanks were seen as a prestigious signifier of a "real" professional military, an important factor for the young Irish state (Farrell 1998; Farrell 2001).

Sechser and Saunders 2010 is the landmark study on military mechanization. They assemble a longitudinal dataset at the country-year level of the mechanization of all states between 1979 and 2001, and conduct regression analysis to identify the effect of covariates on mechanization. They conclude that "choices about mechanization are strongly associated with a state's security environment." The more mechanized a state's geographic neighbors and enemies, the higher the state's own mechanization; also, states learn from defeat in insurgency by subsequently decreasing their mechanization.

2.2 The case for agent-based modeling

The findings of Sechser and Saunders 2010 are ripe for agentization. The conclusions drawn implicitly claim that states are autonomous agents; that they have cognition regarding how to perceive the outside world and how to react to it; that spatiality and neighborhood matter; that inter-agent relationships matter; and that agents learn from experience. Agent-based modeling is uniquely well-suited to represent such phenomena (Gilbert and Troitzsch 2005; Miller and Page 2009).

Importantly, the findings of Sechser and Saunders 2010 imply a positive feedback loop. State A has high mechanization, causing enemy State B to raise their mechanization, causing State A to raise their mechanization... and so on. Such feedback loops are a hallmark of complex systems and again are well-suited for representation by agent-based modeling. This specific one—states changing their military in response to other states change in military in response to... and so on—feedback loop—is often called the "security dilemma" and was a main research interest of Thomas Schelling, one of the pioneers of agent-based modeling (Schelling 1960; Schelling 2006).

2.3 Research question and strategy

I hypothesize that the arguments of Sechser and Saunders 2010 are incomplete and that some omitted variable(s) act(s) as a "brake" on mechanization.[2] An agent-based model is used to test this hypothesis. In broad terms, agents (states) are defined to have the cognitive and learning behavior implicitly claimed by Sechser and Saunders 2010. The model is initialized with real-world data from 1979 and allowed to run until 2001. The micro- and macro-outcomes are then validated against real-world 2001 data. If Sechser and Saunders 2010 are correct, the model's 2001 outcomes should match real-world 2001 outcomes. If the model mechanization levels in 2001 are much higher, then their claimed behavioral rules

[2]By "omitted", I mean that they conclude that the variable is not very important for mechanization, not that they do not address the variable at all.

are incomplete and fail to include some “brake” on mechanization, matching my hypothesis. Proving exactly what that missing variable or set of variables is is outside the scope of this model and paper, though it is discussed.

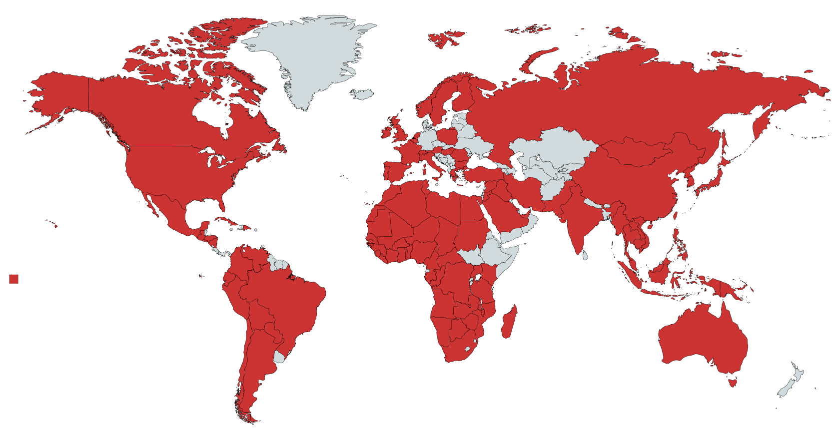
3 Model

This section of the paper describes the model. It does not use the ODD protocol of Grimm et al. 2006 but covers many of the same points.

3.1 Agents

There is one agent type: states. Agents exist at a fixed location and do not move. The set of agents encompasses all diplomatically-recognized states in the world at a particular point in time, minus microstates (defined as those with a population less than 750,000). Some other states were excluded; for why, see the **Time** section. Figure 1 depicts the set of agents.

Figure 1: Agents



Agents have attributes. *Name* is self-explanatory. *Mechanization* is the agent's level of mechanization at a given timestep. Mechanization is calculated as the number of armored vehicles per 100 soldiers, per Sechser and Saunders 2010. *Neighbors* is a list containing the *Names* of an agent's geographic neighbors at a given point in time—more on this in the subsequent **Environment** section. *NeighborsMech* is the average mechanization level of an agent's *Neighbors* at a given point in time. *Enemies* is a list containing the *Names* of an agent's enemies at a given point in time. An enemy is an agent with which the agent in question has had a militarized interstate dispute in the preceding ten years, per the Correlates of War (COW) Militarized Interstate Disputes Database (MIDB) (Palmer et al. forthcoming). *EnemiesMech* is the average mechanization score of enemies. Agents also have attributes that affect their perception of other agents and cognition for changing their own behavior. These attributes are discussed in the **Cognition and Actions** section.

3.2 Environment

Agents exist in a spatial environment. Spatiality is represented by neighbor relationships. Two states are defined as being neighbors if they share a contiguous land border or a stretch of water less than 400 miles. Data on neighbor relationships is taken from the Correlates of War (COW) Direct Continuity dataset (Stinnett et al. 2002). Modeling spatiality as dyadic neighbor relationships, rather than a more detailed raster or vector GIS implementation, is justified on the basis that the academic literature on mechanization suggests that two states neighboring each other is the important factor, not more detailed geographic information (e.g., topographical features along the border). As such, this paper's modeling choice captures the phenomenon of interest while avoiding the overhead of a full-blown GIS implementation coupled with ABM (e.g., Harper, Westervelt, and Shapiro 2002 or Bennett and Tang 2006).

3.3 Cognition

Agents have global perception of other agents: they can "see" the mechanization state of all other agents. This modeling choice is reflective of the real world, in which states devote significant resources to stay informed of the military posture of others. Agent cognition centers on updating their own mechanization in response to the external security environment. This occurs in three ways. One, if an agent's *NeighborsMech* increases—i.e., the agent's neighbors become more mechanized—the agent will increase its own mechanization by some proportional amount controlled by the agent's unique *NeighborMechSensitivity* attribute, which is heterogenous across agents (more on this below). Two, if an agent's *EnemiesMech* increases—i.e., the agent's enemies become more mechanized—the agent will increase its own mechanization by some proportional amount controlled by the agent's unique *EnemyMechSensitivity* attribute, again heterogenous across agents. Three, agents occasionally suffer an "anti-mechanization lesson": defeat in a counter-insurgency conflict. Such events are scripted to occur for agents and years as per the historical record: e.g., the Soviet Union experienced such a lesson in the 1980s in Afghanistan. An agent experiencing such an event will decrease their own mechanization by some amount controlled by the agent's unique *LessonSensitivity* attribute, again heterogenous across agents. Cognition for agent i thus is:

$$
\begin{aligned}
\mathrm{Mech}_i^{(t+1)} = \mathrm{Mech}_i^{(t)} \\
+ (\mathrm{NeighborMechSensitivity}_i \times \mathrm{NeighborMech}_i^{(t)}) \\
+ (\mathrm{EnemyMechSensitivity}_i \times \mathrm{EnemyMech}_i^{(t)}) \\
+ (\mathrm{LessonSensitivity}_i \times I_{\mathrm{Lesson}}(t,i))
\end{aligned}
\quad (1)
$$

with (t) denoting timestep, i indexing agents, and $I_{\mathrm{Lesson}}(t,i)$ an indicator function of whether the agent experienced an anti-mechanization lesson. Table 1 summarizes agent attributes.

Table 1: Attributes, organized by theme

Identity	*Name*
Mechanization	*Mechanization*
Spatiality	*Neighbors*
Inter-agent Relationships	*Enemies*
Perception	*EnemiesMech* *NeighborsMech* *Lesson*
Cognition	*EnemyMechSensitivity* *NeighborsMechSensitivity* *LessonSensitivity*

An important note is that these three factors—neighbors, enemies, and defeat in counter-insurgency—correspond to the factors identified by Sechser and Saunders 2010 as most important for mechanization. Because the research goal is essentially to see whether their findings stand up to agentization, it is critical to make agent cognition work in about the way that their findings predict. Inclusion of other factors not identified as important for mechanization—e.g., alliances, economic factors, culture, etc.—would be interesting but counterproductive to the research question. They are discussed along with this model's findings.

Data for *NeighborsMechSensitivity*, *EnemiesMechSensitivity*, and *LessonSensitivity* come from Sechser and Saunders 2010. Specifically, they estimate coefficients and standard errors for these three factors, thus defining a statistical distribution for each. Upon instantiation, every agent makes a random draw from each of the three distributions, the resulting values of are taken for these three attributes. This modeling choice has two important elements. One, it further enhances agent heterogeneity. Agents already differ in their geographic neighbors, enemies, and experiences with anti-mechanization lessons; now, they also differ in the cognition used to update mechanization based on these factors. It also introduces a stochastic element to the model, meaning that each run differs and so multiple runs must be conducted for each specification.

3.4 Time

The model starts in 1979 and runs in 2-year time increments until 2001. This timespan and periodicity reflects data availability: a longer time period and more frequent updates would be ideal but is not practically achievable. Agent attributes are initialized, and then then the model iterates through timesteps. In discussing what happens each timestep, it is useful to distinguish between things that depend on agents' actions and those that do not.

Some changes are deterministically programmed into the model and do not depend on agent behavior. Every timestep, neighbor relationships and enemy relationships are updated in accordance with the historical record. The occurrence of counter-insurgency defeats also is hardwired into the model and does not depend on agent behavior within the model.

Other changes do depend on agent behavior. Agent activation order in a particular timestep is random. Every timestep, every agent perceives the world aorund them; recalculates *NeighborsMech* and *EnemiesMech*; updates their mechanization level according to *NeighborMechSensitivity* and *EnemyMechSensitivity*; and updates their mechanization level according to *LessonSensitivity* if an anti-mechanization lesson occured.

An important caveat is that the set of agents represented in the model does not change over time: i.e., agents are the same from 1979 onwards. In real life, of course, the agent population was not static over this time period, with many states ceasing to exist in 1991 and new ones forming. Modeling these changes is beyond the scope of this model. How a collapsed state's military assets are divvied up among successor states is complex and not tractable to simple representation (e.g. averaging). For example, the Soviet Union deployed most of its modern military equipment in the far west of the country in anticipation of a conflict with NATO, and so when the USSR collapsed Ukraine inherited the lion's share, leaving little for successor states such as Azerbaijan that were not important military districts (Allison 1993). Such inheritance has a strong effect on the mechanization of of successor states. Designing complex and state-specific "rules of inheritance" was too much for this initial effort but is an area for further development.

3.5 Output Data, Verification, and Validation

The main model output of interest is data on military mechanization. It is provided for every agent and every time-step. These agent-level data also can be aggregated into system-level measures of military mechanization. Per the research design, the intent is to compare the model output to what actually occurred. If the model produces military mechanization levels much higher than reality, it means that Sechser and Saunder's findings do not stand up to agentization and there is some missing "brake" on military mechanization. Note that this research strategy has validation (comparison of model output to empirical data) at its core and so no separate validation is needed. Verification that the model is doing what it is intended was accomplished through manual inspection.

4 Results

At both the system- and agent-level, this agent-based model results in much higher mechanization levels than occurred in the real world. First, let us compare the average mechanization levels across all countries at each time-step of the model. Although the set of agents is not exactly the same between the model and reality (c.f. earlier issues with inheritance), this gross comparison still is a useful measure of comparison. Model results are the average of 100 runs, with all parameters (e.g. *EnemyMechSensitivity*) drawn from the distributions claimed by Sechser and Saunders 2010; empirical results are drawn from the National Mechanization Index compiled by Sechser and Saunders 2010.

Table 2: Comparison

Year	**Model**	**Reality**
1979	0.0156	0.0139
1981	0.0189	0.0167
1983	0.0229	0.0167
1985	0.0280	0.0183
1987	0.0351	0.0187
1989	0.0415	0.0197
1991	0.0512	0.0215
1993	0.0636	0.0229
1995	0.0804	0.0231
1997	0.1014	0.0270
1999	0.1319	0.0272
2001	0.1730	0.0291

Examining results at the agent-level reveals that the higher mechanization levels of the model are much more pronounced for some agents than others. In some cases, the model actually results in *lower* mechanization levels, with Mexico serving as one example.

Table 3: Mexico

Year	**Model**	**Reality**
1979	0.0013	0.0012
1981	0.0014	0.0012
1983	0.0018	0.0026
1985	0.0019	0.0013
1987	0.0021	0.0019
1989	0.0022	0.0027
1991	0.0024	0.0030
1993	0.0026	0.0033
1995	0.0030	0.0035
1997	0.0032	0.0074
1999	0.0036	0.0082
2001	0.0040	0.0075

For some agents, however, mechanization levels are extremely high. Mechanization score is a percentage, and so values over 1 do not make sense, yet some countries end the simulation with mechanization scores over 1. Note that one could easily right-bound values at 1, but this was not done in order to see what values would be organically converged to.

Table 4: Highest mechanization scores, 2001

Agent	**Mechanization Score**
Israel	1.59
USA	1.34
Kuwait	1.14
Russia	1.06

There appears to be a correlation between number of enemies and high mechanization score. For example, both the USA and Russia consistently had some of the highest amount of enemies, peaking with 16 enemies for Russia in 1999 (this high number is attributable to the Kosovo crisis, when a confrontation between Russian and NATO forces at Pristina Airport nearly led to war), and as per the above table are among the most mechanized states. That Israel had many enemies during this time period is obvious.

There also appears to be neighborhood effects. Mechanization is not evenly distributed across the globe. Rather, it is geographically concentrated in a few hot-spots. Agents belonging to the Middle East and North Africa (MENA) region account for about 10% of the overall agent population, yet make up 50% of the top 20 most mechanized agents at simulation end. Other regions are correspondingly under-represented; for example, Asia does not have a single state in the top 20.

Table 5: Top 20 mechanized agents at simulation end, by region

MENA	**Europe & FSU**	**Africa**	**Americas**	**Asia**	**Oceania**
Israel	Russia	Sudan	USA	(none)	(none)
Kuwait	France	S. Africa	Canada		
Iran	UK				
Libya	Greece				
Iraq	Netherlands				
Syria	Poland				
KSA					
Egypt					
Lebanon					
Turkey					

5 Discussion

5.1 Findings

Two conclusions should be drawn. One, the model results in much higher system-level mechanization than occurred in reality. Two, this higher mechanization is not evenly distributed across agents; rather, a small number of agents with many enemies and that all border each other become outliers and hence drive the global average far upward. The explanation for both phenomena lies in a positive feedback loop. Enemies and neighbors adjust their mechanization scores in response to each other; hence, a geographic cluster of enemies (e.g., the Middle East or Cold War-era Europe) will rapidly increase their mechanization.

Three, because this model is a faithful representation of the factors that Sechser and Saunders 2010 claim are most important for mechanization, that model output fails to match reality indicates that their claimed model is incomplete. There must be some "brake" on mechanization; put differently, some countervailing factor(s) must mitigate the effect of the positive feedback loop identified above. This model cannot conclusively identify what that "brake" is. The most plausible candidates are factors examined by Sechser and Saunders 2010 and deemed statistically insignificant such as regime type and economy, and factors not examined by Sechser and Saunders 2010 at all such as culture.

This paper is a novel contribution to the literature. Although agent-based models have found traction in the study of grievance, insurgency, and other population-centric security phenomena (e.g., Epstein 2002), they quite rarely are used to model international relations and state-centric security phenomena despite some early work on this front (e.g., Cederman 1997 and Axelrod 1997). This paper's agentization of an orthodox security studies model thus is novel in method. Its findings also are important. They show that they show a solely "external", security environment-focused view of mechanization does not stand up to agentization. Spatiality, inter-agent relations, autonomous agents with cognition, and positive feedback loops—all hallmarks of a complex system—drive results that significantly diverge from theoretical expectations of the orthodox view.

5.2 Areas for Improvement

Having taken a critical view of Sechser and Saunders 2010, it only is fair that this paper applies that lens to itself. There are two main areas for improvement.

One, this model's representation of Sechser and Saunders 2010 could be tightened up, as there currently is divergence between the two. For example, this model examines a smaller agent set than their paper. Building "inheritance" processes to allow new states to emerge is desirable. This paper's use of statistical coefficients from Sechser and Saunders 2010 also has some methodological problems, a full description of which is omitted here due to space constraints. It suffices to say that a better approach would be to conduct more extensive parameter sweeps of relevant cognitive factors.

Two, this model could incorporate potential explanations of what the missing "brake" on mechanization might be. Economy and culture could be included in the model. Doing so would allow exploration of whether these factors are logically consistent and can act as a countervailing factor that controls the positive feedback loop of mechanization. It cannot *prove* that these or any other factors actually exist in reality, but they can demonstrate how they are or are not consistent in a simulated reality.

My hope is that making these changes will make this a publication-quality paper capable of serving as one of two required papers for the comprehensive exams.

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