Dynamic Complexity in Military Planning:

A Role for System Dynamics

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ABSTRACT:

Military strategists are increasingly recognizing that planned interventions sometimes fail to achieve their goals, especially in the long term, because planning is done with a limited view of possible outcomes rather than a whole-systems perspective. The systems modeling methodology of system dynamics is well-suited to address many of the dynamically complex problems that arise in the context of military planning issues. The purpose of this paper is to highlight key features of the system dynamics method as it might be applied to military planning. The paper develops an illustrative model of a stylized military planning situation and uses it to illustrate typical characteristics of system dynamics models and their use to understand system behavior. The example highlights basic structural features found in system dynamics models including stocks and flows, balancing and reinforcing feedback loops, nonlinearities, and time delays. The example shows how structure causes behavior and identifies several characteristic aspects of the behavior of dynamically complex systems, such as the basic dynamics of stocks and flows, dynamic equilibria, paradoxical patterns of behavior over time (e.g., better before worse), shifts in loop dominance, and tipping points. The paper closes with some thoughts on using system dynamics to improve military planning.

KEYWORDS: System dynamics, military planning, nonlinear dynamics, simulation, models

Introduction

Military professionals and others responsible for national defense continue to face a difficult challenge to meet the objective of reducing the threat of terror while maintaining national security. The defense enterprise is particularly challenged by the changing nature of adversaries (National Strategy for Homeland Security, 2007; Quadrennial Defense Review, 2006). Traditional strategies and tactics have not only proven less effective than in the past but may actually contribute to worsening the situation (Hoffman, 2006).

Military strategists are increasingly recognizing that planned interventions sometimes fail to achieve their goals, especially in the long term, because planning is done with a limited view of possible outcomes, rather than a whole-systems perspective. The somewhat myopic approach is engrained in many of the routine planning and evaluation methods of policy makers and military planners (Bensahel, 2006; Byman, 2005). Conventional analytical tools and planning techniques are generally poorly suited to address situations in which tactical actions have multiple and conflicting effects (often with unintended side effects of greater consequence than the primary effects) and in which actions and consequences are separated in both time and space (Davis & Henninger, 2007).

Such situations exhibit dynamic complexity. Problems that are dynamically complex often have long time delays between causes and effects and may have multiple, sometime conflicting, goals and interests (Sterman, 2000). Identifying and planning the timing and operations of successful interventions is difficult in such situations, because most interventions have unintended consequences and may meet with resistance from opposing interests or be significantly constrained by limited resources or capacities.

The systems modeling methodology of system dynamics is well suited to address the dynamically complex problems that arise in the context of military planning issues. The system dynamics approach involves developing models that portray processes of accumulation and feedback and using these models to systematically test proposed policies for achieving desired outcomes. The purpose of this paper is to highlight key features of the system dynamics method as it might be applied to military planning. To do so, we develop an illustrative model of a stylized military planning situation and use the model to demonstrate typical characteristics of system dynamics models and their use to understand system behavior.

System Dynamics for Military Planning

We believe the systems modeling methodology of system dynamics can help to effectively address the challenges in many cases of dynamic complexity in military planning. The methodology involves developing causal diagrams and building policy-oriented mathematical models for computer simulation of the dynamics of interest. Unique models are developed for unique problem settings, but practitioners often draw on prior modeling work from similar problem settings. Jay W. Forrester developed the approach in the mid-1950s and published a full-length description in the seminal book in the field, *Industrial Dynamics* (Forrester, 1958). Subsequent work elaborated additional principles of systems and extended the application domain to include issues of public policy, for example with the publication of *Urban Dynamics* (Forrester, 1968, 1969, 1971; Forrester & Senge, 1980). In 1983, the International System

Dynamics Society was established, and the society has recently formed a special interest group for topics in international and intra-national conflict.

A central tenet of system dynamics is that the structure of a system causes its behavior. The structure of a system consists of ongoing accumulations known as stocks, the flows that cause those stocks to increase or decrease, and the interacting feedback loops that govern the rates of these flows. The behavior of a system refers to the patterns over time (such as growth, decline, or oscillation) of quantities that describe the system. Thus, the complex behaviors of social systems are the result of ongoing accumulations – of people, financial assets, materials, weapons, supplies, resources, information, capabilities, and even intangibles such as favorable public sentiment or other psychological states - and both balancing and reinforcing feedback mechanisms. The social sciences have drawn on concepts of feedback and accumulation for centuries, and military scholars have employed the concepts in many contexts as well (Richardson, 1991). The system dynamics method is a practical application that uses these concepts as the basis for computer simulation models, which are used first to understand how structure gives rise to system behavior and then to test in a systematic manner various scenarios and alternative policies for achieving more desirable system behavior (Randers, 1980).

A system dynamics model is formally a system of nonlinear differential equations, but the models are usually built and expressed as an interlocking set of simpler algebraic equations that clearly show the causal structure posited and thus provide greater overall model transparency. Equations are developed from a broad range of experiential and measured data, drawing on theory and both quantitative and qualitative empiric data. Modelers strive to build models that are tightly grounded in observations of the system of interest, so that every model concept corresponds to easily recognized features of the focal real-world system. Large complete models may include hundreds or even thousands of equations and appropriate numerical inputs. The modeling process is iterative, moving through phases of scope selection, hypothesis generation, causal diagramming, model specification and quantification, reliability and robustness testing, and policy analysis (Sterman, 2000). The process continues to iterate, refining the model and the modeler's understanding, as the model more and more satisfies standards of realism, robustness, flexibility, clarity, ability to reproduce historical patterns, and the ability to generate useful insights (Homer, 1996). Careful attention to these requirements helps to develop models that can both illuminate reasons for observed past behavior and usefully explore possible futures and support meaningful "what-if" analyses (Morecroft, 1985; Sterman, 2001).

The use of quantitative data in system dynamics models warrants discussion. To use a system dynamics model for simulation, the modeler must specify the model's numerical values inputs – the initial values of the stocks, parameters or constants in the model, and the form of nonlinear functions included in the model. Recorded measurements or accurate parameter estimates are sometimes lacking for variables in a system dynamics model, but this is not a sufficient reason to exclude them. Much of what experience tells us is important in the world is not measured or recorded as quantitative data. When experts familiar with the domain being modeled agree that a factor is important, it is included in the model, and the best effort is made to quantify it in a manner that will inform the modeling process. Methods to do so in rough order of preference include using recorded measurements when available, making inferences from related data, logical analysis to deduce reasonable parameter choices, educated guesswork, or parameter selection by fitting a model's output to historical data (Forrester, 1980; Graham, 1980). The model calibration process is ripe with uncertainty, so sensitivity testing in critical. Empirically, modelers have noted that the behavior, and more importantly the policy implications, of well-built system dynamics models are typically not sensitive to changes in most quantitative inputs, in part because most real-world systems are over-specified (Forrester, 1971). This robustness to parameter uncertainty provides a strong motivation to use reasonable parameter values that are easily available early in the modeling process and then allow sensitivity testing to guide choices about measurement and data collection to refine parameter estimates. When model behavior is found to be sensitive to specific parameter values out of a large milieu of possibilities, especially if parameters identified as key are poorly understood, the modeling work helps to focus future efforts for creating metrics, gathering intelligence, measuring and evaluation, and parameter estimation on those metrics on which the merits of proposed policies and plans hinge.

System dynamics modeling has been applied to issues of military interest since at least the 1980s. Examples of topics that have been studied include:

1. Stability of nation states as challenged by the growth of terrorists (Choucri et al., 2006)
2. The dynamics of conflict (Coyle, 1981; Hackett, 1978)
3. Counter-insurgency warfare and management (Anderson, 2007; Coyle, 1985)
4. Combat models (Wolstenhome, 1990)
5. Defense spending, ship construction, and maintenance (Coyle, 1992a, 1992b, 1996; Coyle & Gardiner, 1991)
6. Project management at defense contractors (Cooper, 1980; Lyneis, Cooper, & Els, 2001; Lyneis & Ford, 2007)

The typical approach in these modeling efforts has been based on the active involvement of practitioners and policy makers with a direct stake in the problem being modeled. Several scholars have developed and documented specific techniques for engaging groups in the system dynamics modeling process (Andersen & Richardson, 1997; Andersen, Richardson, & Vennix, 1997; Richardson, Andersen, & Rohrbaugh, 1992; Vennix, 1996, 1999).

Other modeling and simulation methodologies are widely used in military planning and policy analysis situations. Examples include war game simulations, agent-based simulations, stochastic models, linear programming, and other tools from the realm of operations research. The methods are best viewed as complements, among which there is often significant overlap. The distinctive contribution of various methods is in part reflected by the models that result, but the methodologies used for developing these models often differ in important ways as well, at least in part because the purpose of the models will be different. System dynamics models will tend to be models of aggregate behavior and will in general have broader model boundaries than other types of models. They are likely to include more variables based on the recognition by logic or expert opinion that they are important but for which solid statistical estimates may not be available. System dynamics modelers have found that the search for effective solutions to vexing problems characterized by dynamic complexity is often successful when modelers choose long time horizons, set broad model boundaries, and include realistic causal factors, policy levers, and feedback loops (Sterman, 1988).

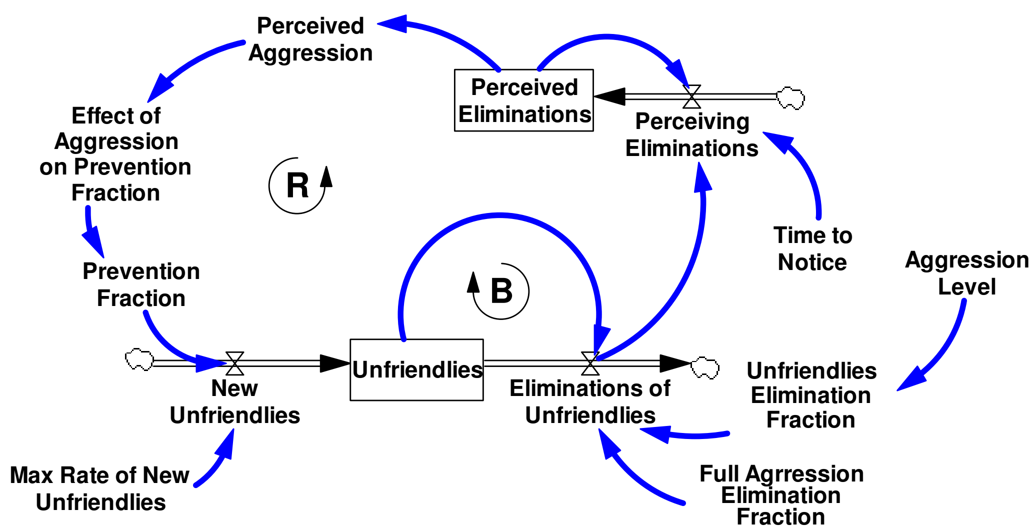
An Illustrative Military Planning Example

The merits of system dynamics modeling are best demonstrated by way of an example. We start with an important and challenging question: why do increasing efforts to reduce the threat from terrorist organizations often make the situation worse such that the perceived threat actually increases? The concern for this paradoxical and undesirable response to United States efforts to improve national security seems to have intensified, especially in the wake of 9/11 and in the current environment of Operation Iraqi Freedom (OIF).

To provide an example of how system dynamics modeling and simulation might lead to some insights about this situation, we have built a relatively simple model exploring how a hypothetical conflict situation might respond to one planning decision – the level of aggression brought to bear to eliminate the unfriendly forces. The model demonstrates how some increases in aggression may have desirable effects but that excessive aggression may make the overall situation even worse, suggesting that an intervention based solely on aggressiveness will have limited effectiveness so that a broader suite of intervention options should be considered. The model structure draws on well-documented empirical findings as well as theory from the social sciences. We present the model structure in this section, referring to relevant literature sources for the key structural relationships as we present them. The model has only one aggregated stock of "Unfriendlies," another stock that captures a metric of public perception, 26 differential and algebraic equations, and 8 numerical inputs plus some additional inputs to generate simulation scenarios, and is based on general knowledge rather than any specific encounter or case data. If this model were to be used for actual policy-making or planning rather than as an example here, one would expect the model to include a more detailed representation of various sectors of the population, social and psychological variables of importance, material and personnel resources, and the causal factors underlying model relationships. Moreover, such a planning model would draw on richer sources of data to develop parameter estimates.

Figure 1 presents the structure of the model, showing the stocks and flows, feedback loops, and policy inputs. This section describes the structure of the model, and the Appendix presents a full set of model equations and a complete sketch of the model structure, including elements used for generating scenarios for testing. The stock of *Unfriendlies*, shown in Figure 1 as a rectangle, represents the people who are enemies and thus are considered a threat to the interests of the stakeholder for whom the model is developed. An insurgent group aligned as antagonists to the current regime is an example of *Unfriendlies*. The stock of *Unfriendlies* is the net accumulation of two flows, an inflow named *New Unfriendlies* and an outflow named *Eliminations of Unfriendlies*. *Eliminations of Unfriendlies* are assumed to occur as the result of efforts by the stakeholder forces, perhaps those of the United States and allies. When the stakeholder asserts a higher level of aggression, the aggression accomplishes a higher *Unfriendlies Elimination Fraction* so the rate of *Eliminations of Unfriendlies* will be accordingly higher and, all else equal (i.e., for the same inflow of *New Friendlies*), the stock of *Unfriendlies* will decrease (Langdon, Sarapu, & Wells, 2004; McClintock, 1992; Rosendorff, 2004). In the stylized model here, the *Level of Aggression* is an exogenous policy lever; that is, the *Level of Aggression* is set by the user and can thus be manipulated to test various scenarios. Alternatively, the *Level of Aggression* could be modeled endogenously as representing a planning decision based on the number of *Unfriendlies*, their activities, or the duration of their opposition compared to some goals of specified by the planners.

Figure 1: A System Dynamics Model for Military Planning



The number of *Unfriendlies* is increased when *New Unfriendlies* join their ranks. Some insurgent groups actively recruit to grow their numbers. Others associate new members as people become disenchanted with prospects for health, safety, and prosperity under the current regime or as people are otherwise directly alienated (O'Neill, 2005). The model assumes that some fraction of the at risk population each period converts to become *New Unfriendlies*. The fraction that converts varies from low to an assumed *Maximum Fraction of New Unfriendlies* (not shown) under conditions most averse to the focal stakeholder. Favorable conditions, such as economic prosperity, low unemployment, strong educational systems, equitable distribution of wealth, strong confidence in systems of government and the incumbent leaders, and safe and secure living environments, mean that the fraction of new unfriendlies will be much lower (Collier et al., 2003; Fearon & Laitlin, 2003; Gurr, 1970; Hegre, Ellingson, Gates, & Gleditsch, 2001). We use the variable *Prevention Fraction* to model the extent to which favorable conditions dissuade at risk people from conversion to unfriendly. When the *Prevention Fraction* is zero, *New Unfriendlies* occur at the rate determined by the *Maximum Fraction of New Unfriendlies* and the size of the at risk population (which for convenience is assumed to be constant[1]). When the *Prevention Fraction* is larger, the flow of New Unfriendlies is proportionally less.

The human psychology and social dynamics that cause people to affiliate with insurgent groups and to take up arms are complicated (O'Neill, 2005). Of the many factors that may play a role in determining the propensity for people to become *New Unfriendlies*, this model explicitly represents the influence of aggression by the stakeholder group. Excessive aggression compromises the capacity of the regime and allies to foster the conditions that will prevent becoming unfriendly, perhaps because violence and unrest are widespread or perhaps on a more personal level because the aggression affects family or friends directly (Choucri et al., 2006; Long, 2006; O'Neill, 1990). The model assumes that when *Perceived Aggression* is high, the *Prevention Fraction* is lower, and thus the likelihood that people will become *New Unfriendlies* is greater. *Perceived Aggression* is the ratio of the current level of *Perceived Eliminations* to a benchmark acceptable level (which is here modeled as the initial level of *Perceived*

[1] A constant value for the at risk population is clearly contrary to fact, since the conversion of people from at risk to unfriendly will, all else equal, deplete the population of at risk people. However, other sources may increase the at risk population as well. The dynamics of the at risk population are excluded from this model in order to keep the focus on the dynamics of the stock of unfriendlies. Expanding the model boundary to include stocks for the at risk and general populations would introduce the possibility that the inflow of New Unfriendlies might be constrained by the source of people who are not already unfriendly, but if indeed this limit becomes meaningful, the stakeholder has already lost.

Eliminations). When *Perceived Aggression* is at or below the acceptable level, the *Prevention Fraction* is at an assumed normal value. But, above the threshold for acceptability, more aggression causes the *Prevention Fraction* to decrease. Thus, the *Effect of Aggression on Prevention Fraction* is a nonlinear function, constant below the threshold and then decreasing in *Perceived Aggression*. *Perceived Eliminations* is a stock variable that adjusts to equal the value of *Eliminations of Unfriendlies* with a delay defined by the *Time to Notice*. The delay captures the important notion that it takes time for the population to become aware of the eliminations and the associated aggression and then update their beliefs about the state of affairs, and even more time still to modify behavior patterns such that the rate of *New Unfriendlies* is influenced by these perceptions (Alagappa, 1995). Because time delays such as this are critical in understanding dynamically complex problems, explicitly modeling such delays is a hallmark of system dynamics modeling,

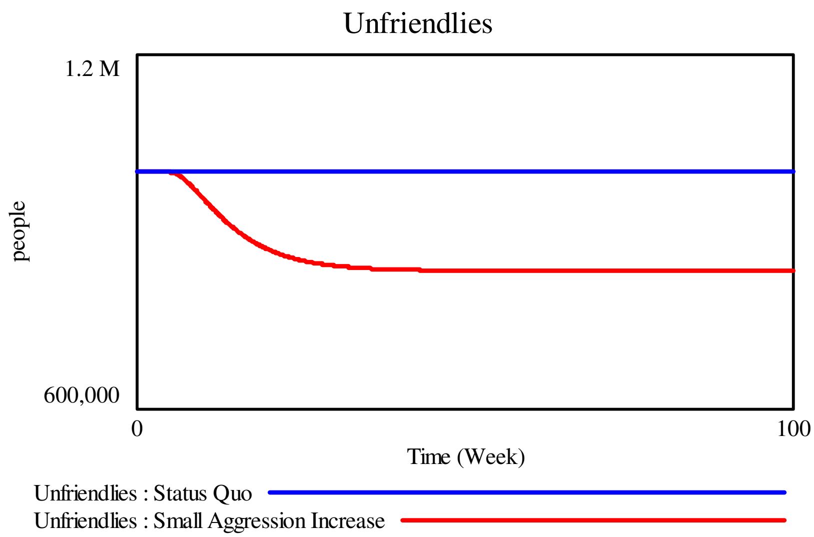
Model Simulation

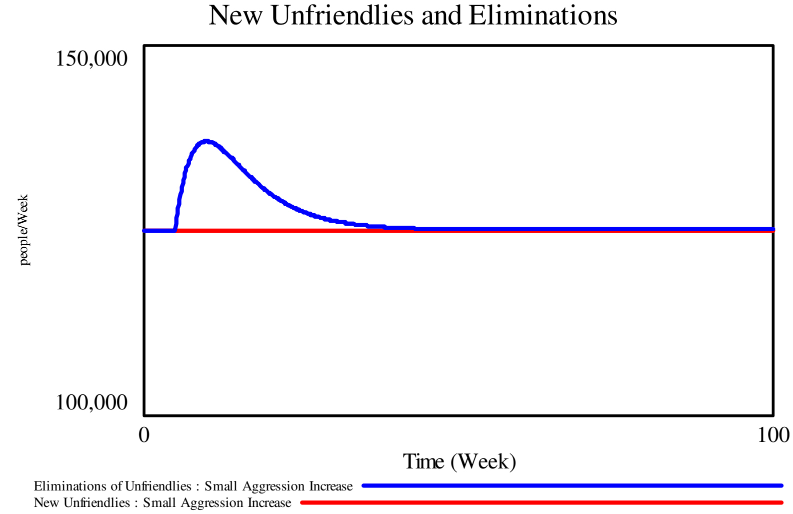
To use the model for simulation, assumptions are made about the maximum rate and the preventable fraction of new unfriendlies, the fractional rate of elimination of unfriendlies, the time delays for perceiving eliminations, and the characteristics of the nonlinear effects of aggression on eliminations and on the prevention fraction. Our starting assumptions are that under the most averse conditions the maximum fraction of new unfriendlies is 5% per week and that under normal conditions 75% of these are prevented. For a given level of aggression, unfriendlies are eliminated at a constant fractional rate such that for maximum aggression one sixth of the unfriendlies are eliminated each week. We begin the simulations with a population of 1 million unfriendlies and 10 million in the at-risk population and set the starting level of aggression at 25% of the maximum. Under these assumptions, the level of aggression is low enough that it does not stimulate any excess new unfriendlies; that is, the Prevention Fraction is at a relatively high level. These conditions describe a balanced situation that might be similar to the local conditions in a country experiencing an ongoing insurgency but before any ambitious attempt has been made to intervene.

We will use the model to explore four scenarios (Status Quo, Small Aggression Increase, Moderate Aggression Increase, and Large Aggression Increase). Figure 2 presents simulation results showing the patterns of behavior over a period of 100 weeks for three key variables (*Unfriendlies,* and on the same graph *New Unfriendlies* and *Eliminations of Unfriendlies*) for the first two scenarios. In all of the scenarios, the model has been initialized in a dynamic equilibrium or steady state in which there are about 125,000 *Eliminations of Unfriendlies* and an equal number of *New Unfriendlies*, so the quantity of *Unfriendlies* is constant at its initial value of 1 million. In the Status Quo scenario, no change to the Aggression Level is introduced, so the system remains in dynamic equilibrium, and the graph lines remain flat. This scenario provides a convenient baseline for comparison. The other scenarios test the response of the system to an increase in aggression, as might take place if the stakeholder chooses to attempt to accelerate the elimination of unfriendlies. In each of these other scenarios, a new target aggression level is set in week 5 and the Aggression Level adjusts over a several week period to reach the new target and then remain there for the duration of the simulation.

In the Small Aggression Increase Scenario, the aggression level is set to increase from its initial value of 25% to a new target level of 40%. As shown in Figure 2, the results appear favorable to the stakeholder. The higher level of aggression causes the rate of eliminations to grow significantly, exceeding the rate at which *New Unfriendlies* are affiliated, and the result is that the total quantity of *Unfriendlies* decreases and remains at a new, lower level for the duration of the simulation. Because the increased rate of eliminations and the associated violence are still within the levels tolerated by the population, the higher level of aggression has no effect on the *New Unfriendlies* rate, and the graph of *New Unfriendlies* remains flat at its constant initial value. The system has found a new dynamic equilibrium, this time with a smaller population of *Unfriendlies*, a situation which is presumably better for the stakeholder.

Figure 2: Status Quo and Response to a Small Aggression Increase

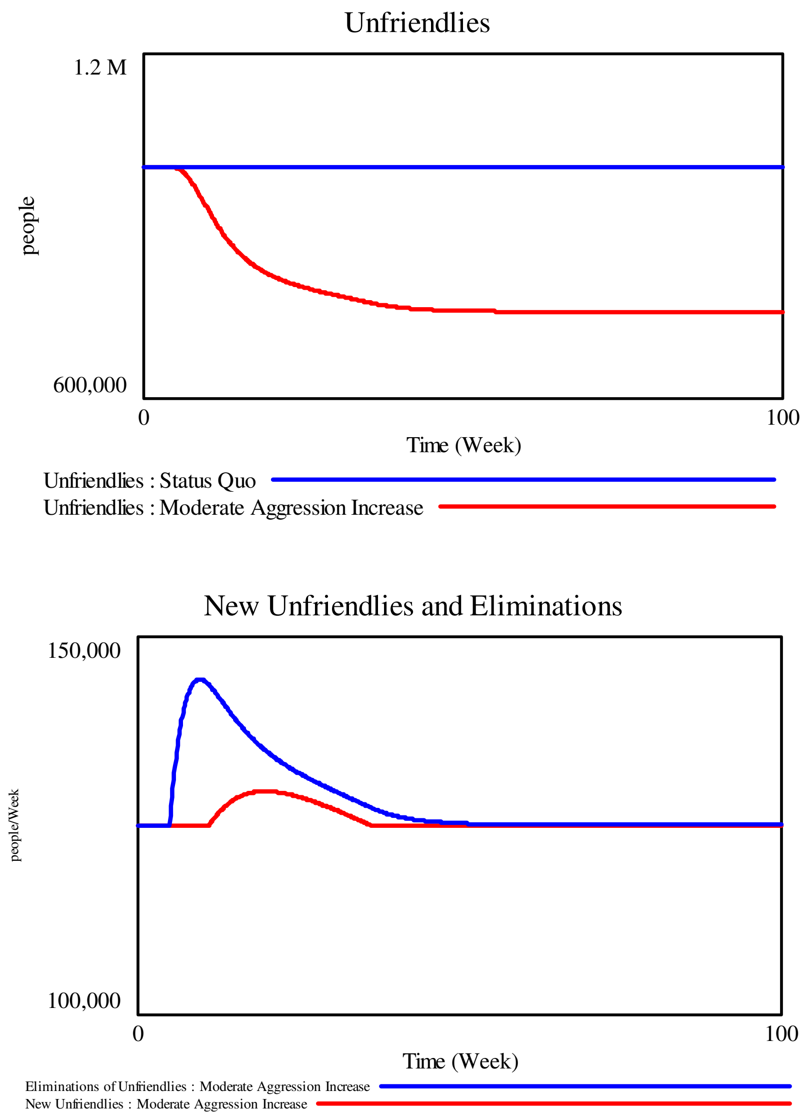




These simulation results display two important features that show how the system's dynamics relate to its structure. First, the level of a stock, in this case the stock of *Unfriendlies*, decreases when the sum of its outflows exceeds the sum of its inflows and conversely increases when the inflows exceed the outflows. We see in the second panel of Figure 2 that the rate of *Eliminations of Unfriendlies* (the outflow) exceeds the rate of *New Unfriendlies* (the inflow) for a period of time so in the first panel we see the stock of *Unfriendlies* decreasing during exactly this period. Second, the system reaches a steady-state equilibrium in which the inflows equal the outflows. The structure responsible for achieving this steady state is the balancing feedback loop, labeled "B" in Figure 1 that governs the rate of eliminations. The rate of eliminations increases at first from week 5 to week 10 as the level of aggression gradually adjusts to it higher target level and then reaches a peak (even before the new level of aggression reaches its peak, not shown) because the higher rate of eliminations begins to deplete the *Unfriendlies*. As the stock of *Unfriendlies* declines, the rate of eliminations also declines (for example because with fewer adversaries it is more difficult to locate and eliminate them), thus causing the stock to decline at a decreasing rate until eliminations equal the rate of *New Unfriendlies*. This balance occurs when the inflows and outflows are at the same rates as in the initial equilibrium because there has been no change in the inflow rate of *New Unfriendlies*. However, because there was a period during which eliminations were greater than the rate of *New Unfriendlies*, the stock of *Unfriendlies* has declined, and the steady state equilibrium now has a smaller number of *Unfriendlies*. The situation is better, but perhaps not good enough, so the stakeholder might consider a stronger increase in aggression.

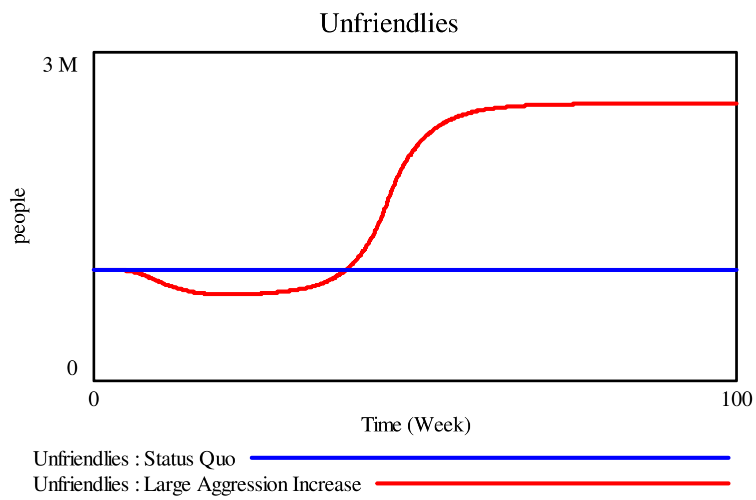
In the next scenario, the Moderate Aggression Increase, the new target Aggression Level is set to 50%. The results, shown in Figure 3, are similar to those in the Small Aggression scenario but with two meaningful differences. First, the new steady state equilibrium level of *Unfriendlies* is even lower (750 thousand for the Moderate scenario versus 833 thousand for the Small scenario), so the situation is arguably even better for the stakeholder. Second, the pattern of *New Unfriendlies* begins to reveal an important effect of the increased level of aggression. The higher rate of eliminations increases *Perceived Eliminations* and thus *Perceived Aggression* to a level above the tolerable threshold, so the *Prevention Fraction* is reduced, and, as the second panel of Figure 3 shows, the rate of *New Unfriendlies* increases above its beginning rate as a consequence. However, the rate of *New Unfriendlies* eventually declines back towards its original rate. As the stock of *Unfriendlies* is depleted by the successful higher aggression, the rate of eliminations eventually declines because there are fewer remaining *Unfriendlies* to eliminate. After some time for perceptions to adjust to the once again lower rates of eliminations, the *Prevention Fraction* eventually recovers to its beginning value, causing the rate of *New Unfriendlies* to return to its beginning value as well. Once again, we see a situation that is better, but perhaps not good enough, so the stakeholder might consider an even stronger increase in aggression.

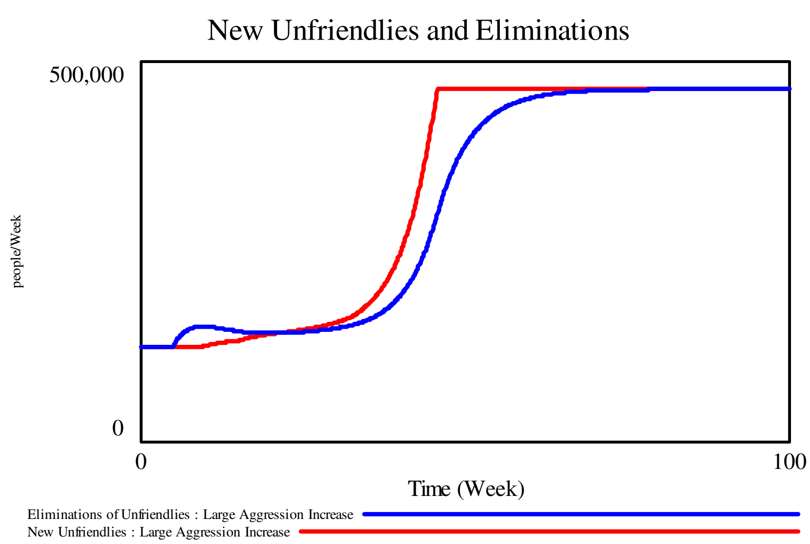
Figure 3: Status Quo and Response to a Moderate Aggression Increase



In our next scenario, Large Aggression Increase, the new target Aggression Level is set to 60%. The results, shown in Figure 4, now show a rather different pattern of behavior and indeed appear to make the stakeholder worse off. The higher level of aggression causes the rate of eliminations to grow, to even higher rates than before, and consequently the stock of *Unfriendlies* begins to decline. However, in contrast to the previous scenarios, the higher rate of aggression is beyond the threshold of tolerance and now has a strong downward effect on the *Prevention Fraction*, so the rate of *New Unfriendlies* begins to grow. Once the rate of *New Unfriendlies* exceeds the rate of eliminations, the stock of *Unfriendlies* begins to grow, and the system is propelled to a qualitatively different steady state, characterized by a sustained larger quantity of *Unfriendlies* as well as sustained higher rates of *Eliminations of Unfriendlies* and *New Unfriendlies.* The high level of aggression has trapped the system in a vicious treadmill of more eliminations only to be thwarted by more *New Unfriendlies* and with the end result that there are always more *Unfriendlies* than before. The scenario appears particularly unattractive to the stakeholder.

Figure 4: Status Quo and Response to a Large Aggression Increase





Three important additional features that show how the system's dynamics relate to its structure are apparent in this scenario. First, the reinforcing feedback loop, labeled "R" in Figure 1, plays an important role in this scenario. Given a small increase in the stock of *Unfriendlies* (as occurs in the first moment that *New Unfriendlies* exceed *Eliminations of Unfriendlies*), *Eliminations of Unfriendlies* increase as well since there are more *Unfriendlies* to eliminate. The level of *Perceived Eliminations* begins to rise as well, increasing *Perceived Aggression*, causing the *Prevention Fraction* to decrease, thus pushing *New Unfriendlies* to a higher rate which in turn causes the stock of *Unfriendlies* to increase still further. The vicious cycle continues, and left unchecked the reinforcing loop drives the system to a different, in this case less desirable, region of behavior. The cycle ends only when the *Prevention Fraction* has been squeezed down to its minimum level, so the simulation results show a steady state at which the *New Unfriendlies* rate can grow no further. Once this inflow has reached its maximum, the balancing loop acts to raise the elimination rate high enough to balance the high inflow, and the stock of *Unfriendlies* stops growing.

The second feature of the dynamics in this scenario is a pattern of behavior over time that can be described as better before worse. A dynamic pattern such as this could be particularly vexing to the military planner or operators actually experiencing the dynamics. The very first response of the system after the intervention to increase aggression is that the situation improves: eliminations increase and the stock of *Unfriendlies* declines, presumably as was the intent of the intervention. Yet, after a period of time, the situation reverses and as we have seen ends up worse than it started. The better before worse pattern results in part from the presence of a time delay in the reinforcing loop. The delay in this case is represented by the *Time to Notice*. There are two effects of the increase in aggression. One is the rather immediate increase in the rate of eliminations, which works to reduce the stock of *Unfriendlies*. The other effect is a reduction in the *Prevention Fraction* causing a higher rate of *New Unfriendlies*. This effect works to increase the stock of *Unfriendlies*, but it manifests itself only after a time delay. Situations that display better before worse patterns of behavior are especially problematic for learning, because our traditional analytical tools and mental models are poorly suited to make inferences about cause and effect in these conditions (Sterman, 1994).

A third characteristic of the dynamics in this scenario is closely related to the better before worse pattern of behavior. This overall pattern is caused by a shift in loop dominance that occurs endogenously in the course of the simulation (Richardson, 1984). In the first few weeks after the intervention, the balancing loop dominates the behavior of the system as the immediate effect of aggression on eliminations outweighs the effect on preventions and we observe a decline in the stock of *Unfriendlies*. But as *Perceived Eliminations* and thus *Perceived Aggression* move further and further beyond the tolerable level, the reinforcing loop gains in strength because the *Prevention Fraction* decreases. When the reinforcing loop becomes strong enough to overtake the balancing loop, there is a shift in loop dominance, and then the stock of *Unfriendlies* grows at an increasing rate. When the reinforcing loop reaches the limits imposed by the minimum *Prevention Fraction*, the balancing loop once again takes over to bring the system back to a dynamic equilibrium. Shifts in loop dominance are possible in nonlinear systems (Richardson, 1984). The key nonlinearity in this situation is the nonlinear effect that aggression has on the prevention fraction: small increases in aggression below the threshold have no effect, but larger increases have increasingly large effects.

Taken together, the three increased aggression scenarios display another characteristic of some dynamically complex problems that severely limits the usefulness of many traditional analytical tools, especially those based on linear models of cause and effect. Small changes in an input, in this case the aggression level, can lead to profound differences in macro behavior. In the simulations shown so far, we have seen that increasing aggression to 50% results in a long term reduction in the stock of *Unfriendlies*, but an increase to 60% aggression results in an increase, an outcome in the opposite direction. Further analysis not shown here shows that under the simulation conditions used here, the tipping point that separates these two different modes of behavior is between 58% and 59% level of aggression. Thus, a small difference from below to above this critical threshold dramatically alters the behavior. Tipping points have been observed in models of the growth of infectious disease (Sterman, 2000), the spread of fads (Gladwell, 2000), the adoption of new products (Rogers, 1995), the management of product development processes (Repenning, Goncalves, & Black, 2001), the growth of terrorism (Choucri et al., 2006), the implementation of process improvement (Morrison, 2003), the development of new skills according to learning curves (Morrison, forthcoming), the response to a crisis situation (Rudolph & Repenning, 2002), and other social settings. Planning in situations prone to such dynamics is especially challenging, because increases in the use of a successful tactic may indeed lead to undesirable outcomes if they move the system beyond the tipping point. These settings also often lead to getting locked in to undesirable outcomes, the recovery from which would require passing the tipping point in the other direction.

Planning Implications

Developing, simulating, and analyzing small system dynamics models can help to build an informed understanding of how a real-world system's structure causes its behavior, an understanding that often leads to important insights and that can be used to formulate plans for moving towards desired outcomes (Lyneis, 1999). For example, several planning implications emerge from consideration of the lessons of our illustrative model of Unfriendly dynamics.

1. Moderate use of aggression may be more effective than heavy use of aggression: Moderately increased aggression has the apparent benefit of accelerating the elimination of unfriendlies and can lead to a sustainable decrease in the unfriendly population, and thus of the overall threat level. However, excessive aggression potentially alienates some of the general population increasing the likelihood that more new unfriendlies will occur, indeed so much so as to overwhelm the beneficial reductions and result in a net increase in the unfriendly population. Under this scenario, higher levels of aggression (e.g., greater troop strength and higher ongoing losses) would be needed just to contain the unfriendly population at a constant level that is higher than the level before the intervention. This undesirable behavior has a simple explanation based on the structure of the situation, an explanation that once given seems almost trivially obvious. However, in real planning situations, such unintended side effects can be quite surprising to the participants (Morecroft, 1984).

2. We are prone to underestimate the risks of increasing the use of aggression: The insidious nature of systems that are prone to tipping dynamics is that it is generally not easy to know when the system is approaching a tipping point. The stakeholder might be operating at a level of aggression that is dangerously close to the tipping point without knowing it. A small increase in aggression, that because it is small may seem to be of limited risk, might take the situation beyond the tipping point, propelling the system into an entirely different region of behavior. Because shifts in loop dominance fundamentally alter a system's dynamics, a small change may have disproportionately large consequences. Worse, because tipping points occur when reinforcing loops are dominant, once past the tipping point, the system will move rapidly beyond, so the option of gradually increase aggression until reaching the tipping point will be ineffective.

3. Short-term evaluations are likely to be incomplete and potentially misleading: The immediate result of an increase in aggression is a reduction in the number of Unfriendlies, but the effect on New Unfriendlies does not materialize for some time. In both the scenarios that lead to long-term improvement and those that later degenerate because of the undesirable side effects, the first indications will confirm that the increases in aggression are working as planned. Monitoring the number of eliminations or more difficultly the number of unfriendlies will potentially mislead the analyst because early signals will be encouraging and fail to distinguish the beginning of an improvement from the beginning of a disaster. The time delay for perception and behavior change that manifests as the undesirable increase in *New Unfriendlies* means that time horizons for assessment of results must be much longer than what is needed to evaluate the direct effects of the aggressive activities. Moreover, yielding to the temptation to increase aggression if recent increases have shown encouraging results might insidiously push the system beyond the tipping point and into the vicious spiral of more and more eliminations.

4. Tactics to reduce the strength of the reinforcing loop will be beneficial. Identifying the feedback loop responsible for undesirable system behavior can focus the search for better options on interventions that will affect the implicated loop. In the scenarios that lead to undesirable outcomes, the reinforcing loop (See Figure 1) dominates, driving the system to a state with increased numbers of *Unfriendlies*. Intervention options that dramatically weaken this reinforcing loop may prevent the undesirable tipping dynamics, and even options that moderately weaken the loop can be beneficial in one of two ways. First, they can shift the tipping point, so that for example it becomes possible to use higher levels of aggression, and thus accomplish more eliminations, without triggering the excessive increase in *New Unfriendlies*. Second, although of only limited merit, they can also reduce the steady state quantity of *Unfriendlies* if the system does move beyond the tipping point. Options that weaken any link in the loop will weaken the loop. For example, if using media campaigns to sway public opinion mitigates the effect of increased aggression on the Perceived Aggression, such media campaigns would weaken the loop.

5. Intervention options that work to reduce the inflow of new unfriendlies are needed. Interventions aimed solely at eliminations cannot eradicate the Unfiendlies in this system where New Unfriendlies are continually flowing in. Options aimed at increasing the rate of eliminations are inherently self-limiting. In the system modeled here, these are inescapable conclusions that rest not on quantitative parameters of the model but only on the basic stock and flow structure. Aggression aimed at eliminating unfriendlies acts by increasing the rate of outflow from the stock. An effective suite of interventions must also include means to reduce the inflow of New Unfriendlies, such as by generating more favorable public opinion.

6. Over the long-term, intelligence efforts to better define the magnitude of "side effects" should be undertaken. The preceding five planning implications stem from the stock and flow and feedback structure shown in Figure 1 and are not based on any particular choice of quantitative parameters. However, quantitative outcomes shown in the simulations are of course dependent on quantitative inputs. There is considerable uncertainty about the values of some of these parameters, pointing to important gaps in our knowledge. Future intelligence gathering and data collection efforts should be focused on bolstering our understanding of the quantitative nature of some of these key relationships. For example, while we can be relatively sure that the Effect of Aggression on Prevention is a downward sloping function, we need to know much more to accurately specify this nonlinear relationship.

Towards Informed Use of Feedback Models in Military Planning

Model users should bear in mind that the intended purpose of a model has an important influence on the process of building it, the choice of model boundary (what to include), and the resulting model itself. Experts in the system dynamics method frequently admonish novice modelers and model consumers alike to be wary of attempts to model an entire social or economic system rather than a problem (Sterman, 1988). One main reason is that the usefulness of the model lies in its ability to simplify the system, putting it in a form that enables greater comprehensibility. The intended use of most system dynamics models is not that of a "black box answer machine" in which an uninformed user or technician enters some inputs and relies on the model to generate an answer. Some models developed in other disciplines, and indeed even a small subset of system dynamics models, are used in this matter. But most system dynamics models are intended to be used as counterparts to active and engaged thinking by the planners rather than as a substitute for human judgment (Morecroft, 1984). We offer some suggestions for ways in which military planners and others might incorporate the use of system dynamics models into the ongoing practice of military planning.

Use Feedback Models for "What-if" Analyses in the Evaluation of Planning Options.

When considering an intervention in a social or military setting, one of the most accessible ways to use a system dynamics model is as a laboratory for experimenting with various planning options to explore how their effects might play out over time. Even a simple concept model, such as the example presented here, can be usefully employed as a tool to simulate the behavior of the simplified system in response to actions by the stakeholder or others. A typical setting is one in which the planners have a defined set of options to compare, such as diplomatic, informational, military, and economic actions to intervene in a situation with apparently rising numbers of unfriendlies. To assess the merits of a particular option, the planner or other domain expert would describe the rationale for why each option might be expected to yield beneficial effects. The process of describing the underlying rationale provides a tool to identify the causal logic, which can then be translated to a specified test scenario defining conditions for simulating the model. Many intervention options will have multiple effects that should be represented. The test scenario might require setting initial conditions, choosing various parameters, or using exogenous changes during the course of the simulation to represent the various effects of the intervention. Simulating to model under conditions defined to represent the various intervention options will then allow for a comparison of results. Skillful interpretation of these results can then help to make more informed planning choices from among the defined set of options.

Use Feedback Models for Insights into System Behavior and for Building Critical Thinking Skills. The use of feedback models as described above for what-if analyses is a useful first step, but the potential contribution of feedback models is far greater. However, tapping into this greater potential requires a different kind of relationship between the model user and the model, one that is perhaps different from the way many military planners are accustomed to using models today. The use of a model for what-if analysis evokes the image of using a model as one step in a process that is a series of steps in which using the model to test or evaluate the merits of a proposed solution is one step. A model used in this manner can help to either support or reject a contemplated intervention. A more powerful use of feedback models evokes the image of using a model in parallel with the critical and engaged thinking of the model users as they consider how to address the problem situation. In this image, the emphasis shifts from using a model as a tool developed by other people towards examining the problem through a feedback lens informed by modeling that enriches the planners' understanding of the situation. The planners are actively engaged in iterations through which people make explicit their knowledge of the domain of interest, this knowledge is explicitly represented in formal models, simulation tools are used to reliably compute the dynamic consequences of their assumptions, and the resulting simulations help to identify both ways to make the formal model better as well as ways to think better about the problem. Modeling used in this manner can help to evaluate possible interventions as before, but more importantly, is likely to help generate new possibilities. Planners will not only develop better formal models and better mental models of the particular problems studied but will also develop better skills in critically thinking about dynamically complex social settings.

Use Feedback Models to Guide Long-term Programs that Develop Our Knowledge of Dynamically Complex Social Systems. As the nature of threats to our national security and the type of adversaries we face has changed, our perspectives have broadened, the range of intervention options has grown, and the consequences of our actions have become more complex. But these changes have occurred more rapidly than our ability to understand the more complicated interacting web of political, military, economic, social, informational and infrastructural systems we face. The process of explicitly modeling these systems exposes the gap between our current knowledge of these systems and the level of understanding we need to consistently develop effective policies and make appropriate planning decisions. Attempts to explicitly model these systems are often thwarted by our collective lack of adequate understanding of how they work. Some view this as a reason to avoid formal modeling, but this view is inherently self-limiting. Instead, we need to recognize the gaps in what we know and take concerted action to close these gaps. When modeling efforts expose gaps in our knowledge, we often must make choices in the moment based on our limited knowledge. But we should also acknowledge the need for better understanding and proactively chart a course of action to close the gaps. Controlled experimentation is rarely possible in social systems. Learning from our actions is complicated by the difficulty of gathering downstream information (e.g., about public sentiment towards the US), delays between cause and effect (e.g., what and when are the effects of distributing informational pamphlets?) and nonlinear response to our actions (e.g., what are the thresholds for tolerance of aggression?). Feedback models have an important role to play as a roadmap to building this more nuanced understanding as they help shape the approach to exploring and learning about these inherently complicated systems.

Conclusion

We have presented a simple example to illustrate some key aspects of the system dynamics modeling approach using a military planning setting. The example highlights basic structural features found in system dynamics models including stocks and flows, balancing and reinforcing feedback loops, nonlinearities, and time delays. We used the example to show how structure causes behavior and identified several characteristic aspects of the behavior of dynamically complex systems, such as the basic dynamics of stocks and flows, dynamic equilibria, paradoxical patterns of behavior over time (e.g., better before worse), shifts in loop dominance, and tipping points.

Inasmuch as there are many dynamically complex military planning situations, there should be a useful role for the system dynamics approach in the suite of planning and policy making tools. System dynamics has already made some important contributions in areas identified above. There is still much to be learned about the dynamic interrelationships among allied interests, local state regimes and populations, and unfriendly groups that may be threats to national security in order to build a better understanding of the nuances of these complex situations. There is also much to be learned about the best ways to effectively integrate the use of system dynamics models in order to improve the practice of military planning. System dynamics models could also be useful to develop frameworks for coordinating strategic activities that span governmental departments and employ a range of interventions, giving a more realistic picture of possible outcomes or helping to identify potential risks, especially when various interventions can be mutually reinforcing.

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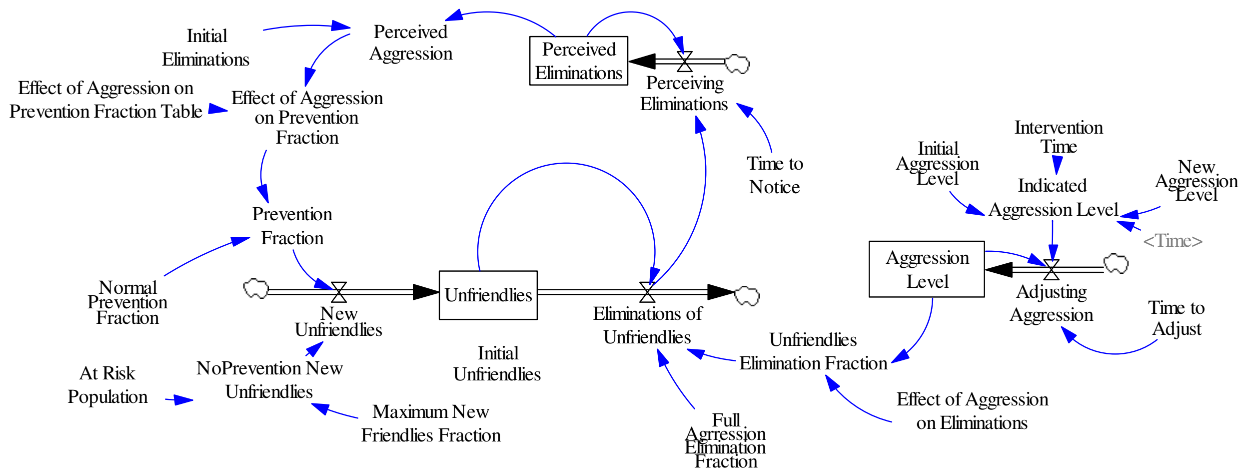
APPENDIX

Diagram of Complete Model Structure



Model Equations

Adjusting Aggression=(Indicated Aggression Level-Aggression Level)/Time to Adjust
Units: Dmnl/Week

Aggression Level= INTEG (Adjusting Aggression, Indicated Aggression Level)
Units: Dmnl

At Risk Population=1e+007 Units: people

Avg Time to Elimination=1/Full Agrression Elimination Fraction
Units: Week

Effect of Aggresion on Prevention Fraction Table([(0.75,0.1)-(1.5,1)],(0.75,1),(0.8,1),(0.85,1),(0.9,1),(0.95,1),(1,1),(1.05,1),(1.1,0.98),(1.15,0.9),(1.2,0.78),(1.25,0.66),(1.3,0.54),(1.35,0.42),(1.4,0.3),(1.45,0.2),(1.5,0.1))
Units: Dmnl

Effect of Aggression on Eliminations
([(0,0)(1,1.5)],(0,0),(0.1,0.4),(0.15,0.6),(0.2,0.7),(0.25,0.75),(0.3,0.8),(0.4,0.9),(0.5,1),(0.6,1.1),(0.7,1.2),(0.75,1.25),(0.8,1.3),(0.9,1.37),(1,1.4))
Units: Dmnl

Effect of Aggression on Prevention Fraction=Effect of Aggresion on Prevention Fraction Table(Perceived Aggression)
Units: Dmnl

Eliminations of Unfriendlies=Unfriendlies Elimination Fraction*Full Agrression Elimination Fraction*Unfriendlies
Units: people/Week

FINAL TIME = 100
Units: Week

Full Agrression Elimination Fraction= INITIAL((Maximum New Friendlies Fraction*(1-Normal Prevention Fraction)*At Risk Population)/(Unfriendlies Elimination Fraction*Initial Unfriendlies))
Units: 1/Week

Indicated Aggression Level=IF THEN ELSE(Time<Intervention Time, Initial Aggression Level, New Aggression Level)
Units: Dmnl

Initial Aggression Level=0.25
Units: Dmnl

Initial Eliminations= INITIAL(Eliminations of Unfriendlies)
Units: people/Week

INITIAL TIME = 0
Units: Week

Initial Unfriendlies=1e+006
Units: people

Intervention Time=5
Units: Week

Maximum New Friendlies Fraction=0.05
Units: 1/Week

New Aggression Level=0.25
Units: Dmnl

New Unfriendlies=(1-Prevention Fraction)*NoPrevention New Unfriendlies
Units: people/Week

NoPrevention New Unfriendlies=Maximum New Friendlies Fraction*At Risk Population
Units: people/Week
Normal Prevention Fraction=0.75
Units: Dmnl

Perceived Aggression=Perceived Eliminations/Initial Eliminations
Units: Dmnl

Perceived Eliminations= INTEG (Perceiving Eliminations,Initial Eliminations)
Units: people/Week

Perceiving Eliminations=(Eliminations of Unfriendlies-Perceived Eliminations)/Time to Notice
Units: people/Week/Week

Prevention Fraction=Effect of Aggression on Prevention Fraction*Normal Prevention Fraction
Units: Dmnl

SAVEPER = TIME STEP
Units: Week [0,?]

TIME STEP = 0.125
Units: Week [0,?]

Time to Adjust=4
Units: Week

Time to Notice=12
Units: Week

Unfriendlies= INTEG (+New Unfriendlies-Eliminations of Unfriendlies, Initial Unfriendlies)
Units: people

Unfriendlies Elimination Fraction=Effect of Aggression on Eliminations(Aggression Level)
Units: Dmnl

Diagrams of Non-Linear Relations