Working with "living" models: Emergent methodological contributions from modeling for critical infrastructure protection

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Abstract

Critical infrastructures are increasingly automated and interdependent, subject to possibly cascading vulnerabilities due to equipment failures, natural disasters, and terrorist attacks. The government seeks to ensure that disruptions are infrequent, brief, manageable, and cause the least harm possible. The system dynamics (SD) approach is particularly promising as a way to understand these complex systems, interactions, and issues. Problems in critical infrastructure protection are being investigated with a collection of SD models developed expressly for these concerns, including agriculture models. This paper discusses the technical and social modeling context that makes this SD modeling effort seem uncommon. It involves a modular approach, a model-reassembling technology, a formal process for testing and evaluation, and a social process for managing the development and use of "living" models.

Keywords: "Living" models, critical infrastructure protection, agriculture modeling

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Introduction

This work is part of a larger effort to use system dynamics (SD) modeling to study critical infrastructures and their interdependencies in order to identify vulnerabilities and mitigate disruptions caused by equipment failures, human errors, natural disasters, diseases, and terrorist attacks. The technical and social modeling context includes a modular approach for building and maintaining the models. Modules can be developed, in coordination but independently, by different modelers at different sites. A technology specially developed for this work quickly assembles the modules to create an executable composite model. This ongoing, multimodeler, multiproblem, modular approach to working with “living” models calls for special considerations of the social processes for managing the development and use of models.

Critical infrastructure protection (CIP)

It is the policy of the United States to assure the continuity and viability of critical infrastructures and guard against operational disruptions. This effort protects the people, economy, human and government services, and national security. It also ensures that disruptions are infrequent, of minimal duration, manageable, and cause the least harm possible. This policy was established prior to the events of September 11, 2001 (PDD-63, 1998), and it enjoys bipartisan support (EO/CIP, 2001).

The term “critical infrastructure” means systems and assets so vital that their incapacity or destruction would have a significant debilitating impact on national security, the economy, public health and safety, or any combination of those aspects of U.S. life (USA PATRIOT, 2001). An open and technologically complex society includes a wide array of critical infrastructures. Many of them have historically been physically and logically separate systems that had little interdependence. As a result of advances in information technology and the necessity of improved efficiency, however, these infrastructures have become increasingly automated and interdependent. These same advances have created new and possibly cascading vulnerabilities (Rinaldi *et al.*, 2001).

Critical infrastructures have also become potential terrorist targets. Such nontraditional attacks on infrastructure and information systems may significantly undermine the country. Thus, the Homeland Security Act (HSA, 2002) formed the U.S. Department of Homeland Security (DHS) to, among other things, leverage the nation’s scientific and technological capabilities in order to address homeland security vulnerabilities and possible threats. It charged the Department with the responsibility of evaluating vulnerabilities and ensuring that steps are implemented to protect the high-risk elements of critical infrastructures, including agriculture, banking and finance, chemical and defense industries, energy, food and water, health and emergency services, postal and shipping services, transportation, and telecommunications.

A key research center involved in this effort is the National Infrastructure Simulation and Analysis Center (NISAC). NISAC is a repository for several large-scale, high-resolution simulation systems.[5] Related to this effort is the Critical Infrastructure Protection Decision

[5] http://www.sandia.gov/nisac/

Support System (CIPDSS) Project. CIPDSS has the charter to model all critical infrastructures, key asset categories, and infrastructure interdependencies. In addition, CIPDSS was created to provide fast, order-of-magnitude assessments of the potential impacts that could result from disruptions (Bush *et al.*, 2005). NISAC uses SD as one of several modeling capabilities (see Ellison *et al.* 2007; Kelic *et al.* 2007). CIPDSS used SD predominantly to analyze a variety of threat scenarios, including the introduction of infectious diseases (Powell *et al.*, 2005), loss of multiple telecommunications assets (LeClaire and O’Reilly, 2005), and accidental release of toxic industrial chemicals (Samsa *et al.*, 2007), among others.

Computer modeling and simulation technology is a cost-effective means to explore CIP options; it enables uncertainty quantification and sensitivity analysis and provides a test bed for evaluating the effectiveness of alternative prevention, response, and recovery actions before their actual implementation. This technology is crucial, since additional security should enable, and not unnecessarily burden, the operations of critical infrastructures. The latter would undermine the overall economic security of the United States in a global economy. Such multisector, multiscenario models also support decisions regarding tradeoffs between protective investments in the various critical infrastructure sectors, given the overall budget limitations for such investments. A holistic and coordinated modeling perspective is considered critical in the White House Directive on Critical Infrastructure Identification, Prioritization and Protection (HSPD-7, 2003).

With respect to the agriculture infrastructure, HSPD-9 (2004) mandates sector vulnerability assessments to defend the agriculture and food systems against terrorist attacks, major disasters, and other emergencies. CIPDSS agricultural analyses have addressed responses to disruptions of considerable magnitude in the beef and dairy economies (BSE Report, 2003; Conrad, 2004) and the impacts that have resulted from the introduction of windborne soybean rust in the United States following Hurricane Katrina (Soybean Rust Reports, 2005; Zagonel *et al.,* 2005; DeLand *et al.,* 2005). In assessing the sustainability of this research program, particularly in using the SD approach, it is important to consider the special nature of the modeling context involved in these efforts.

Technical and social modeling context

To our knowledge, modeling practice seldom resembles the CIP efforts just discussed. We know of a few exceptions: the Limits to Growth studies (Meadows *et al.*, 1972, 1992), Pugh-Roberts Associates’ work in business strategy and project dynamics (e.g., Lyneis, 1980; Stephens *et al.*, 2005), and Forrester’s National Model (Forrester, 1989). All of these appear to draw on “living” models, meaning models that can be reused, whether refined to revisit the same issues with more confidence or adapted to address new questions. They tend to be large modeling projects involving multiple modelers. This work must be effectively coordinated, properly documented, systematically tested, and objectively evaluated for validity. Ideally, it is supported by technology that facilitates and enables reuse of, refinements to, and links between models. Such work must use a social process for modeling that is conducive to creating an efficient multimodeler development environment. The CIPDSS development effort also faced a geographically dispersed task force with some degree of turnover. Furthermore, models developed under CIPDSS focus on one infrastructure at a time, and scenario analyses involve multiple interacting infrastructures.

Two hypothetical situations illustrate this need in general:

- **Firm A** is working on a large model on a tight schedule. The senior modeler has developed a small proof-of-concept model to test the dynamic hypothesis. The larger conceptual model contains several sectors with feedbacks existing between sectors, as specified in a subsystem diagram. Previous work done by the firm contains core pieces of weathered formulation that will be useful in building this new model. The proof-of-concept model contains, in high-level form, all of the basic elements of the subsystems and important feedback. To make fast progress and meet the project deadline, junior modelers have been assigned to formulate the subsystems and conduct some preliminary tests to make sure that they function as expected. In 3 days, the modeling team will reconvene to combine the sector models, at which point more tests will be done with the whole model. It is likely that further subsystem development will ensue, and new merging will be required. All of the development and testing need to be done quickly to meet the deliverable.

- **Firm B** had a very successful experience using a large model to address a common problem for a particular type of business. As a result of its success, several companies involved in this economic activity became interested in using this model to look at similar issues, but by drawing on their specific data. Careful inspection has revealed that the adaptation of the original model to different businesses will require more work than simply parameterization and calibration of a generic model. The variation across businesses in their practices, at least for some sectors of the model, is sufficient to justify a relatively different conceptualization and formulation of the subsystems. In the first effort, an experienced, articulate modeler interacted with all of the important stakeholders. She was able to obtain lots of good information from them and get everyone really excited about the project. Now she needs to bring a group of newly hired junior modelers up to speed to handle the volume of work required to tailor the model to different clients.

What technologies and modeling approaches should be used to enable these firms to proceed quickly and effectively? In both cases, the objective is to make the best use of the firm's staff expertise and institutional knowledge while efficiently meeting the deliverables and building client confidence. If modular modeling is to be supported, what form should the models and documentation take to facilitate the understanding of, refinements to, and reuse of existing models? If work on large projects under severe time constraints is required, how can model pieces readily be assembled into a whole model and then taken apart again? The experience, strengths, and weaknesses of the modelers will vary, yet model building, testing, and documentation should be consistent and clear across model subsystems and over the lifespan of the modeling efforts. This result will require a large degree of coordination and some uniformity in practice.

Little has been said about the technologies and social processes involved in effectively managing modeling projects spanning years of cumulative research and drawing upon living models. Lyneis's recent presentation (2006) on "Managing Large SD Modeling Projects" is one exception. On the basis of the Pugh-Roberts Associates (now PA Consulting) experience, he draws upon a number of valuable lessons:

- The typical project involves a modeling team and spans at least several months.
- Problems are "fuzzy," often with no clear reference mode of behavior; this aspect presents challenges to determining model boundary.
- Clients expect to be presented with a compelling case based on a robust and accurate model. They worry about the bottom line. Building the clients' confidence usually requires educating them in SD and the roles of models.
- Managing the project itself and the project team is difficult. The fuzzy scope makes allocating and controlling resources critical.

Lyneis warns of three important risks: modeling "the system" rather than a problem, losing the client, and overrunning the budget. He suggests these actions for a successful modeling team:

- Avoid simply adding modelers in order to "charge ahead" and meet the schedule.
- Avoid modeling "systems" (constructing large, detailed models with little impact); instead, build problem-focused models.
- Balance the need for the right process (modeling involving the clients, usually with small, insight-based models) and the right products (detailed, calibrated models that have a compelling logic).
- Carefully allocate work, manage schedule pressures and overtime, obtain information and data in a timely fashion, and minimize rework.

He adds that important, high-stake problems are found at the top levels of organizations. Detailed, complex models are needed to address these problems. These models employ a significant amount of data and require extensive analysis and testing. The downside of large models is the risk of the "black-box" syndrome for those not involved in building the model. The models are also expensive. It is more difficult for the modelers to understand model behaviors. There is greater chance of undiscovered errors. In order to avoid these pitfalls, Pugh Roberts developed a four-phased approach. It begins with a conceptual model, and then builds into a small, insight-based computer model. This is later developed into a detailed, calibrated model. The last phase involves implementation of model-based recommendations (see Lyneis, 1999).

Drawing upon their experience in software development, Thompson and Bush (2005) proposed the technological basis for modular program development for SD modeling. The technology would apply concepts such as scope definition, modularity, encapsulation, and modeling standards to create protocols that would support living models, promote reuse of formulations, and enable distributed development of models (Alexander, 1977; Gamma *et al.*, 1995; Holzner, 2006). The primary problem to be solved was that of variable identification and use in different models. To address this problem, we proposed and adopted a set of shared modeling conventions and standards that would support merging a set of files into a single file that could subsequently be simulated.

Here we discuss the tools and processes that we developed to enable us to find solutions to the problems we confronted in our CIP efforts. Our experience is organized around four main points:

1. A standards-based modular approach to modeling and documenting,
2. A model-assembling technology for merging modules,
3. A formal process to test and evaluate the models and generate confidence, and
4. A social process to support modular development.

The agriculture infrastructure

Background

We built an agriculture model to explore the propagating effects of large-scale disruptive events, such as animal and plant diseases. The initial version of the model contained three interconnected sectors — beef, dairy, and corn (Conrad, 2004). These three commodities are tightly coupled; almost 60 percent of the corn produced is used as animal feed. Together, they account for nearly 40 percent of the U.S. agricultural economy (see Figure 1).

<Figure_1_about_here>

This work built upon Meadow’s (1970) “hogs” model of commodity production cycles. The basic feedback structure, including interactions between the three commodities, is shown in Figure 2.

<Figure_2_about_here>

The prices of these commodities form the center of a pair of negative feedback loops that eliminate imbalances between demand and supply, thereby promoting efficient allocation of resources. These commodities are interdependent because corn is produced for animal feed, and the price of feed influences decisions regarding beef and dairy production rates, which, in turn, alter the corn consumption rate and influence corn prices. However, oscillations result from bounded decision making and producer delays in capacity acquisition.

We used the model to look at the effects of a pair of scenarios involving bovine spongiform encephalopathy (BSE) and foot-and-mouth disease (FMD) to assess the implications of containment and eradication policies. The simulations of a short-term decrease in demand for beef due to the BSE outbreak showed long-term repercussions in the beef and corn markets. Per Figure 3, in the case of the less dangerous but more contagious FMD disease, the simulations showed that “exempting” cow-and-calf operations from the existing depopulation policy would help stabilize beef prices, beef sales, and beef cattle populations without significantly increasing the risk of contagion.[6] Cow-and-calf operations are at the head of the supply chain for beef. The

[6] Cow-and-calf operations tend to be relatively isolated and far less prone to contagion than other operations further along the aging chain, which are far more exposed to unfamiliar animals in transportation, trading farms, feedlots,

impact to the beef economy can be minimized, and normalcy reestablished more quickly, to the extent that we can shield these operations from disruptions.

<Figure_3_about_here>

Model testing and evaluation

The initial model was examined extensively. The tests performed were conducted by both external and internal reviewers (Rasmussen and Becker, 2004; Agriculture Model Report, 2004), and followed SD guidelines for confidence building and model refinement (Forrester and Senge, 1980; Sterman, 2000).

Original beef production module

The critical delays in capacity acquisition result primarily from the production processes inherent in each of the commodities. For corn, this process involves planting, harvesting, storing, selling, and distributing. Also, corn is a seasonal crop, planted in the spring and harvested in the fall, with year-long dependencies on boundedly rational decisions that involve multiple factors (e.g., expected demand, carrying inventory, subsidies and price), resulting in an aggregate desired harvest, which is then subject to weather conditions and crop diseases. Similarly, in the production of beef and milk, there are aging processes associated with breeding and growing the cattle. Aging chains are used to capture the demographic structure of a population, its changes through time, and its responses to disruptive events. The original beef production module used the aging chain represented in Figure 4 (see also supplemental file "N-Ag-Bf-Pr-Original.mdl").[7]

<Figure_4_about_here>

Related and ongoing applications

The production module for the beef commodity was revised with marginal additional effort and is captured in file "N-Ag-Bf-Pr.mdl." Both the original and the revised modules are operational and can be used interchangeably with the rest of the modules.[8]

By expanding and refining the original modules, we can explore a variety of agricultural disruptions, such as a sudden change in demand for agricultural products, a food contamination incident, use of commodity crops for energy production, significant crop losses due to disease or drought, loss of exports (e.g., that experienced by the United States when BSE was detected in Washington State), and widespread animal disease (e.g., bird flu), and many other threat

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and packing plants. Underlying the notion of exempting cow-and-calf operations from the existing depopulation policy is the idea of making these operations a policy priority through temporary insulation and special sanitary measures, in an attempt to avoid stamping out of the disease by depopulation in these maternities.

[7] The reader may ignore, for now, the variable prefixes and color coding used in the diagram. They serve to inform the model assembling process, as is discussed later in the paper (see also Thompson and Bush, 2005; Powell *et al.*, 2006).

[8] The supplemental file "Beef Model.mdl" includes all of the beef modules (but not dairy or corn).

scenarios. Preliminary model analysis using a single-disruption scenario has shown promise in helping government agencies formulate improved policies for responding to major disruptive events.

Emergent methodological contributions

The agriculture model has five sectors per commodity: production, inventory, market, willingness to supply, and willingness to demand. The aging chain used as an illustration is the stock-and-flow structure of the beef production sector. A full disclosure of the beef model unfolds into six components, one for each sector and one for the commodity as a whole (see supplemental file). For three commodities, there are 19 components (six per commodity plus one for the interactions among them); for six there are at least 37 components.

Agriculture is one of many critical infrastructures. The Congressional Research Service states that the meaning of critical infrastructures in the public policy context has been evolving and is still open to debate (CRS, 2004). Table 1 illustrates how this number changed from six infrastructures in 1983 to more than 20 today.

<Table_1_about_here>

On the basis of present experience and a conservative assumption that the average infrastructure can be represented with 10 sectors, it would take a minimum of 200+ sectors to capture all of the critical infrastructures. Moreover, for different purposes and problems, more than one sector representation may be needed for the same infrastructure component. Consequently, to be efficient, modeling teams must consider guidelines carefully to determine the breadth and depth requirements for SD infrastructure models (Becker *et al.*, 2004).

According to the National Infrastructure Protection Plan (NIPP, 2006), properly maintaining useful models, databases, simulations, and other tools involves long-term support, coordination, and resource commitments. A modular approach to developing, documenting, and testing models seems a reasonable strategy for effective use of resources.

Modular approach to standardized modeling and documentation

Modular approaches to system design and development are well established in software and systems engineering. In SD, from a technical perspective, a modular approach allows the modeler to formulate small, testable modules. Thoughtful delineation of module interfaces allows modules to be “extended” or interchanged to provide an appropriate level of abstraction for different analyses.

We have illustrated what a module would look like and how expansions and refinements can be used. We feel that two other elements are useful to complement this documentation. The first is a summary that captures core information about a given module (illustrated in Appendix 1). The second is a subsystem diagram to show how this module relates to other modules or models (illustrated in Appendix 2).

Model-assembling technology for merging modules

In order to use either one of the two modules with other modules and/or models, we need a model-assembling technology. Ideally, SD modeling environments (e.g., Vensim™) would enable models to be merged without cumbersome cutting and pasting. But since this is not the case, a “Conductor” tool was developed to achieve this result for the CIPDSS Project models. For the tool to work, the models must meet certain standards and follow certain conventions. The variables in the model must be linked to their specific modules; the tool performs and checks the links, relying on the standardized variable naming conventions (the prefixes preceding the variable names in the diagrams). The color conventions capture such things as variables that are exchanged between modules. For example, the red “desired breeding stock” variable is imported from the Willingness to Supply Module, whereas the blue “slaughtering beef cattle” variable is exported to the Inventory Module. There have been several iterations in the development of the Conductor. At the Nijmegen Conference, Powell *et al.* (2006) demonstrated an earlier version.

Decomposing large problems into interacting modules is a powerful software development paradigm. As applied to SD modeling, we believe it can make a significant contribution, particularly in the context of living models. The many benefits of a modular approach to modeling include improved maintainability of formulations and documentation, possibility of asynchronous model progress, and the use of shared protocols that tend to induce best practices and sustain model quality.

Modular testing and evaluation — accumulating confidence

A related effort is underway to reorganize the tests to build confidence in SD models (Zagonel and Corbet, 2006). The idea is to produce a testing framework that specifies tests targeted to the variety of model purposes (e.g., understanding vs. forecasting) and serve as a guide to documenting model tests and refinements. Currently we document model testing using Sterman’s (2000) classification. See Table 2 for an example.

<Table_2_about_here>

Items unmarked have not been done, a situation that points to nonapplicability or opportunities for further testing and refinement. The presence of more checked items does not imply acceptable levels of confidence in the module; however, in relative terms, they serve as a proxy for the accumulation of confidence across modules.

Social process to support modular development

An integral element of modular model development is a social process in which modelers, project leaders, and other stakeholders must communicate on the standards “contract” as well as on module boundaries, testing, documentation, version control, etc. The Conductor tool requires a contract with the modelers in the form of a set of modeling standards that are complete and comprehensive to enable merging. However, the Conductor does not specify the standards — the modelers do. This task was a challenge for the CIDPSS team. The technical staff across participating sites had to agree on a common set of standards.[9]

Another aspect of social process in modular development is the identification of modules, module boundaries, and interfaces. The modularity expressed in the Agricultural model described in this paper is but one form of module partitioning. Other domains in the critical infrastructure models have different module partitions. We believe it would be beneficial to establish a common rationale for module creation.

The general philosophy is to define a domain (e.g., agriculture) and then describe the pertinent subdomains (e.g., beef, dairy, corn, soybeans, hogs, broilers). Each subdomain is formed by a number of modules. The domain is essentially defined by the performance of the subdomains, although it may include unique information and can be represented as a module that primarily links the subdomain models. Within a module, the system is described as an SD model, but where information that must be found in another module is required is identified as an interface variable for incoming information. This variable is defined exactly as the variable name in the other module and given a default value, enabling the module to run in standalone mode.

The Conductor, when merging the modules, connects the local variable to the variable defined in the other module so that dynamic values are available to the module at run time. The variables in the model that are meant to be used in other modules are specially designated as export variables and denoted in the diagrams with a specific color. Conductor enforces the defined standards for import and export variables, which gives rise to the social process carried out among modelers to communicate their "public interface" for the module. A modeler working on a different module can still access non-import/export variables, but the practice is discouraged to promote encapsulation. Clearly, a substantial discussion among the model builders must occur for them to create preliminary interface definitions and subsequently maintain interactions to assure that the information needs of other modules are met.

In conclusion

The use of a modular approach to modeling and documentation, coupled with a model-assembling technology for merging modules, can help manage the volume and quality of the models developed to investigate problems and threats in critical infrastructure protection. This technology addressed a call for a coordinated effort to build knowledge as analyses based on SD models accumulate over time. The four novelties discussed in this paper were not trivial to implement and adopt, but they seemed to be essential if a long-term consequential research

[9] A common objection was that namespace prefixes were cumbersome to use and interfered with the readability of the model. Several expressed the opinion that modules, by their nature, tended to "break up" the flow of feedback loops that traversed domains and interfered with the understandability of the whole system. Thus, our use of subsystem diagrams resulted. More insidious were the feelings that a group of modelers desired to impose (unreasonable) standards while unwilling to consider or accept standards devised by another group. The social aspects associated with just establishing the standards contract require time and careful, reflective discussion and should not be underestimated. We feel that the airing of our modeling styles and differences was mutually beneficial, although it was strenuous.

agenda using SD modeling is to be fruitful in protecting critical infrastructures. These innovations addressed a challenging technical and social modeling context. With them, we hoped to facilitate the use of existing resources and expedite refinements and expansions to models as new problems arise for investigation. We intended to enable modeling work to progress in parallel at both the subsystem and whole-model levels, aided by tools that bring together, as often as necessary, these two levels of development and analysis. Ideally, both model development and testing can progress and be documented by employing these innovations in ways that are conducive to an efficiency- and quality-driven modeling effort.

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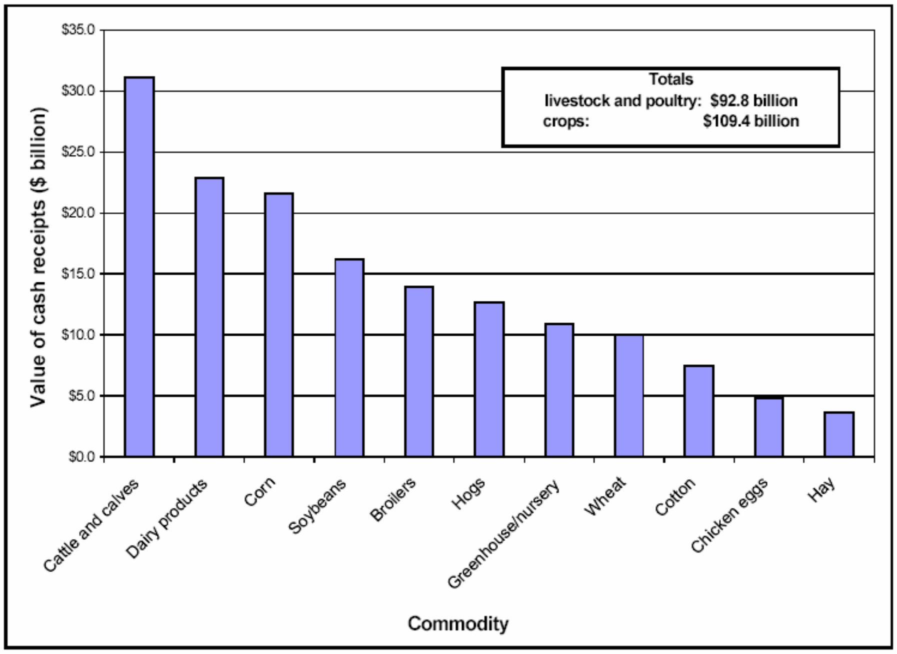


Source: *Agriculture Fact Book 1998*, U.S. Department of Agriculture, Office of Communications, November 1998, pp. 43-44.

Figure 1.
Values of the top 10 agricultural commodities in the United States, 1996

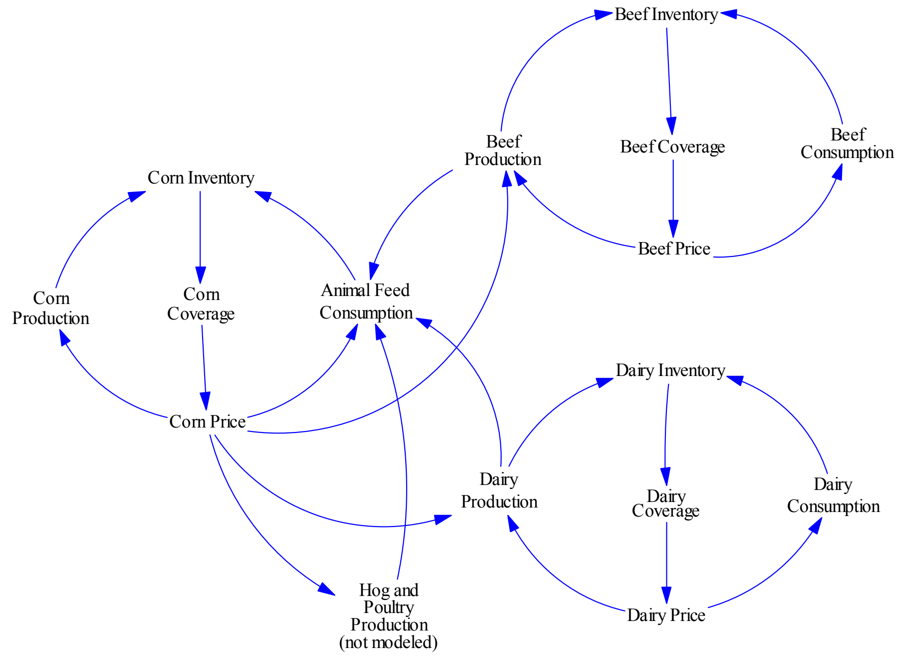
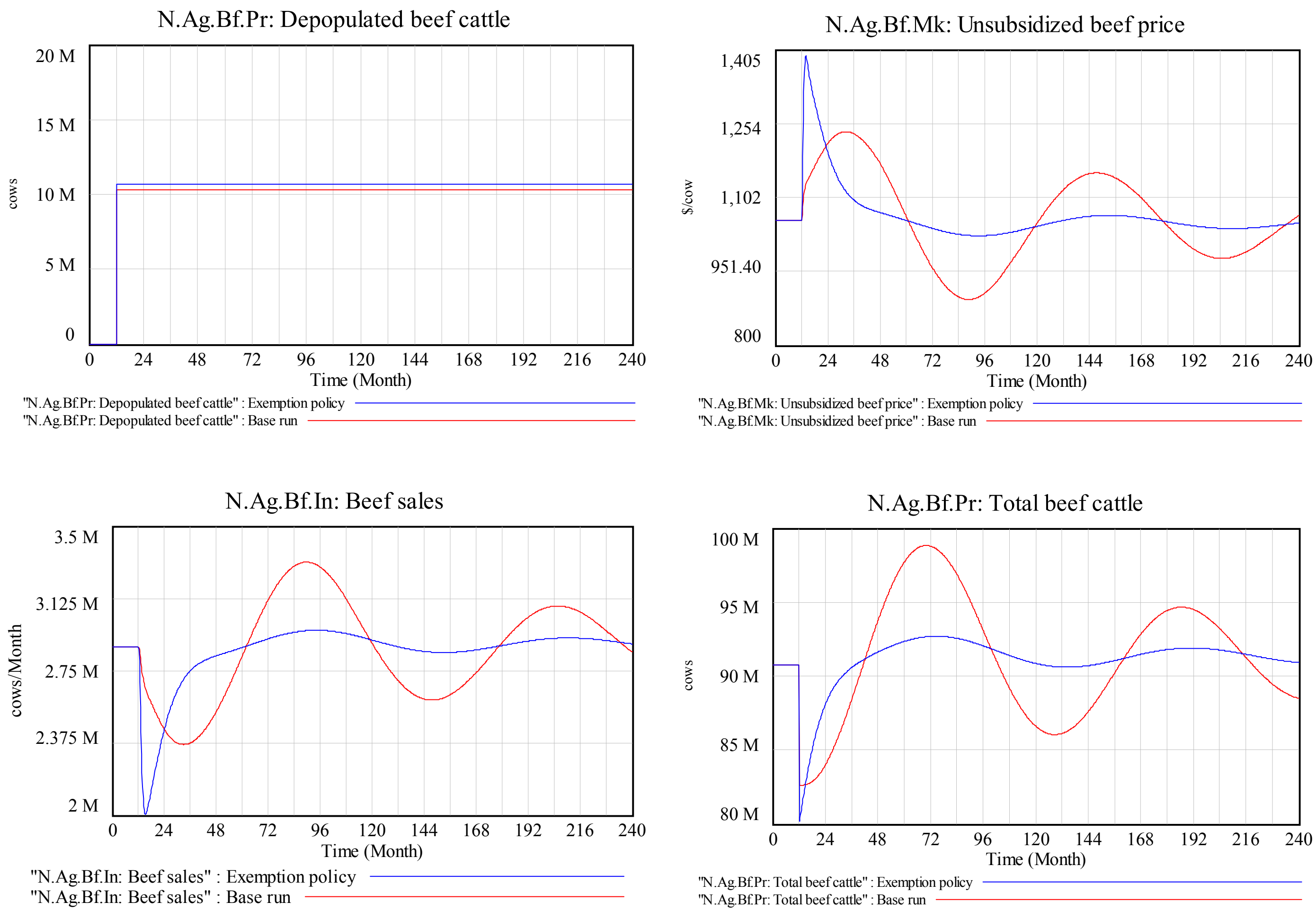


Figure 2.
Basic feedback structure of the three-commodity model



Figures 3A, 3B, 3C, and 3D
More efficient management of FMD through exemption of cow-and-calf operations from existing depopulation policy[10]

[10] The base run entails the depopulation of all animals within a certain radius of the manifestation of the disease. The exemption policy run is of the same magnitude (about 10 million animals); however it excludes cow-and-calf operations.

N.Ag.Bf.Pr: This

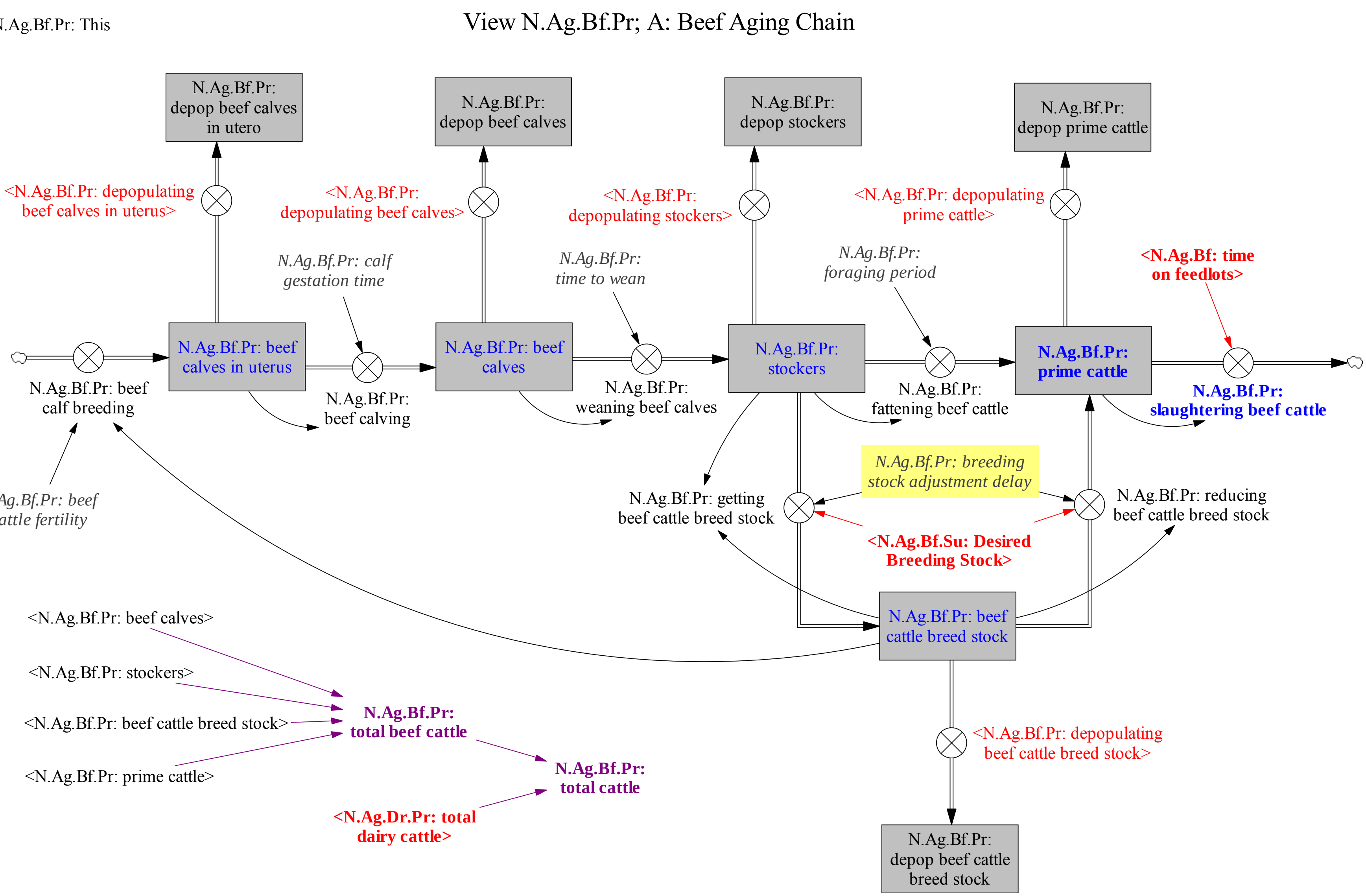


Figure 4.
The aging chain of the beef sector in the original beef production module

Critical Infrastructure and Key Assets Over Time

Infrastructure	U.S. Government Reports and Executive Orders							
	CBO (1983)	NCPWI (1988)	E.O. 13010 (1996)	PDD-63 (1998)	E.O. 13228 (2001)	NSHS (2002)	NSPP (2003)	HSPD-7 (2003)
Transportation	X	X	X	X	X	X	X	X
Water supply /waste water treatment	X	X	X	X	X	X	X	X
Education	X							
Public health	X			X		X	X	X
Prisons	X							
Industrial capacity	X							
Waste services		X						
Telecommunications			X	X	X	X	X	X
Energy			X	X	X	X	X	X
Banking and finance			X	X		X	X	X
Emergency services			X	X		X	X	X
Government continuity			X	X		X	X	
Information systems				X	X	X	X	X
Nuclear facilities					X			
Special events					X			
Agriculture/food supply					X	X	X	X
Defense industrial base						X	X	X
Chemical industry						X	X	X
Postal / shipping services						X	X	X
Monuments and icons							X	X
Key industry / tech. sites							X	
Large gathering sites							X	

Table 1.
"Critical Infrastructures" Meaning (CRS, 2004)

Tests for Assessment of Dynamic Models (Sterman, 2000, Chapter 21)		
√ Boundary adequacy √ Structure assessment √ Dimensional consistency √ Parameter assessment	√ Extreme conditions √ Integration error √ Behavior reproduction ▪ Behavior anomaly	▪ Family member ▪ Surprise behavior √ Sensitivity analysis ▪ System improvement

(√) Denotes categories of tests performed

Table 2.
Tests performed to the Beef Production Module

Appendix 1
Module Summary

Name of module:	Brief description of module:
N.Ag.Bf.Pr Production	Aging chain of the beef cattle. The main input to this module is the desired breeding stock. The main output is the number of cows being slaughtered per time period. The amount of time on feedlots depends upon price gains due to weight gain, and feedlot costs per time period. The depopulating scenario depletes from the animal stocks

Imported variables: (**red & bold**)	Exported variables (**blue & bold**)
N.Ag.Bf: Desired Breeding Stock	N.Ag.Bf.Pr: Slaughtering Beef Cattle

Metrics (**bold & purple**)	Policy/scenario sliders (*yellow highlight*)
N.Ag.Bf.Pr: Depopulated Beef Cattle N.Ag.Bf.Pr: Total Beef Cattle	*N.Ag.B.Prf: Breeding Stock Adjustment Delay* *N.Ag.B.Prf: Time to adjust stock of female beef calves*

Data: (*grey & italic*)	Type:	Observations:
N.Ag.B.Pr: Average Beef Calving Interval *N.Ag.B.Pr: Beef Calving Percentage* *N.Ag.B.Pr: Time to Wean* *N.Ag.B.Pr: Foraging Period* *N.Ag.B.Pr: Breeding Stock Adjustment Delay* *N.Ag.B.Pr: Breeding Duration* *N.Ag.B.Pr: Initial Breeding Stock* *N.Ag.B.Pr: Beef Calf Mortality* *N.Ag.B.Pr: Beef Heifer Mortality* *N.Ag.B.Pr: Beef Cattle Mortality*	National-data	
N.Ag.B.Pr: Fraction of Male Births *N.Ag.B.Pr: Calf Gestation Time*	Constant	

Observations/questions/issues/problems/suggestions for refinements and changes:

Appendix 2
Module Subsystem Diagram

This is the subsystem diagram that displays the interconnections between the beef modules (and the dairy and corn models)