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Application of Complex Adaptive Systems of Systems Engineering to Tobacco Products

Nancy S. Brodsky, Arlo L. Ames, Robert J. Glass, Theresa J. Brown, Patrick D. Finley, Thomas W. Moore, John M. Linebarger, Aldo A. Zagonel, S. Louise Maffitt
Sandia National Laboratories
Albuquerque, NM USA
Complex Adaptive Systems of Systems (CASoS) Engineering Initiative
nsbrods@sandia.gov

The tobacco products system includes many subsystems – the public, product manufacturers, farmers, government agencies, nongovernmental organizations, the health care industry, insurers, retailers, and many others. These subsystems, whose interaction via local rules yields emergent structure and cascading behaviors, cannot be understood simply as the sum of the behaviors of independent parts. These attributes make the tobacco products system, like many other socio-economic-technical systems, a Complex Adaptive System of Systems (CASoS). Understanding and predicting the behaviors of these systems is difficult: defining the problem space is uncertain, analysis of the full system can be intractable while analysis of subsets of the system can be misleading, and the real-world system changes over time. However, a systematic approach to designing influence in such systems is emerging, a discipline we call CASoS Engineering. In this paper we begin to apply CASoS Engineering to the tobacco products system, and discuss how aspirations for influencing the tobacco products CASoS can be mapped to interventions designed to achieve them.

1 Introduction

Cigarette smoking is the leading preventable cause of death in the United States; tobacco-related illnesses are responsible for 443,000 premature deaths each year [CDC 2008, CDC 2002]. Although smoking rates in the U.S. adult population have been declining since the mid 1960s, the rates of decline have diminished in recent years, raising concerns about the Nation's future health.

Tobacco use exists within a complex set of interwoven and evolving personal, social and economic systems. These include cultural and familial associations, social networks and behaviors, personal identities, and physical

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addiction. The tobacco industry is also a contributor to the U.S. economy, providing jobs and adding to U.S. GDP[1] as well as to tax revenues. The tobacco control and tobacco regulation communities serve as a counterbalancing force to the tobacco industry. These groups seek to reduce social harm caused by tobacco use through advocacy, education and regulatory oversight. Often, seemingly simple modifications by the tobacco community may have limited or no positive impact on individual health risk [CDC 2010, Sheldon 2001] or on population health [Mejia 2009]. Studies suggest that some alternative tobacco products may be less harmful than cigarettes [Foulds 2003], but the past history of unforeseen consequences from seemingly benign developments in tobacco products indicates that such alternative products may not have positive overall effects. The tobacco-control and regulation communities seek to reduce overall harm; their challenge is to act effectively.

The production, distribution, regulation, and consumption of tobacco products, and the attendant economic systems constitute a Complex Adaptive System of Systems, or CASoS. The practice of CASoS Engineering seeks to design effective means for influencing a CASoS in socially beneficial directions. In this paper we will outline our basis for defining tobacco products as a CASoS. Next we will demonstrate how generating conceptual models of the system can help define achievable aspirations for influencing the tobacco products CASoS. Lastly, we will show how these aspirations can be mapped to interventions specifically designed to influence the tobacco products CASoS in a direction that lowers mortality, morbidity and costs associated with tobacco use.

2 CASoS Characteristics

There is no single universally agreed upon definition of a complex system. Complex system definitions often include concepts such as scale independence, emergent behavior, and continuous evolution. A key property of complex systems is irreducibility – the behavior of the complete system cannot be understood through analysis of only individual system components. This property is sometimes described as system behavior being greater than the sum of the parts. That said, many authors have put forward definitions of complex systems:

> "Consisting of many diverse and autonomous but interrelated and interdependent components or parts linked through many (dense) interconnections. Complex systems cannot be described by a single rule and their characteristics are not reducible to one level of description. They exhibit

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[1] The U.S. Census Bureau, EC0700A1: Economy-Wide Key Statistics: 2007, reports that for NAICS code 3122, Tobacco Manufacturers, revenues totaled $40.2 billion in 2007, with just over 19,000 people employed. (http://factfinder.census.gov/servlet/IBQTable?_bm=y&-ds_name=EC0700A1&-NAICS2007=3122&-_lang=en , accessed April 2011). A full economic analysis was not conducted, but would include many additional factors.

> properties that emerge from the interaction of their parts and which cannot be predicted from the properties of the parts." [Business Dictionary 2011]
>
> "The science of complexity, as befits its name, lacks a simple definition. It has been used to refer to the study of systems that operate at the 'edge of chaos' (itself a loosely defined concept); to infer structure in the complex properties of systems that are intermediate between perfect order and perfect disorder; or even as a simple restatement of the cliché that the behaviour of some systems as a whole can be more than the sum of their parts." [Ziemelis 2001]
>
> "Complexity arises when the dependencies among the elements become important. In such a system, removing one such element destroys system behavior to an extent that goes well beyond what is embodied by the particular element that is removed." [Miller 2007]

We define complex systems as being composed of interdependent components whose interactions via local rules yields emergent structure and behaviors. Complex system behavior is generated by many entities interacting via simple, often nonlinear rules. Their dynamics exhibit a wide range of time scales, complicating prediction of system behavior and design of effective interventions.

The definition of a CASoS goes beyond the definition of a complex system [Glass 2008a]. CASoS are adaptive in that the system entities or components can change their behavior, which can result in a change in system structure in response to external stimuli. Additionally, system elements exert directional or bidirectional influences on one another that can change the system structure or behavior. CASoS are also systems-of-systems in that they are comprised of individual but connected systems, each of which is irreducible, and in that the behavior and functionality of the CASoS differ from the sum of the behaviors and functionalities of the individual systems of which it is composed. In a system of systems, not only can each entity be characterized as a system with its own rules and agenda, but the interaction among the systems can cause behavioral or structural modifications within the larger, interconnected CASoS.

CASoS behavior is often recursive and hysteretic, so that building an understanding through testing is difficult because repeatable initial conditions are generally not achievable and simultaneous tests are often not independent. Modeling is often the only practical option for effectively evaluating the consequences of acting on a CASoS and providing insight into possible cascading behaviors. Understanding the range of behaviors that can result from an intervention can minimize unexpected side effects and assist in finding workable solutions to problems. On the other hand, a CASoS may also offer an increased variety of opportunities for implementing change: leverage points may be available in complex, adaptive, or system of systems behaviors that wouldn't otherwise be available or effective in simpler systems. For example, social networks are often prominent components of complex systems; these networks present a potential locus for influencing the system. For example, an effective strategy for stemming the spread of influenza is based in reconfiguring social networks [Glass 2006].

One challenge in CASoS analysis is identifying and obtaining relevant metrics. As a consequence of the system-of-systems aspect of CASoS, the constituent subsystems are often far different in structure and behavior. Developing cross-cutting metrics to measure system condition and performance often requires defining meta-quantities which transcend the subsystem boundaries to allow quantitative comparisons.

3 The Tobacco Products CASoS

The tobacco products system includes many component parts that are highly interdependent. The component parts adapt and evolve in both structure and behavior. An overview of the subsystems that make up the tobacco products CASoS within the U.S. is shown in Figure 1. This diagram is simplified; we do not suggest that it represents the full spectrum of relevant entities and influences.

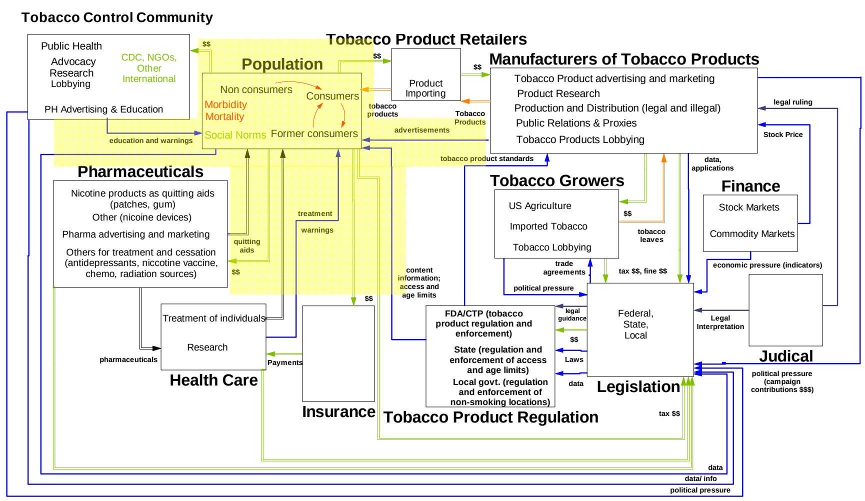

Figure 1: Overview of Tobacco products CASoS Entities and Relationships. Flows between entities include money, information (e.g., advertisements, study results), services, tobacco/tobacco products, and other goods. Yellow denotes a part of the CASoS that has high relevance to reducing the morbidity and mortality of the population.

The systems shown within the sphere of tobacco products include tobacco growers, manufacturers, distributors, users, non-users, regulators, pro-tobacco and anti-tobacco groups as well as elements of the health-care, financial legislative, and law enforcement systems. Many of these entities function as quasi-independent systems with their own rules and agendas, adaptive structures, and irreducibility. As an example, legislators are an irreducible system, behaving according to rules and agendas defined by themselves and their constituents. However, legislators are elected based upon their positions on a collection of issues, not just tobacco. Thus, issues completely outside the scope of tobacco can affect tobacco policy decisions.

Factors outside the scope of tobacco issues also influence tobacco users and non-users, such as job status, social contacts, and income. The tobacco products industry is subject to rules and influences external to tobacco that may impact tobacco products, including organizational dynamics, agricultural growing cycles, markets, labor issues, and international events.

It is often difficult to draw an appropriate boundary around a CASoS because small, often non-linear dynamics can have cascading impacts. The environment external to the system shown in Figure 1 includes international influences; executive, legislative and judicial issues outside of tobacco, and non-tobacco-related behaviors of tobacco users and non-users. However, since tobacco use is pervasive in the U.S. society, boundaries imposed around the tobacco product CASoS may not be sharply defined.

Full characterization of the tobacco product CASoS requires identifying and delineating relevant entities and their inter-relationships. However, subsets of the CASoS are relevant to specific questions arising from a chosen aspiration. These subsets may be of a scale amenable to analysis in isolation. However, this disaggregation of the CASoS for analytical purposes can result in drawing a boundary too narrowly and deriving misleading conclusions. Even if tobacco use could be eliminated in one nation, international influence could cause resurgence over time. As a general rule, the scope of the analysis can be expanded until further expansion does not affect the outcome of the analysis.

The behavior of the tobacco product CASoS is the result of emergent behaviors among multiple entities, interactions among adapting individuals, social networks, commercial, civic, and government entities, and evolving dynamic structures. This CASoS is also highly adaptive. Social norms change, smokers adapt to low-nicotine cigarettes by smoking more, or by inhaling more deeply. Tobacco-control and regulation communities adapt policy to be relevant to new products and to respond to findings by the health care community. As awareness of the health impacts associated with tobacco have developed, policies have been designed to curb the spread of tobacco use. The industry adapted to changes in regulation and in the market by changing marketing tactics and products so as to be less susceptible to regulation. The processes of adaptation, interaction, and evolution of new emergent behaviors continue. The tobacco products industry continues to develop innovative products and implement new marketing strategies. Regulators and tobacco-control advocates evolve compensatory responses, control policies, and educational outreach efforts. The social landscape evolves through continuous reformation of influence networks, public reactions, and changing behaviors.

4 CASoS Engineering and Tobacco Products

The last section described the tobacco products CASoS composed of tobacco production, distribution, regulation, consumers, and economic systems. A CASoS Engineering Framework has been developed [Glass 2008b, Ames 2011] to provide a methodology to analyze the system and to investigate potential engineering interventions that might solve problems, exploit opportunities or achieve goals. Here, we outline the framework and provide a high level description of how it can be applied to the tobacco products CASoS. The CASoS Framework embodies multiple principles:

1. Begin thinking at a high level, move to the details as needed.
2. Address issues broadly, in terms of understanding the entire behavior space of the CASoS as well as the ramifications of potential changes to the CASoS.
3. Analysis is an iterative process; steps may be revisited as many times as necessary to accomplish the goal/aspiration of the analysis.
4. Complexity science is still developing; thus engineering processes related to CASoS are still evolving.

Figure 2 illustrates an overview of the CASoS Engineering process. The three major phases of work are: Defining the Problem, Designing and Testing Solutions, and Actualizing. Note that the process diagram includes plentiful opportunities for iteration among and within the phases, as lessons learned from downstream activities may encourage new thinking that influences upstream activities.

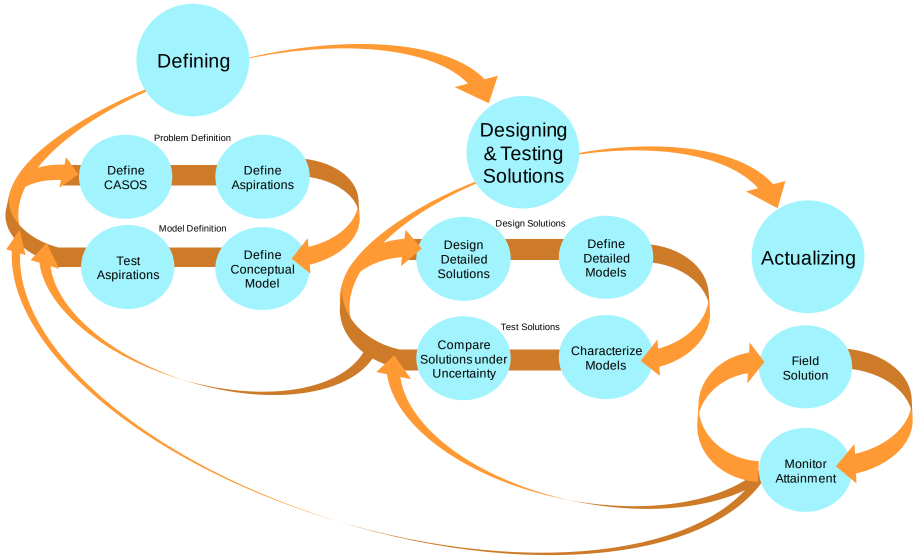

Figure 2: Diagram of CASoS Engineering Framework Components and Process

4.1 Defining Phase: Aspirations, Problem, and Model Definitions

The defining phase of the framework includes problem definition (understanding the CASoS of interest; evaluating and choosing aspirations) and model definition (choosing appropriate methods and theories, development of a conceptual model that captures an appropriate level of detail, and identification of data needed to support model development and validation). These steps are best visualized as a single logical sequence but in practice the steps are interrelated and must be addressed concurrently and iteratively.

The products of the defining phase may vary depending on the questions being asked of the system. For example, if we wish to reduce prevalence of cigarette use for a certain age group through increased pricing, we might focus population modeling efforts on the effects of changes in product appeal, the role of economics in individual decision-making, and the resulting changes in social network structure. If we wish to reduce prevalence by reducing the addictiveness of tobacco products, the population modeling effort might focus more on the physiological effects of addiction on behavior, and encompass additional entities and relationships as necessary.

The defining phase begins with definition of the CASoS (as presented in Section 3). The systems shown in Figure 1 may not present a complete picture (i.e., international influences are not included); however, the system can be redefined and expanded if necessary to address a given aspiration. Multiple aspirations are relevant to this system including: reducing prevalence of tobacco use, reducing prevalence in certain age groups, or increasing cessation. As an illustration, we choose as our overarching aspiration the reduction of tobacco-induced harm, or more specifically, reduction of tobacco-related morbidity and mortality at the population level. While this aspiration is primarily of interest to the tobacco-control and tobacco regulation communities, it is also of potential interest to the tobacco industry searching for long-term survival strategies. Of course, these entities would likely differ with regard to acceptable potential solutions and interventions.

Our large-picture view of the tobacco CASoS shows that while all subsystems are relevant to the problem, some are more relevant to our chosen aspiration. The decision to use tobacco is made by members of the population, and individuals' behaviors must be accounted for in any comprehensive analysis of tobacco use. Therefore, analyses of influences on the population, and tobacco-use within the population (shaded in yellow in Figure 1) forms a reasonable initial focus for conceptual model formulation.

Appropriate models must include representations of feedback loops, dependences, and interdependencies. Analysis of interventions such as advertisements at short times scales can be accomplished with a model in which individuals can act within social networks. Agent-based or individual-based modeling approaches are ideal for implementing such models. Preliminary intervention-focused modeling based on theories of opinion and behavior propagation for a tobacco system is provided by Moore et al., [Moore 2011]. At longer time scales, both interventions and the population may be aggregated, the latter into a small number of representative age groups. For this view, modeling approaches from system dynamics are well suited to represent population changes at long time scales (years to decades to centuries) [Zagonel 2011].

Identification of required data is an ongoing activity. Although substantial amounts of data have been compiled with regard to tobacco use, much of it does not fully represent diverse socio-economic groups, or the use of different tobacco products. Diverse relative risk information may be needed to convert local effects to tobacco-induced harm estimates for the population as a whole. Data are also needed to adequately characterize relevant social networks.

4.2 Designing and Testing Phase: Solution-Driven Analysis

The designing and testing of solutions is problem dependent, focused on answering three general sets of questions relevant to any aspiration: 1) What are feasible choices within the multi-objective space, 2) how robust are these choices to uncertainties in assumptions, and 3) what are the critical enablers that increase system resilience. Included in this process is the delineation of unintended consequences and potential amelioration/mitigation actions. The designing and testing of solutions can entail developing or using computational models; data mining, integration, and analysis; uncertainty quantification, experiment; or other means for implementation of the conceptual model. For a tobacco-control application, legislation determines feasible choices of policy options that can be implemented. The range of possible outcomes of policies or of policy combinations must reflect the uncertainty that characterizes inputs (e.g., data, model parameters) and the modeling process. In an adaptive system, one in which innovation can occur, it may be particularly difficult to characterize uncertainty for some inputs. Therefore, actions or combinations of actions must be evaluated to optimize the probability of success given the uncertainty in response/reaction.

Figure 3 shows one possible representation of solution-driven analysis for the illustrative overarching aspiration chosen above, reduction of tobacco-related morbidity and mortality at the population level. A set of possible solutions or interventions is identified. Individually, or in combination, they can modify the environment, and affect individual behaviors (upper path). Through social influences, individual behaviors can move or even cascade through social networks. Changes in behaviors are then converted to possible population level impacts. Alternative views, models and representations of the impacts of these solutions can also be analyzed. Simulated experiments can be conducted to assess the best solutions, combinations of solutions, or sequence in which possible solutions can be applied. Results must be viewed in the context of uncertainty analysis [Finley 2011]. Solutions may be found to be inadequate with regard to achieving an aspiration or being robust to uncertainty thus instigating iteration in designing and testing that may involve revision to conceptual/computational models to reduce uncertainty or possibly a return to the defining phase and a revision of aspirations.

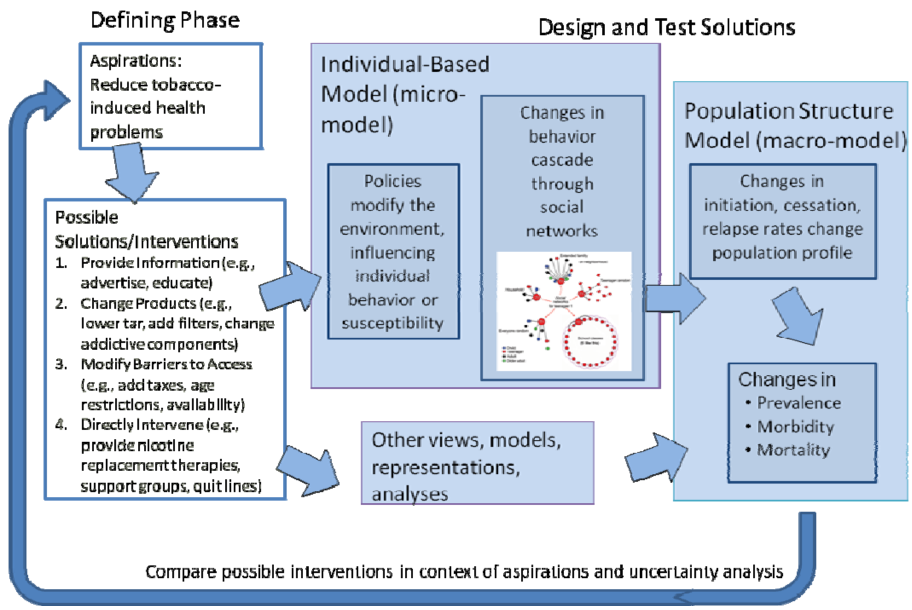

Figure 3: Example of solution-driven analysis process. Uncertainty quantification and finding solutions robust to uncertainty is an integral part of the process.

4.3 Actualization Phase: Influencing the CASoS

This phase involves fielding the engineered solutions within the real-world system to effect change. The work accomplished in the earlier phases is put into practice, results are observed and an evaluation is made as to whether the approach accomplishes the aspiration or if the approach needs to be modified. The engineered solution may be a concept, a computational tool, a sensor, or other artifact, and may take the form of a policy or other intervention. Actualization may involve working with decision makers to change the system, working with other researchers to evolve the methodologies, and/or working with those affected by a change to better understand the impact. In high-consequence systems that adapt to change, actualization involvement requires a long-term commitment. By providing the basis for system-changing decision/implementation, the analyst becomes part of the system, with concurrent responsibilities through a solution's lifecycle.

For several decades, engineered solutions have been tested within the real-world tobacco-product CASoS. Some solutions have been engineered by the tobacco industry for its purposes (e.g., developing the rolling machine, reconstituting tobacco, manufacturing milder blends, using effective advertising), some have come from the tobacco-control and tobacco-regulation communities (e.g., Surgeon General's Reports, broadcast advertisement ban, taxes), and some changes have been the result of circumstances exogenous to the system (e.g., the Great Depression, WWII). For the aspiration of reducing population level morbidity and mortality, policy options found in the designing and testing phase should be effective even in the face of uncertainty. However, the impacts of such policies once implemented must be closely monitored for effectiveness and the range of resulting adaptations. Repeated analyses may be required over time as the system changes, so that appropriate modifications may be implemented.

Actualizing a solution, especially one that involves multiple actions, can have inherent constraints. A sudden change to the market might be optimal; however regulations that influence that market may require a lengthy review process. The effectiveness of multiple actions may depend upon whether they are implemented simultaneously or in sequence, and the time delays involved. A pilot study may show effective (or ineffective) results in one region or socio-economic group, but provide a different result elsewhere. This variability calls for a solution design that is as robust as possible to such uncertainties.

5 Conclusions

Tobacco product use causes great harm to the U.S. population in the form of increased sickness, death, and economic burdens. Effecting changes to reduce the health and economic impact of tobacco product use requires a sound understanding of controlling factors. Rates of tobacco product use reflect complex interactions of a myriad of entities at a wide range of scales. The tobacco product industry, government regulatory structures, and the health care industry are some of the large-scale influences on tobacco product use. Individual decision making, peer pressure, and addiction are some of the small-scale drivers of tobacco product use. The interrelated subsystems that influence tobacco use constitute a Complex Adaptive System of Systems (CASoS). Thinking of the tobacco product system as a CASoS enables us to apply a well-defined methodology to design, test, and compare policies for interventions to lessen the harmful effects of tobacco product use.

In this paper we have presented an overview of the scope and complexity of tobacco product use in the U.S. We demonstrated how the characteristics of the tobacco system match well those of a CASoS. We described the CASoS Engineering Framework which provides an approach to affecting change to these large and complex systems. We discussed some of the challenging factors surrounding tobacco product use which complicate analysis, leading us to use CASoS methodologies to achieve the desired aspiration of improving public health. A narrower view of this problem-space, one that does not attempt to account for emergent behaviors, system adaptation, or iterative testing against real-world data, could provide insufficient or misleading results.

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