THE CONCEPT OF THE “CLIOS PROCESS”: INTEGRATING THE STUDY OF PHYSICAL AND POLICY SYSTEMS USING MEXICO CITY AS AN EXAMPLE

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March 5, 2004
ABSTRACT

Complex, large-scale, integrated, open systems (CLIOS) are a class of systems of special interest in the socio-technical domain. Because of the many sub-systems, the uncertainty in subsystem behavior and interaction and the degree of human agency involved, the emergent behavior of CLIOS is difficult to predict and often counterintuitive, even when subsystem behavior is readily predictable. These attributes make it difficult to represent and study CLIOS. We have developed a CLIOS Process for studying systems of interest. The CLIOS Process can be used as an organizing mechanism for understanding a system’s underlying structure and behavior, identifying strategic options for improving the system’s performance, and deploying and monitoring those strategic options.

A key motivation behind the need for a CLIOS Process is the presence of “nested complexity”, which results when a physical system is nested inside a policy system, where both are complex and interdependent. The study of the CLIOS will require that a variety of tools and processes be employed, with quantitative engineering and economic models being used for the physical system and more qualitative institutional, organizational and stakeholder frameworks being used for the policy system. An important aspect of the CLIOS Process is the integration of physical and policy system analysis.

The CLIOS Process can be thought of as a Christmas Tree and its ornaments; the tree represents the overall process and the ornaments represent the specific tools (e.g. benefit-cost analysis, probabilistic risk assessment, stakeholder analysis, etc.) one uses in a particular application. This paper describes the overall CLIOS process and particular regimes of tools that can be used in the study of CLIOS; we use Mexico City as an example.

The CLIOS Process consists of three major phases: representation of the CLIOS structure and behavior, design and evaluation of CLIOS performance and options, considering various strategic options and implementation of the selected options. The representation phase is diagramatic in nature. Diagrams are used to represent the structure and behavior of the CLIOS, by graphically illustrating the elements (components, policy drivers and common drivers) and interactions of the physical and policy systems. To aid in the difficult job of effectively representing complexity in a CLIOS diagramatically, the idea of expanding and layering are introduced.

To demonstrate constructing such a diagram, the Mexico City passenger transportation system is presented as an example. The passenger transportation system is a subsystem of the Mexico City megacity CLIOS; Mexico City is attempting to improve air quality under the pressures of a growing population and economy, and the concomitant expansion of demand for goods and services, housing, transportation, and energy.

In the CLIOS Process, our intent is to provide a structured process for undertaking the analysis, increase the amount of rigor and validity in the analysis, and facilitate the identification of options that are relevant to the actors on the policy sphere.

We suggest that the CLIOS Process provides an innovative systems approach that represents the entire system--physical and policy-- in an integrated form. The CLIOS Process explicitly includes the policy world as part of the system, recognizing that changes to existing institutional structures are not only an option, but are often necessary in order to implement options to improve the system’s performance.

KEYWORDS: Policy Analysis, Complex Systems, Engineering Systems, Transportation Systems, Environment, Organizations
1. INTRODUCTION

1.1 CLIOS Definition

The term CLIOS (Complex, Large-scale, Integrated, Open Systems) was conceived as a way to capture the salient characteristics of a class of socio-technical systems that are of growing interest to researchers, decisionmakers, policy makers and stakeholders. These systems range from an air traffic control system to the global climate system, and from National Missile Defense to the eBay online trading system (Magee and Weck, 2002; Zuckerman, 2002).

We start by defining the primary characteristics of CLIOS. First, a system is “complex” when it is composed of a group of interrelated units (component and subsystems, to be defined), for which the degree and nature of the relationships is imperfectly known, with varying directionality, magnitude and time-scales of interactions. Second, CLIOS have impacts that are large in magnitude, and often long-lived and of “large-scale” geographical extent. Third, subsystems within CLIOS are “integrated”, closely coupled through feedback loops. Finally, by “open” we mean that CLIOS explicitly include social, political and economic aspects (Sussman, 2000a). With CLIOS we are as concerned with the complexity of the organizational and institutional parts of the systems as we are with the physical system. In fact, understanding the organizational and institutional structure and its interaction with the physical system is one of the key potential values of a CLIOS Process.

1.2 Motivation for a CLIOS Process

The primary motivation for this paper is the authors’ perception that there is a critical need for a new framework for both analyzing and managing this class of systems. Because of the many subsystems involved, the uncertainty in the behavior of the subsystems and their interactions, and the degree of human agency involved, the emergent behavior of CLIOS is difficult to predict and often counterintuitive. This holds true even when subsystem behavior is readily predictable. Developing quantitative models that will predict the performance of the physical system can be very difficult, and management challenges are even more difficult. Increasingly sophisticated systems models have evolved to incorporate economic, social and political interactions with the physical system (Marks, 2002). Yet, the ability to integrate economic, social and political issues into a systems framework has continued to be limited by a relatively weaker understanding of organizational and institutional structures (Flood and Carson, 1993).

To place this paper in its own institutional context, the CLIOS framework is being developed in a time of major transitions in many of the engineering disciplines, such as transportation, at MIT and elsewhere (Sussman, 2002b). We view engineering systems as “open” systems, meaning that the profession is responsible for dealing with and working in the broader social, economic and political environments in which engineering projects are implemented. Illustrative of this transformation is the new Engineering Systems Division at MIT, created to respond to the intellectual and professional challenges of engineering systems, as described on the ESD website <esd.mit.edu>.

While CLIOS can describe many different systems, including natural and social systems, an engineering system is defined as a special case of a CLIOS in which technology plays an important role. Technology can be one of the integrators of the system, such as a telecommunications network, or technology can be important because of its impact on the performance of the system. For example, vehicle technologies play a key role in a transportation system, because of the impacts on mobility and other important attributes such as air quality and urban sprawl. We suggest that the CLIOS Process, when applied to an engineering system, provides an integrated analysis of the interactions of the technologies and institutions by bringing a systems perspective to both.
This paper defines the concept of a CLIOS Process as a tool for policy design and implementation based upon a systems framework. In developing this new methodology, we drew heavily upon the Mexico City CLIOS, which incorporates its transportation, environmental, and land-use systems. We will refer to the Mexico City CLIOS frequently, as illustrative of the various steps in the CLIOS Process.

2. KEY CLIOS CONCEPTS

2.1 A CLIOS Representation

A critical part of the CLIOS Process is the first step: representation. Because of the scope and complexity associated with a CLIOS, simply creating a common understanding of the salient features of the system is a major challenge. Generating a common understanding of the system among various analysts, stakeholders and decision makers, each with different perspectives, time commitments and level of detailed interests, requires that some form of representing the CLIOS be put in place to facilitate communications among all relevant actors. Creating a representation that is inclusive and detailed enough to capture relevant aspects of the CLIOS, while simultaneously being simple and clear enough to easily convey this information to all actors is a key motivation for the representation phase of the CLIOS Process. Because the representation is primarily qualitative, the CLIOS Process also allows for participation of a range of actors with different levels of expertise.

The CLIOS Process begins with a “representation” of the CLIOS both diagrammatically as well as with supporting text. The motivation for the CLIOS representation is to convey the structural relationships and direction of influence between the components within a system. In this sense, the CLIOS representation is an organizing mechanism for first mapping out the system’s underlying structure and behavior -- a precursor to identifying options and strategies for improving the system’s performance.

The steps outlined below for developing a CLIOS representation are intended to assist one in capturing the key characteristics of a system in an organized and systematic manner, and therefore avoiding the omission of salient factors in both its physical and organizational/institutional manifestations. Developing a CLIOS representation is largely a conceptual process. Rather than expecting quantitative results from the CLIOS representation, the purpose to develop insight into the emergent behavior of the CLIOS and possible strategies to enhance its performance. However, quantitative analysis is certainly needed for other aspects of the CLIOS Process, such as the design and evaluation of options for performance improvements.

2.2 Nested Complexity

A key motivation for a CLIOS Process is the idea of “nested complexity.” According to this concept, a CLIOS is comprised of a complex physical system, which follows quantitative principles that can be approximated by engineering and economic models, surrounded by a “messier” policy or institutional system. The physical system can be envisioned as embedded within a sphere, representing the complex policy or institutional system (See Figure 1). On this sphere is the organizational and institutional network of policymakers, firms, non-governmental organizations, and stakeholders that together comprise the broad policy system that acts upon the physical system.1 Analyzing this outer sphere of organizations

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1 We realize that representing the physical and policy systems in this manner – more structured and quantifiable physical systems, compared to messier, more chaotic, and more complex, human-based policy systems – runs the risk of overstating the dichotomy between systems composed of “things” and systems composed of “people.” This discussion has been taken up by researchers from many disciplines, we would refer the reader to Almond and Genco, 1977 and Flood and Carson, 1993 (in particular, pp. 251-2).
and institutions requires different methodologies – usually qualitative in nature and often more participatory, such as evaluation of stakeholder perspectives and organizational analysis.

[Figure 1]

We therefore have “nested complexity” when the physical system is being “impacted” or “managed” by a complex organizational and policymaking system, whether intentionally or not. However, while we make a distinction between the physical system and policy system – which captures the primary stakeholders as well as the policymaking and other decision-making institutions – we also need to explicitly represent the connections between the physical and policy systems. Indeed, an important step in the CLIOS representation process is to identify and characterize these policy-physical system links. Understanding nested complexity is a necessary step in moving towards better integrating institutional and policy design with physical system design. How to represent and analyze these connections is a key area for future work.

2.3 Types of Complexity

Another function of the CLIOS representation is to explore the nature and primary sources of the complexity of the system. While there is a long and growing list of the different types of complexity that characterize systems (Sussman, 2002c, Lloyd, 2002), here we find it useful to think of complexity along the three dimensions (Sussman, 2000b):

(a) internal complexity (i.e. the number of components in the system and the network of interconnections between them),
(b) behavioral complexity (i.e. the type of behavior that emerges due to the manner in which sets of components interact), and
(c) evaluative complexity (i.e. the competing perspectives of decisionmakers and stakeholders in the system who have alternate views of “good” system performance).

Because we envision CLIOS Process as a tool in identifying policy or management interventions to improve the system, understanding the source of the complexity of the system becomes crucial. Understanding the internal and behavioral complexity – basically, how the CLIOS works – enables the analyst to identify changes to the system to achieve more desirable outcomes. Once those changes are identified, however, the evaluative complexity will determine the feasibility of actually implementing those options, by highlighting areas where barriers to implementation, resulting from different stakeholders views, might exist.

3. OVERVIEW OF THE CLIOS PROCESS

A CLIOS Process is composed of three phases. In phase one, the CLIOS representation is created and considered with reference to both its structure and behavior. In phase two, the CLIOS in its current state is evaluated and options for performance improvements to the physical system are developed with some selected. In phase three, implementation issues and evaluation issues are dealt with, possibly by suggesting improvements that would modify the current institutional system.

With these three phases, the CLIOS Process encompasses the ability to analyze the CLIOS over all aspects of the system’s scope and life-cycle. The scope of the CLIOS includes the physical and institutional systems, and the life-cycle runs through problem definition, problem solving, strategy implementation, sustainment, and feedback. This allows the CLIOS to be systematically analyzed across both the systems (physical and institutional) and through time, which facilitates a more complete understanding of the CLIOS and the potential to implement better strategies.
The three phases of the CLIOS Process are conducted in an iterative manner. Instead of simply proceeding through each phase in a sequential manner, it is often good practice, to revisit analysis and decisions made in earlier phases. The availability of additional information, changing information and the need to conduct more detailed analysis are all reasons why iteration through the three phases is needed. Some of the major iterations are identified with feedback arrows in Figure 2.

The outputs from each phase of the CLIOS Process can be summarized as follows:

- **Phase one (representation)** – System description, issue identification, goal identification
- **Phase two (design and evaluation)** – Identification of performance measures, identification and design of physical performance improvement options, evaluation of options and uncertainties
- **Phase three (implementation)** – Implementation strategy for options, creation and evaluation of institutional performance improvement options, post-implementation evaluation

When conducting a CLIOS Process, the analyst has the opportunity to tailor the CLIOS Process to best meet the needs of the problems and actors involved. When determining how to use the CLIOS Process the analyst will likely need to ask various questions and utilize various tools. Below is a sample of some of the questions that the analyst could ask in each of the three phases. Presented later in this paper is an overview of various tools and how these different tools can be selected to “hang on the CLIOS Process Christmas Tree”.

In phase one, regarding the representation of the CLIOS structure, we can ask questions such as the following:

(a) What are the technical, economic, social, political and other subsystems?
(b) How are the physical subsystems embedded in a political and institutional structure?
(c) In the physical system, can we break out several relatively independent types of physical systems that are “layered” upon one another? Can this be done for the policy system as well?

Also in phase one, regarding the representation of the behavior of the CLIOS, we can ask:

(a) What is the degree and nature of the connections between subsystems?
(b) Are the connections weak or strong?
(c) Are there important feedback loops connecting subsystems?
(d) What insights can we gain into emergent behavior?

In both of the structural and behavioral representation of the system, the analyst is guided by the issues and goals of the system, which help to bound the system and highlight the characteristics most relevant to the problem(s) motivating the analysis.

Turning to the design and evaluation in phase two, we look at both performance as well as preferences of different stakeholders.

(a) How is performance measured for the entire CLIOS as well as the physical subsystems?
(b) How do key stakeholders and decisionmakers measure or rank different types of performance?
(c) What are the tradeoffs among the various dimensions of performance (e.g. cost vs. performance)
(d) What strategic options can lead to improved performance?

Finally, reaching phase three, implementation, of the CLIOS Process, we can ask the following:

(a) How do these performance improvements actually get implemented, if at all?
(b) What compromises have to be made in the name of implementation?
(c) What actors/organizations on the policy sphere have an influence on the parts of the system targeted for intervention? How are these actors/organizations related to each other?
(d) Do the types of policies made by different organizations on the policy sphere reinforce or counter each other?
(e) Under the current institutional structure, can organizations manage the system to achieve target levels of performance?

In summary, the first phase is used to understand behavioral, internal and evaluative complexity; the second phase is used to create and evaluate alternative options for improving system performance; and the final phase brings various options for the physical and institutional systems together to form a feasible strategy for improving the CLIOS. One of the departures of the CLIOS Process from other system approaches is that the strategic options for implementation may include changes to both the physical and institutional systems.

The following discussion will outline the structure of a CLIOS Process, as illustrated in Figure 2. We will first present the “12 Steps in a CLIOS Process”, so that the reader has an idea of the overall process, and then define and discuss each step in greater detail. Although we will be explicit about the steps involved in the methodology, recognize this is an iterative process, and not a rigid, once-through process. To illustrate, we will focus on the case of Mexico City, one of the world’s largest megacities, which is attempting to improve its air quality under the pressures of a growing population and economy, and the concomitant expansion of demand for goods and services, housing, transportation, and energy. With a complex institutional structure as well, Mexico City is certainly a CLIOS by any standard.

While each of the three phases is discussed below, we emphasize phase one, representation. Due to space limitations, the authors will delve into more detail associated with phases two and three in future work.

4. REPRESENTATION – STRUCTURE

The representation phase aids in the understanding of the complete CLIOS by examining the structures, behaviors and interactions between the physical and institutional systems. The CLIOS Process uses a combination of diagrams and text to capture the critical aspects of the CLIOS and present them in an easy to comprehend format. This allows the analyst and the various actors to understand the CLIOS and participate more fully in future phases.

The purpose of the representation phase is to create a common understanding of the CLIOS among actors so that issues and goals associated with the CLIOS can be reasonably discussed. Some agreement on the issues and goals is necessary to be able to successfully create and implement system performance improvement options in later phases.

4.1 Describe System: Issue and Goal Identification (Step 1)

The first step in developing the CLIOS representation is to provide an overarching description of the CLIOS, identifying the salient characteristics and issues. This step can be simply a list or an in-depth description, but should address the questions posed by Puccia and Levins (1985), “what is it about the system that makes it interesting?” Puccia and Levins suggest drawing upon not only reports in the literature, but also previous experience with this or other related systems. Important CLIOS characteristics relate to: (a) the temporal and geographic scale of the system, (b) the core technologies and systems, (c) the natural physical conditions that impact or are impacted by the system, (d) the key economic and market issues, (e) important social or political issues or controversies related to the system, and (f) persistent or irresolvable problems.

This initial description of the system also serves the role of a valuable checklist for the rest of the analysis. In particular, as the CLIOS representation is developed, one can return to this checklist to
identify any major issues that have been omitted from the representation. Above all, this description and issue identification should capture the concerns and needs of policymakers, managers and stakeholders. While this is essentially an overview or scan of the overall system, embedded in this overarching description of the CLIOS is a problem definition relevant to the various actors. As the CLILOS Process is intended to facilitate better management of the system, one has to ask: “What are the management and policy questions that need to be addressed?” and “What are the goals for the CLILOS?”

This first step also implies a preliminary “bounding” of the system. For example, given that CLILOS are, by definition, large-scale systems, the analysis needs to take into account the actual scale of the system (spatial and temporal), and the magnitude and scope of its impacts, whether these impacts are physical, economical, political or social. This will not only determine where the system boundaries are drawn, but also which subsystems and components will be included. The relationships between the CLILOS and the broader external environment cannot be ignored, and will be important in the uncertainty analysis to follow. For example, in a CLILOS Process for a metropolitan level transportation and environmental system, one may not include the national or global economic system as an integral part of the CLILOS. Nevertheless, one would need to think through issues such as the impact of globalization, the health of the global economy or major shifts in world oil prices on the local regional economy and what that would mean for the development of the transportation system and the local environment. As will be discussed later, scenario building will be one tool to think systematically about these linkages between the CLILOS and the broader environment.

We emphasize that this is an iterative process. At later stages, one may realize that the system has not been bounded correctly, or that some important parts of the CLILOS have been left out or only partially represented. In this case the analyst might even return to the first step, and redefine the boundaries of the system. Often, this redefinition will be an expansion of the CLILOS boundaries. Senge (1994) illustrates through a simple case of beer retailers and wholesalers why there needs to be broader systems viewpoint for systems to be managed successfully.

While setting system boundaries is one case where iteration is necessary, identifying system goals is another. In Step 1, some preliminary system goals will be identified as the overarching description of the CLILOS is developed. However, these goals will be revisited in greater depth in Step 6 (Refine System Goals and Identify Performance Measures), after the CLILOS representation has been developed in more detail. Operationalizing system goals into performance measures may lead one to revisit the system goals as originally conceived.

4.1.1 Describing the Mexico City CLILOS – Application Example of Step 1

In developing a CLILOS representation for the Mexico City Metropolitan Area (MCMA), we turn first to the policy issues that motivate the analysis. Our intention is to examine opportunities for air pollution emissions reductions, in order to mitigate future damage to public health, and to enhance economic productivity and quality of life. The combination of topography and meteorological conditions, together with the pressures of industrial growth and increased auto ownership (triggered by growth in per capita GDP) has produced an air quality problem of the first magnitude. While air quality is recognized as an important policy objective, economic and industrial growth have historically been the overriding policy concerns for Mexican politicians.

Although in recent years there have been tendencies toward demographic, economic and political decentralization, Mexico remains a highly centralized system due to the historical concentration of investment and growth in the core of Mexico City, the Federal District. While the capital city has been the focus of many regional and national development goals, as with many developing countries there is a tremendous range in wealth among its citizens. This inequality influences everything from the use of the
transportation system, particularly the relative split of private to public transport, to the patterns of residential development. In the past few decades, the city has experienced an increasingly sprawling land use pattern fueled by both illegal settlements on the fringes and suburbanization by its wealthier citizens, and the resistance of central city districts to densification.

Urban sprawl is related to other important environmental issues including deforestation, soil erosion, and overexploitation of local and regional water supplies (Molina and Molina, 2001). But this phenomenon is also tightly interconnected with air quality through operation of the surface transportation system. As land use patterns become less dense and not well planned, the efficacy of public transit systems deteriorates, trip lengths increase and the costs of service provision escalate. As one of the major contributors of emissions, the transportation system is also subject to substantial congestion, which not only exacerbates the air quality issues in the MCMA, but also impacts the quality of life of residents through lost travel time, and poses a constraint to the efficient operation of industries transporting their goods in and out of the metropolitan area.

While we must draw certain system boundaries to focus the analysis and understand the CLIOS’ internal structure and behavior, the openness of the system must also be recognized. For the MCMA, while the state of the national economy and trends in internal migration and natural population growth might not be a factor that is included within the CLIOS, the impact of crucial links to the outside need to be recognized, such as fluctuations in the economic health of other countries, especially the US. As we will see later, these external factors pose important uncertainties, and should be considered in the development of policies.

As a first step in the CLIOS Process, we provide a checklist for the CLIOS Process, where we can extract some of the most salient issues that come to bear upon the issue of air quality and transportation in Mexico City.

(a) “Megacity” close to 20 million people in Mexico City Metropolitan Area (MCMA)
(b) A combination of topography and meteorological conditions, together with increased auto ownership, producing an air quality problem of the first magnitude
(c) As with many developing countries, a tremendous range in wealth among its citizens
(d) A sprawling land use pattern fueled by both illegal settlements on the fringes and “suburbanization” and the resistance of central city “delegaciones” to densification
(e) A surface transportation subject to substantial congestion – throughout the day in some parts of the city – exacerbating the air quality issue in the MCMA
(f) The MCMA as institutionally complex, considering its relation to the federal government and relationship between the Federal District (DF) and the State of Mexico (EM)
(g) The MCMA as the economic engine of Mexico, but dependent on the economic health of its neighbor to the north
(h) Economic growth as a driving policy, with the automotive industry as an important part of the national economy
(i) A potentially extraordinary political shift for Mexico with the election of President Fox in 2000, after 71 years of presidential rule by the same party

Through an iterative process, based upon not only the checklist above, but also the system diagrams and performance measures shown in later steps (see Figure 8), we identified several critical goals for the MCMA. These goals and brief descriptions of their rationale are outlined below.

(a) Foster modal shares that improve both congestion and environmental quality, favoring modes with newer and cleaner fleets. Human health and quality of life are the key drivers for this goal.
(b) Manage congestion in a manner that will not induce additional traffic in a substantial way. Congestion not only exacerbates air quality, but lowers productivity due to travel delays and unreliability
(c) Find mechanisms that separate auto ownership from auto use/mode choice. This is essential considering both the difficulty in delinking GDP/capita from auto ownership, and the economic development benefits related to a strong automotive industry.

(d) Design long-run land use strategies, able to cope with a range of population growth scenarios, that (i) maintain accessibility without spurring additional transportation demand, and (ii) promote a modal share that favors public transit use. This will likely require major institutional changes given that the sprawl extends deeply into the State of Mexico.

Again, we emphasize that these goals were the outcome of an iterative process. In the first pass through the CLIOS Process, the critical goals listed above will be less well defined.

4.2 Identify Major Subsystems (Step 2)

The next step is then to determine which major subsystems – technical, natural, economic, social, and political – make up the CLIOS and how they relate to one another on a macro-level, in order to outline the general structure of the CLIOS. One way to identify these subsystems is by grouping the phenomena and issues identified in the first step. In the case of a Mexico City CLIOS, by grouping the issues highlighted above, the major physical subsystems would include the environment, land use, transportation, and economic activity (Sussman, 2002a).

Since many CLIOS will encompass several types of technological or physical subsystems, they can often be organized according to their common technological characteristics, functions or needs of the various actors. This will depend on the questions that need to be addressed for the analysis. For example, the transportation system as a whole can be considered as one subsystem, or one could separate the transportation system into freight and passenger transportation, which have similar technological bases but different functions and operations. This would also alter how the decisionmakers and stakeholders on the outer policy sphere (as shown later in Figure 7) are arranged with respect to these subsystems. The major subsystems may be grouped according to specific policy or disciplinary domains, while bearing in mind that a disciplinary or policy bias can also be too constraining and leave out important parts of subsystems or connections between them.

4.3 Develop the CLIOS Diagram: Nesting, Layering, and Expanding (Step 3)

In this step, an initial CLIOS diagram is created by breaking out each subsystem – passenger transportation, land use, the environment, etc. – into greater detail and identifying the major components in each subsystem. The CLIOS is mapped with the individual subsystems (transportation, land use, etc.) represented by a system diagram that shows its major components and links indicating influence of one component upon the other. This type of basic system diagram is common in systems sciences, “defined as having elements and relations that may be represented (at least in principle) as a network-type diagram with nodes representing elements2 and lines the relationships” (Flood and Carson, 1993).

While this initial systems diagram helps to map out the system, the use of this type of diagram on its own quickly reaches its limits. There is a cognitive upper bound to the number of subsystems or “components” that can be represented within such a diagram, while still providing an opportunity for

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2 We use the term “components” to mean the same as “elements” in Flood and Carson (1993).
insight for the creator or user of the diagram. However, remaining within this cognitive limit can result in oversimplification of the system, leaving many of its technological, economic, social and political subsystems poorly represented. Therefore, in order to expand the system diagram into a fuller representation of the system, we will develop three mechanisms for expanding the system without overwhelming the users (or the creators) of the diagram: nesting, layering and expanding.

Before turning to the issues of nesting, layering and expanding, it may be helpful to examine an actual example of a diagram for a key subsystem in the Mexico City case: the passenger transportation system. While Figure 5 will be developed here in its simplified form, after further discussion of the CLIOS representation, we will return to the same diagram (in Figure 10), representing it in its more complex form, and including the notation for “components” that will be described later.

[Figure 5]

The diagram shown for the Mexico City passenger transportation system provides a comprehensive overview of the critical components in the passenger transportation system in the context of air quality. Two aspects of this diagram should be noted. First, while this represents one subsystem described in detail, many of the other subsystems – such as land use, environment, and electric power – appear in the diagram as single components. Clearly, we cannot expand each of these components fully within the same diagram without the diagram becoming overwhelmingly complicated. Second, while some of the components such as “investment” and “policy” are policy-related components, none of the components of the policy system are shown. This physical subsystem is embedded within a policy system; further, this subsystem represents but one layer in a multi-layered physical system.

4.3.1 Nesting

By nesting the systems (as shown in Figure 1) the basic CLIOS diagram is separated into the inner physical system and outer policy sphere. Because many CLIOS are engineering systems, a major part of the physical sphere may be oriented around a system of technologies (e.g. transportation, information and communication technologies, energy) but can also represent a natural system (e.g. climate, ecosystem). While the policy sphere will include the usual actors – policymakers and decisionmakers who most visibly influence the system – it may also include other actors whose decisions impact the system in a subtler manner. These are actors or stakeholders who impact the system, but are not involved in managing large parts of the system. For example, while in Mexico City the environmental authorities and transportation planners would clearly be included, so would stakeholders such as bus companies, taxi associations and non-governmental organizations.

For the CLIOS representation shown in Figure 5) for passenger transportation, nesting would be accomplished by linking the policy components of “investment” and “policy” decisions to policymakers, decisionmakers and stakeholders on the policy sphere. Therefore, the policy sphere would need to include actors such as the Secretaries of Transportation for the Federal District and State of Mexico, financial institutions, private sector firms, and public transit operators.

4.3.2 Layering

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3 From the authors’ experience, a single subsystem diagram should contain approximately 20 components, although that number may be substantially more or less depending upon the preferences of the analyst.

4 An engineering system is a CLIOS with an important technical component. However, there may be CLIOS that do not include an important technical or engineering component, and are therefore not considered an engineering system by our definition.
Another organizing tool is the layering of physical systems into several separate but interrelated subsystems of a similar scale, as shown in Figure 6. The layering format serves two main purposes. First, it permits the further expansion of the subsystems, without resulting in a two-dimensional subsystems diagram containing a number of components beyond one’s cognitive limit, such that gaining insight is difficult or impossible. Second, it forces the analyst to identify both where subsystems are separable and distinct physical systems, as well as where they are interlinked, either because of common components, which may even be exogenous to the systems, or because of direct links where a component in one layer influences a component in another layer. The layering of the systems can be determined according to the predominant technologies involved or the functions of those subsystems. For definitional clarity, there is one physical “system”, which is then layered into several physical “subsystems”. There may be some CLIOS for which the physical system cannot be divided into distinct subsystems, in which the system would resemble Figure 1, in which a single system layer is embedded in the policy sphere.

As we decouple the subsystems into layers, we look for interactions between the subsystems, but also for the common drivers. In the case of Mexico City, the common drivers across the subsystem layers of passenger transportation, freight transportation, industry, land use, would include population growth, regional production, income levels and inequality, and employment. As is suggested in Figure 6, a generic depiction of layered subsystems, the common drivers do not necessarily have to go through all of the layers. For example, income levels would be an important driver for passenger transportation and land use, while regional production would be relevant common drivers for freight transportation, industry, and land use.

While we know at a basic level that population and economic growth drives the entire Mexico City CLIOS, by looking at its differential impact on individual subsystems, we can begin to unravel the more subtle ways that these drivers influence the overall system. For example, as a critical “common driver” of the system, slow growth in GDP per capita and an inequitable income distribution is one of the contributing factors to illegal land invasions that are leading to the unplanned and sprawling residential developments that are emerging along the fringe of the urban area. At the same time, the low-income families represent the group most likely to use the public transportation systems, the so-called “captive riders” of public transit. Therefore, by looking at the competing influence of this driver – GDP per capita and income distribution – on two different layers, passenger transportation and land use, we can begin to deal with this disparity between the growth in the potential demand for public transportation, and the inefficient urbanization patterns which make it more difficult to actually provide public transportation services to these particular groups.

By identifying the tension between these layers, which are interconnected by their common drivers, we can use the CLIOS diagram to identify sources of potential problems. In fact, one of the consequences of this tension between the supply and demand for public transportation services has been the explosion of a paratransit services known as "colectivos" or collective taxis. These low to medium capacity vehicles have filled an important gap in transportation supply that could not be met by traditional bus services or private autos. Yet, despite their important role in providing mobility, the colectivos are viewed negatively by the Mexico City authorities, who cite impacts on congestion and air quality, as well as operational practices of the colectivos.

Bringing together the ideas of nested complexity and layering, as seen in Figure 7, these two concepts can help to convey a more intuitive sense of the interaction between the outer policy sphere, which houses the institutional, organizational, political and social actors, and the physical layers which represent technological, natural as well as economic subsystems. As will be discussed later, given the potential...
audiences for the methodology behind the CLIOS representation, this visualization element of the CLIOS diagram can be very important, since insights will be drawn more through this more qualitative and diagrammatic representation, rather than a quantitative analysis or stand-alone text.

[Figure 7]

This separation into the policy and physical also requires that the analyst clarify the set of actual decisionmakers that influence the development of the system. For example, one could have colectivo owner-operators as actors within the physical system, with a focus on their individual economic decisions. However, if the colectivo operators organized in route associations with sufficient political influence, they would be considered as relevant actors in policy decisions, and would then be represented on the policy sphere. As policy actors, their decisions and input could alter several components in the physical system, such as colectivo fleet size and turnover, or they could have an impact on investment decisions, for example, in intermodal facilities to allow for transfers from colectivos to the Metro system. In summary, the primary difference is that the individual colectivo operators make private, economic decisions, while the colectivo route associations make more public, political decisions.

4.3.3 Expanding

Finally, there is the method of expanding. This represents an alternative technique to nesting or layering, for exploring certain aspects of the system in more detail. If one of the components in a subsystem, congestion for example, seems to be an important component of the system, by opening the “black box”, we can look more closely at the internal dynamics. Rather than creating an entire additional subsystem, which we might do for other components such as land use or the environment, the component of interest is simply “pulled out” of the system, in order to perform a mini-analysis of that specific component. After that component is analyzed, we can “reinsert” the component into the system diagram, now with a much clearer idea of what drives the dynamics and the variation internal to that component.

5. REPRESENTATION – BEHAVIOR

Having developed the general structure of the CLIOS, the next steps (Steps 4A, 4B, and 5) are to characterize the behavior of the system, first in terms of its individual components and links, and then in terms of its emergent behavior. While much of this is shown diagrammatically, to some extent the representation of the behavior will also need to be done with supporting text, since attempting to have enough symbols for components and links to reflect all of their relevant characteristics would probably be more confusing than illuminating.

5.1 Describe Individual Components (Step 4A)

Up to this point, the components have been considered as generic elements in the subsystems. In this step we more carefully characterize the nature of the individual components. Within the physical system, there are three types of components. Components (indicated by circles) are the basic elements of the CLIOS diagram within the physical system. These elements can be expressed in different forms, and can be qualitative or quantitative. They can refer to simple concepts, or can contain complex internal structures. Policy Levers (indicated by rectangles) are the elements within the physical system that are most directly controlled or influenced by decisions by the institutions and organizations of the outer policy sphere. Common Drivers (indicated by diamonds) are elements that are shared across multiple and

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5 Whether these components are broken out in more detail within the main subsystem diagram depends on the focus of the CLIOS representation. Analytic insights may be better gained by “expanding” a particular component, as described earlier.
possibly all layers of the physical system. These elements may also be influenced by macro-level factors outside of the boundaries of the CLIOS.

While most of the elements within the system will be described simply as components, the other two component types are derived from the earlier process of nesting and layering. Most relevant to the process of nested complexity, the policy levers are the elements that directly link the policy system to changes in the physical system. The common drivers, on the other hand, emerge from the process of layering the systems. The common drivers are important both for understanding the behavior of the system as well as for the later stages of implementing changes to the system. First, they may be exogenous to the physical system. Second, they may constitute major sources of uncertainty, since they impact the physical system at several different layers. The uncertainty of the common drivers, such as population and economic growth, will have to be taken into account in any evaluation of options for system improvements.

5.1.1 Describing the Mexico City System Components – Application Example of Step 4

In the Mexico City CLIOS, from a policy standpoint, we are interested in the rate at which technologies change, since many policy options dealing with transportation and environmental issues require a technological change or substitution. For example, we could look at a fleet of vehicles for private autos, buses, or heavy freight trucks. While the vehicle fleet may be represented as a single component within the diagram, there are still complex dynamics within this component. The component’s variation could be the growth in absolute number of vehicles or changes in the average fuel efficiency and emissions performance of the fleet. This component variation can be driven by the natural turnover of vehicles, and/or policy options that affect the rate at which new vehicles enter the fleet (incentives for buying new vehicles) or vehicles leave (scrappage programs). Therefore, the internal dynamics of the vehicle fleet component dictate slower, more continuous change. In comparison, there is the variation of the road infrastructure, another component, but one with less continuous variation. Infrastructure investment tends to be discontinuous or “lumpy” because one can, say, either build a bridge or not (Sussman, 2000b).

A motivation for understanding internal variation in the components is that this links to the issue of the time scale on which the systems are operating. It is important both to know how fast and how strong the links are between components (as will be described in the next step), but also to understand the internal changes within the components themselves. While some of the more important or complex components may undergo “expansion” in the diagram, therefore transforming internal variation into more visible linkages, this concept of “variation” can remind us that the components are not static elements.

5.2 Describe Individual Links (Step 4B)

Similarly, as the components were characterized and divided into different types, we also need to characterize the nature of the links. As stated earlier, one key perspective is the need to be “disciplined” in one’s diagrammatic notation. Links and arrows need to be consistent; if they mean different things, one will have to use different diagrammatic elements (Flood and Carson, 1993). In the diagrams used in the CLIOS representation, these links will be largely qualitative. However, while hesitating to suggest a notation that would work for all CLIOS, at least the links should indicate directionality of influence and feedback loops, as well as the magnitude of influence (big/important or small/marginal impacts on the adjoining components). Other possible characteristics to include in the notation for the links could include the timeframe of influence (short-, medium-, or long-term lags), functional form of the influence.

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6 Feedback loops in which one component has a feedback loop directly back onto itself would not be used in a CLIOS representation. Instead, the intervening components need to be identified, to provide insight into the chain of causality that creates this feedback.
(linear/non-linear functions of various forms or threshold effects, step functions), continuous or discontinuous (under what conditions the link is active or inactive), uncertainty in the effect of one component upon another (including uncertainty in all of the above characteristics).

While directionality and magnitude of influence are straightforward characteristics that would be included in any CLIOS diagram, the other possible characteristics that need to be captured will probably vary for different CLIOS. Within the Mexico City CLIOS, there is a range of characteristics across links that could be considered. The land use subsystem has long-term lags on the order of years, for example, the growth of informal squatter settlements and the provision of infrastructure. Alternatively, the influence of links in the environmental subsystem can manifest themselves in hours, as emissions are transformed into concentrations of pollutants such as ozone. In terms of the functional form, another highly important link is that of GDP per capita and motorization. There appears to be a threshold effect in many developing country cities, where once average incomes reach a certain critical level, auto ownership increases dramatically. However, for simplification, in the diagrams presented here, only direction and magnitude of influence are indicated.

In thinking about the linkages, one of the key aspects of the CLIOS representation is to develop a framework for thinking about and describing the links in the system. Drawing upon the idea of nested complexity, we can identify three classes of links: (a) Class 1 links between components within the physical system, (b) Class 2 links between components within the physical system and components within the policy system, and (c) Class 3 links between components within the policy system.

There are different approaches appropriate to each class of links. Generally the links within the physical system (Class 1) can be analyzed using engineering- and microeconomics-based methods, and will often be quantifiable. Regarding the links from the policy sphere to the physical layers (Class 2), quantitative analysis is less useful, since human agency and organizational and stakeholders interests come into play as they attempt to induce changes in the physical system. Finally, there are the interactions that take place within the policy system itself (Class 3). Understanding this class of links requires methods drawing upon organizational theory, and institutional and policy analyses.

While the interactions within the physical system and within the policy systems more readily fall under the domain of more traditional disciplinary perspectives, we would argue that the interactions between the policy and physical systems are of serious interest to the evolving field of engineering systems. Borrowing a phrase from Karl Popper (1972), “obviously what we want is to understand how such non-physical things as purposes, deliberations, plans, decisions, theories, intentions and values, can play a part in bringing about physical changes in the physical world” (cited in Almond and Genco (1977), emphasis in original).

5.3 Seek Insight about System Behavior (Step 5)

Once the general structure of the CLIOS has been established, and the behavior of individual components and links has been relatively well characterized, the next stage is to use this information to gain a better understanding of the overall system behavior, and where possible, counterintuitive or emergent system behavior. This step entails essentially tracing through the system at its different levels – the physical layers and policy spheres. However, many of the most important insights about the system behavior will come during the process of creating the diagrams, and the discipline of bringing a systems mindset to a large complex system. As illustrated in Figure 7, a core concern and motivation for this type of CLIOS Process is to think through the systemic impact that the organizations on the policy sphere can have on the physical system, and vice versa. For this reason, the policy levers have to be well identified.
By tracing through the pathways in the CLIOS, there are several sources of important systems behavior that can be identified by asking the following types of leading questions. First, with respect to the physical layers (Class 1 links), are there strong interactions within or between subsystems? Are there chains of links with fast-moving, high-influence interactions? Are some of the paths of links non-linear and/or irreversible in their impact? Finally, can strong positive or negative feedback loops be identified?

Second, looking at the links between the policy and the physical sphere (Class 2 links), can we identify components within the physical systems that are influenced by many different organizations in the policy sphere (“A” in Figure 7)? If so, are they pushing the system in the same direction, or is there competition among organizations in the direction of influence? Alternatively, do some organizations on the policy sphere have an influence on many components within the physical system (“B” in Figure 7)?

Finally, within the policy system itself (Class 3 links), are the relationships between organizations characterized by conflict or cooperation? Are there any high-influence interactions, or particularly strong organizations that have direct impacts on many other organizations within the policy sphere? What is the hierarchical structure of the policy system, and are there strong command and control relations among the organizations, and or are they more loosely coupled? What is the nature of interaction between organizations that both influence the same subsystems within the physical system (“A” in Figure 7)?

In this stage, rather than attempting to quantify the relationships, the focus should be more on simply “getting the sign right” (Marks, 2002) or understanding the direction of change through a series of complex and uncertain chains of links. Furthermore, here we may also begin to develop a catalogue of potential issues and solutions for the CLIOS. The idea is that in a CLIOS representation, certain types of links –fast, large magnitude, irreversible, etc. – should raise a warning flag that there could be a potential problem (or opportunity) arising from this link or sequence of links, forming a loop, which can create a “vicious” or “virtuous” cycle. In addition to these high impact links or chains of links, certain components may be pulled in two directions simultaneously by two different loops. These loops can be purely within the physical system, but are also likely to arise when different actors on the policy sphere have an influence on the same components within the physical system (as identified in Figure 7 as “A”).

6. SOLUTION DESIGN AND EVALUATION

Having considered the CLIOS from the standpoint of its structure and behavior, the next steps focus on the design and evaluation aspects of the CLIOS. We therefore begin to investigate in greater depth the evaluative complexity of the CLIOS, in order to identify opportunities for improving both the physical and the policy system, culminating in both the development of robust options for system improvements, as well as the organizational and institutional changes that may be necessary to implement these physical system strategies.

6.1 Identify Performance Measures and Refine System Goals (Step 6)

We first need to identify those system components that matter for the performance of a subsystem. Diagrammatically, we represent this for any of the system elements – components, common drivers, or policy levers – by a double line for the border.

Performance measures for CLIOS are often difficult to define, and it is not uncommon that consensus fails to be reached on even how to measure or prioritize different performance measures. In this sense, we are confronted with the evaluative complexity inherent in CLIOS. “Performance” will depend heavily upon the viewpoint of the analysts, decisionmakers, and stakeholders. However, it is also important that each of these actors involved in the CLIOS understand other actors’ measures of performance. One may even find that difficulties in defining performance measures that capture all of the phenomena of interest,
lead one back to the first step, to challenge the initial description and bounding of the system. This suggests that this process is highly iterative, since the following step, “Identify and Design Options for System Improvements” will provide important feedback regarding how to measure performance.

Referring to the diagram of the Passenger Transportation Subsystem, certain common drivers such as economic development or GDP per capita, are important performance measures for many stakeholders. Not only do these measures reflect the economic health of the city, but also because economic growth depends in part upon the efficacy of the transportation system to bring goods to customers, customers to stores, and employees to work, then economic health can indirectly reflect a well-functioning transportation system. Policy levers can also be performance measures in themselves. For example, the level of investment in public transport can be viewed as a performance measure, although it actually measures the financial inputs to the system, and not necessarily the output of that investment (e.g. better roads, cleaner bus fleets). Finally, components such as congestion or human health can be key performance measures.

Now with the notation for the CLIOS representation fully developed, we return briefly to the original diagram (Figure 5) of the passenger transportation subsystem. Figure 8 represents the same system as in Figure 5 after incorporating the notation for different elements – components, common drivers, and policy levers – some of which are performance measures as well. In addition, we have identified components that can be layered into separate subsystems (although we have not included these diagrams in this paper). These are identified by dashed lines for their boundaries.

[Figure 8]

6.2 Identify and Design Options for System Improvements (Step 7)

As the performance measures for the system and subsystems are established, it will naturally lead to questions about how the physical system’s performance can be improved. Indeed, performance improvements can be identified using the CLIOS representation in two directions. In terms of the diagram of nested complexity, we can think through options from the “outside in” or from the “inside out.”

Thinking through system performance from the “inside out” (from the inner physical layers to the outer policy sphere), is a more bottom-up engineering approach, in which we look first at the physical system, and ask how the subsystems in the physical system, through changes to the components or perhaps, in some cases, changes to the links between them, can lead to better performance. This approach usually leads to more technology-driven policy options such as technology mandates and standards, since there are clear specifications about the performance goals that need to be reached. Once the improvements “inside” the physical system are identified, one then looks “out” at the policy systems, to highlight the interventions that need to be made by the policy system to accomplish those changes to the physical system.

The alternative method is to look at the impact of policy options from the “outside in.” This approach to identifying system improvements is common when speaking of policy measures that rely on incentives or disincentives such as taxes, subsidies, voluntary agreements, and restrictions on certain behaviors. Implicit in these types of options is usually an assumption about how a policy change, beginning on the policy sphere, will cascade through the physical system, and what target for the performance measure will be reached. Following this process can also reveal where policy options are counterproductive, diminishing the performance in other parts of the system.
Here is an illustration of the distinction between these two approaches that considers emissions from private automobiles. The “inside out” approach is exemplified by technology mandates such as CAFE standards, in which a performance measure for a part of the physical system – average emissions by the fleet of vehicles – was targeted directly for improvement, with the final performance target explicitly set. The other approach, from the “outside in” would be the different types of behavioral change policies that have intended to reduce the aggregate number of vehicle kilometers traveled. These are policies such as congestion pricing, in which the policies are generally conceived first on the outer policy sphere, with a less precise idea exactly how it will work through the physical system.

Regardless of the approach taken, the insights from Step 5, where we identified areas of high-impact, counterintuitive and emergent behavior, are important in this step. Even for policies that are narrowly targeted on specific subsystems or components, the systemic impacts of all policies need to be considered, particularly if specific options targeting one performance measure can spillover to other performance measures.

6.3 Flag Important Areas of Uncertainty (Step 8)

A parallel activity to the identification of options for system performance improvements is to look for the uncertainty in the performance of the CLIOS, both at the subsystem and the CLIOS-wide level. In identifying the important uncertainties, one must rely on the insights gained in Step 5, in which we looked for chains of strong interactions, areas of conflict between policy organizations, or emergent behavior from positive feedback loops. For example, such signals included individual links or loops that had large magnitude, fast-moving, non-linear or irreversible influences on other components within the system.

The common drivers are another key source of uncertainty. Common drivers such as GDP and population can be highly uncertain in their long-term trends, and their overall impact on the CLIOS may be counterintuitive at times. Since these factors can simultaneously influence different subsystems in very different ways, the overall impact of the common drivers can be difficult to ascertain without systematically tracing through the CLIOS at each layer. These common drivers can have a particularly strong influence on the physical system when one considers the longer-run evolution of the CLIOS. For example, whether the Mexican economy grows only gradually, with many sharp downturns, or suddenly takes off, can radically influence the entire CLIOS through changes in demand for goods and services, including transportation and energy, levels of investment available, changes in land use patterns, supply and demand for different types of technologies, and the relative value placed on the environment and economic growth.

Finally, while flagging important areas of uncertainty, we should also highlight the “openness” of the system, and analyze the impact of these external factors, such as macroeconomic growth, international fuel prices, and national and international political trends that link the CLIOS to a even broader system. For this reason, we need to look for different tools and methodologies for understanding uncertainty in complex and, most importantly, highly open systems.

6.3.1 Understanding Uncertainty in Mexico City using Scenarios – Application Example of Step 8

One methodology for identifying key uncertainties and understanding their impact on the CLIOS is scenario planning, a tool developed by Royal Dutch/Shell in the years leading up to the oil shocks of the 1970s. Ged Davis, the current head of Shell’s Scenarios Team, defines scenarios as “coherent, credible stories about alternative futures” (Davis, 2002). Scenarios are used in the corporate context to make decisions in a complex and uncertain environment by fostering a new way of thinking about the future and its impact on strategy. While scenario planning has continued to evolve within Shell, becoming an
integral part of Shell’s strategic planning process, it has also found applications in a wide range of contexts besides corporate strategy.

We suggest that scenario planning can be a tool for “thinking through” the CLIOS-level impact of key uncertainties, including common drivers such as economic growth, population shifts, and rates of technological change. The basic steps for developing scenarios are: (a) identify the focal issue or decision, which is similar to Step 1 of the CLIOS Process, (b) identify the primary “driving forces”, including social dynamics, economic issues, political issues, and technological issues, often the “common drivers” of the CLIOS, (c) develop the scenario “logics”, in particular, looking at how these “driving forces” are intertwined, and what are the different paths they could follow, (d) flesh out the scenarios into coherent narratives or stories about alternative futures, and (e) explore the implications of the scenarios for the decisions and focal issues identified earlier.7

In the context of CLIOS, the most straightforward approach for scenario building would be to look at several combinations of trends in the common drivers, using these combinations as the basis for a handful of scenario logics or plots, and explore the implications of these scenarios. However, a more meaningful set of scenarios would link the CLIOS to the broader environment – since CLIOS are “open” systems, and the most significant uncertainties may come from outside the CLIOS. Therefore, one would look beyond the common drivers, perhaps to identify the external forces that influence the common drivers – forces such as international trade regimes, societal attitudes, environmental movements, and many others. This scenario building exercise has been done for the MCMA within the context of the Integrated Program on Urban, Regional and Global Air Pollution (Connors, et al, 2003, Dodder, 2003). The three scenarios – Changing Climates, Divided City, and Growth Unbound – were developed using the common drivers of environmental conditions including global climate change, urban form and sprawl, economic growth, population growth, social inequality and civic participation, political trends, and investment in technology and innovation. Table 1 summarizes the Mexico City scenarios or “future stories” according to the six common drivers.

[Table 1]

Scenario planning may be an important tool not only to identify and understand these key uncertainties, but also to evaluate the performance of options across uncertainties, as discussed in the next step.

6.4 Evaluate Options and Select Robust Ones that Perform “Best” Across Uncertainties (Step 9)

Robustness is defined as the ability of an option to perform reasonably well under different scenarios of the future. This represents a different approach than that of identifying an optimal option, which may only perform optimally under a constrained set of conditions. In fact, we would argue that achieving “optimal performance” is an unrealistic goal for a CLIOS. Given the range of performance measures involved, different stakeholder views, and trade-offs needed to obtain the necessary support for option implementation, simply finding a feasible option (one that works) may be the best expectation. One way of displaying robustness is with a matrix, where the columns represent different scenarios and the rows represent policy options; then we can see how the options perform compared across a range of futures.

[Table 2]

Where we see positive outcomes in each of the scenarios (Option 2, in the example) then the option is considered robust. In this case, the choice is straightforward. However, if choosing between Option 1

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7 The scenario planning concepts discussed here were developed by scenario planners such as Schwartz (1996) and Wack (1985). For a discussion of the extension of scenario planning to regional transportation planning, see Sussman and Conklin (2001).
and 3, this would depend upon the desire to avoid negative outcomes, in which case Option 3 would be preferable, even though Option 1 performs well in two out of the three scenarios, and extremely well in one of the scenarios. In further developing and refining both options and strategies, as will be described below, the focus should be upon combining options that can make strategies more robust across the entire set of possible futures.

Implicit in this discussion is that the design and evaluation of policy options will require some modeling and quantitative analysis. Most of the quantitative modeling will focus on specific parts of the system; such as policies to change passenger transportation mode share in Mexico City. While a focused quantitative analysis is necessary for better characterizing certain options, understanding how those options impact the rest of the system, both quantitatively and qualitatively, is an essential part of the design and evaluation of options. Therefore, an evaluation of an option might be presented in two parts, the first of which might be an engineering-based or benefit-cost analysis. The second part outlines the impacts on (1) other aspects of the same subsystem layer, (2) other subsystems, and (3) the actors on the policy sphere. This last step will also set the stage for the implementation phase of the CLIOS Process, as described below.

7. IMPLEMENTATION

7.1 Design Strategy for Implementation (Step 10)

Once a set of promising policy options is identified, the next crucial (but often overlooked) step is to design a strategy for implementation. Many policy analyses come to an end at Step 9 with a list of recommendations, but with little guidance as to what obstacles might arise in the implementation of these recommendations, how these recommended options can or should be combined into a coherent and integrated strategy, or how the realities of implementation will affect the design of the options and strategies. In the CLIOS Process, identifying a strategy for implementation requires taking the set of good options and identifying combinations of policy options that fit together in a comprehensive strategy.

By combining options, one may accomplish two goals. First, one can mitigate and/or compensate for negative impacts. Given the interconnectedness of the system, improvements along one dimension of performance may degrade performance in other areas of the system. Therefore, one should look for options that can either attenuate those negative impacts, or compensate those actors and stakeholders on the policy sphere that are negatively impacted, by including policy options that address their needs, even though these options might not have made the initial cut in Step 9.

Second, different combinations for options can improve the robustness of the overall strategy. Given the uncertainties in the individual options, certain combinations of options can provide insurance against extreme changes or shocks to the system, such as major shifts in the common drivers. For example, a certain option aimed at private automobiles may be highly sensitive to changes in household income levels, and might perform poorly in periods of extremely high or low economic growth. However, if we find that investments in public transportation seem to be less sensitive to economic growth, it may be that this option, in conjunction with the option aimed at private autos, provides a more dependable, if not necessarily an “optimal” outcome.

In working toward both of these goals, it is important to focus on all of the performance measures, and the trade-offs between them. Neglecting certain performance measures, especially those measures which are highly valued by certain actors on the policy sphere, can make a strategy vulnerable to strong resistance from groups that feel that their interests are threatened. This highlights another key task in developing a strategy for implementation, which is the use of the CLIOS representation to identify who is going to implement and enforce what option, as well as who has the potential to impede its implementation.
Looking along the policy sphere, to assess how each option impacts their interests, one can look for both the winners and losers resulting from certain actions. Then, returning to the issue of mitigation or compensation, one can begin to build coalitions that will overcome resistance created from the losers.

7.2 Identify Opportunities for Institutional Changes and Architecture (Step 11)

The structure of the institutional system itself may affect the ability to implement a strategy. For this reason, we consider Step 11 to be a parallel activity to Step 10, with institutional changes and architecture explicitly being a central part of the overarching strategy for implementation. Here, we define the architecture as a representation of organizational interactions among the institutions on the policy sphere of the CLIOS that manage the physical system. Therefore, part of Step 11 should be to evaluate the institutional arrangements that govern the management of the CLIOS. We suggest that this is one of the strengths of the CLIOS framework – that the analysis can be used to inform the development of an institutional architecture that is better able to support a well-functioning physical and technical architecture.

Returning to the concept of nested complexity, institutional architecture is central to the CLIOS Process for several reasons. First, by separating the policy sphere from the rest of the system, primarily the physical systems, we draw attention to the fact that the policy system is a complex system in its own right. Policy decisions cannot simply be subsumed as an additional element or component in a systems model, without losing the organizational and institutional context within which those decisions are made. Second, the separation of the policy sphere also highlights that different tools are needed to understand this aspect of the CLIOS. While the systems tools themselves can bring some insights, they need to be augmented by drawing upon the literature on political economy, institutions, organizational theory, and administrative science. Some useful tools and process from the economic, social, political and organizational perspectives are outlined in the Appendix.

While we typically focus on the influence of the policy sphere acting upon the physical sphere (taking the policy sphere to be static) the direction of interaction can also be from the physical system to the policy system as well, as seen in the bi-directional arrows in Figure 7. For example, changes (especially rapid changes) in the physical-technological systems can generate calls for policy intervention and induce major shifts in the policy and organizational structure.

Mexico City provides a clear example of how changes in the physical system can impact the types of policy-institutional structures that are needed to manage certain issues. To begin, the physical expansion of the urbanized area has progressed beyond the Federal District across state boundaries to the State of Mexico, and more recently, to the State of Hidalgo. This has put increasing pressure on policymakers to forge closer interjurisdictional linkages in order to coordinate across dozens of municipalities and three states, although political differences make sustained coordination difficult. In this manner, the physical system changes have generated a tension across the policy sphere, requiring new institutional arrangements at the metropolitan-level for environmental, transportation, human settlement and other metropolitan-wide issues. Attempts at reorganization along the policy sphere has been spurred not only by the expansion of the urban area, but also by the linkages between the many layers of the physical system – passenger transportation, freight, land use, industrial production, services, informal commerce.

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8 This definition is adapted from Sussman and Conklin (2001), where a regional architecture is defined “as a methodology for designing organizational interactions among the various agencies and private-sector firms that would participate in providing transportation services of any type at a regional scale”. Indeed, one can consider a regional architecture as a special case of an architecture, where the CLIOS is a regional transportation system.

9 The concept of developing an institutional architecture in parallel with a technical architecture comes from the RES/SITE work undertaken at MIT. See Sussman and Conklin (2001) and Gakenheimer, et al (1999) for a comprehensive review of this research.
and production, residential energy consumption, and the environment. However, with rapidly increasing
demand for transportation, this sector increasingly dominates the share of total emissions, therefore
intensifying the transportation-environment link in the physical system, and putting pressure on the
organizations on the policy sphere to deal with the transportation-environmental problem in a more
coordinated manner.

A final point regarding institutional changes-- When focusing on how the institutional architecture can be
modified to achieve the CLIOS goals, due consideration should be given to the organizations’ individual
and collective goals. Institutional changes may work against the goals of the organizations, and generate
not only external conflict among organizations, but also internal conflict as organizations attempt to adapt
to new institutional interactions. While organizations must “change internally as well as in their
institutional interactions with other organizations”, it is also true that “organizations, by their very nature,
change slowly” (Sussman, 2000b).

7.3 Post-Implementation Evaluation and Modification (Step 12)

Once strategies have been implemented, the following step is to monitor and observe whether the
intended improvement in system performance actually occurred. One should also be careful to identify
any unintended degradation in the performance of one subsystem, due to policies aimed at another
subsystem. The capability to monitor the success of policy options is often absent, and therefore one may
include monitoring systems as part of the strategy for implementation.

If the policy failed to achieve improved system performance, one should return to the CLIOS
representation to assess where and in what manner the failure actually occurred. Looking first at the
physical system, one could ask if there was any unanticipated emergent behavior that altered the
performance of the system or if any of the links were misrepresented or functioned differently than
expected. The lack of performance improvement could also indicate a failure within the policy system.
For example, are policy actors working in coordination or competition with one another (as identified in
Step 5), or were there fundamental disagreements on the performance measures, and therefore the type of
performance that was desirable (Step 6)?

7.3.1 Monitoring Policy Outcomes in Mexico City

In the case of Mexico City, one aspect of improved system performance would entail an improvement in
health due to reductions in pollutant emissions and concentrations. The most frequently cited statistics to
reflect these improvements are daily concentrations of the main pollutants – ozone (O\textsubscript{3}), carbon monoxide
(CO), nitrogen dioxide (NO\textsubscript{2}), sulfur dioxide (SO\textsubscript{2}), coarse particulate matter (PM10) and total suspended
particulates (TSP). Yet, assessing the real performance of policy options involves two additional types of
performance measures, beyond atmospheric concentrations: (a) avoided health costs in terms of decreased
mortality and morbidity, or fewer reduced activity days and school absences, and (b) lower actual
emissions from those sources that were actually targeted for emissions reductions, to see if the policy
interventions did in fact contribute to the observed declines in concentrations.

To take an example, measuring only decreases in ozone obscures much of the underlying dynamics. To
look more deeply, we need to identify the health benefits of that reduction, such as declines in ozone-
related mortality and morbidity. Furthermore, to identify the cause of reductions in ozone concentrations,
a secondary pollutant, we need to look at the relative changes in NO\textsubscript{x} and hydrocarbons (HC) that
contribute to ozone formation. Without this information, it is difficult to assess whether improvement in
ozone were the result of lower NO\textsubscript{x} emissions from sources such as private automobiles or lower HC
emissions from activities such as dry cleaning or solvent use.
This leads back to the complexity and uncertainty in the CLIOS. Because cause and effect are not straightforward in a CLIOS, in order to monitor and evaluate the effectiveness of individual policy options, one needs to measure changes in performance across multiple dimensions. In this manner, we can increase our confidence that the changes in performance outcomes were due to the policy options, rather than to undetected changes in other parts of the systems, or even the results of natural “noise” of the system, such as natural variability in the local meteorology. In fact, improvements in the ability to monitor and evaluate the impacts of policy measures on air quality may be a policy option in itself (Molina and Molina, 2002).

8. THE CLIOS PROCESS AS A CHRISTMAS TREE

To effectively utilize the CLIOS Process, additional existing tools and processes must be employed to successfully complete each of the 12 steps. Each of the 12 steps states what task should be completed when utilizing the CLIOS Process, but none of the steps explicitly describes how the task should be completed. The “how” is accomplished through the use of one or more specific processes and/or tools.

The “how” is left up to the analysts to determine, as this will be very CLIOS specific. The set of processes and tools that are chosen will vary from project to project, while the overarching CLIOS Process remains invariant. The CLIOS Process can be thought of as a Christmas Tree, with the various processes and tools used in the analysis comprising the ornaments hanging on the tree. The structure of the tree stays constant, while the choice of ornaments hanging on the tree varies to suit the taste or needs of the user. It is likely that analyzing a CLIOS will require processes and tools from a wide range of disciplines. Ideally, CLIOS Process analysts will have expertise, or access to expertise, spanning the range of disciplines relevant to their particular CLIOS, in order to help choose and utilize appropriate processes and tools, and to integrate the results produced therein. If the CLIOS Process is carried out within the context of an interdisciplinary team, each member can choose their processes and tools, while remaining conscious of where their work fits within the overarching structure of the 12 steps.

In general, the use of the CLIOS Process will require that appropriate existing processes and tools be employed in an iterative manner, usually beginning with a more qualitative analysis that progressively becomes more qualitative in nature as additional understanding is realized.

Since a CLIOS will involve nested complexity between a technical system and an organizational/institutional/management/policy system, processes and tools that can help analyze and shape both the technical and institutional systems are necessary. The nested complexity of the CLIOS generates a bi-directional symbiotic relationship between the physical and institutional systems, creating a need for tools with the ability to affect change in the physical and the institutional systems.

It is stressed here that the CLIOS Process is a high-level process that is used to systematically organize the understanding of problems affecting a CLIOS and the generation of solutions. The CLIOS Process is not the only process one could use to guide the analysis of problems and generation of solutions. However, we believe that the CLIOS Process is a useful way to organize the various lower-level processes and tools that are needed to adequately analyze problems and generate solutions for a CLIOS. This combination of consistency in the high-level process or framework, and flexibility in the lower-level tools and processes one of the major contributions to interdisciplinary systems research.

8.1 Hanging the Ornaments on the CLIOS Christmas Tree

To show how various tools and processes are mapped onto the CLIOS process, Figures 9), 10) and 11) are present. Each figure shows how various familiar tools and processes in different domains are mapped onto the CLIOS Process. Each figure is divided into two main parts. On the left hand side of each figure

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is the CLIOS Process, reproduced in its entirety for easy reference. On the right hand side of the figures are various processes and tools that have been identified. Three aspects of the structure – perspectives, process, and tools – used to create this portion of the figures are explained below. More detailed explanations of each of the mappings is presented in the Appendix.

8.1.1 Perspectives

Three different perspectives -- technical, economic and social/political/organizational -- have been identified. These three perspectives were chosen because the processes and tools are often different in each\(^\text{10}\). The technical perspective is a general category containing processes and tools, such as those based in science and engineering, etc. The economic perspective includes processes and tools, such as finance, accounting, econometrics, etc. The social/political perspective includes several domains, such as management, politics, administrative science, etc.

It can be argued that additional perspectives should be included (for example, inclusion of an environmental perspective) or that a finer division between perspectives should be presented (for example, separate political and management tools into different perspectives). While both points have merit, for the purpose of this paper of explaining how different processes and tools hang on the CLIOS Process, the three perspectives used here are deemed sufficient.

8.1.2 Processes

Processes denote a set of steps that help the user systematically understand and solve problems. Processes often tell the user what steps to take, but as with the CLIOS itself leave it up to the user to decide how to complete the tasks described in each step.

8.1.3 Tools

Tools are employed to help achieve a specific result. Tools are often employed as the means to accomplishing what a process denotes as a task. The difference between processes and tools is not always sharp, as tools themselves often have a process that must be followed if they are to be used properly. However, in general, the processes denote a set of steps stating what should be done while tools provide the specific means for accomplishing the tasks denoted in processes.

Analysis Tools - Tools can be used for either analysis or implementation purposes. Analysis tools enable us to understand problems and develop solutions.

Implementation Tools - Implementation tools are used to implement the plan previously developed. The distinction between analysis and implementation tools is not always clear cut, as some tools are used in different contexts to help both the analysis and the implementation.

[Figure 9]

[Figure 10]

[Figure 11]

\(^{10}\) While it is believed that each perspective is substantially different from one another, it is recognized that there is some overlap. This appears as some tools appearing in multiple perspectives. It should be noted that while some tools appear in multiple perspectives, their usage and utility to users is often different when employed in different perspectives.
9. CLIOS PROCESS WITHIN THE CONTEXT OF SYSTEMS APPROACHES

9.1 Analysts and Audiences

In thinking about the “market” for the CLIOS Process for approaching engineering systems, we are inclined to focus on more qualitatively-oriented analysts, who must grapple with both highly complex physical systems and policy systems. In this sense, the organizing framework of the CLIOS Process provides an approach that encompasses the physical and policy systems, while also focusing qualitatively on the links between the two and the emergent behavior that arises as a result.

CLIOS may prove to be better at allowing for the broad scope of analysis undertaken by those involved in policy and planning. The CLIOS Process, by recognizing that these are “open” systems, can be used to include a broader range of issues and phenomena that might be difficult to characterize using a quantitative system analysis that suggests a more “closed” system.

Thinking about both the analysts and the policymakers/stakeholders for whom the analysis is being developed, we can ask whether the CLIOS Process: (a) communicates the dynamics of the system and the tradeoffs among different performance measures to decision makers and stakeholders, (b) supports dialogue between decision makers, each of whom may have jurisdiction over certain parts of the system, to understand where they interact, and where their actions may be in conflict or could possibly work in the same direction, and (c) building on this dialogue, assists in the development of an institutional architecture that is better able to manage the system (Mostashari, 2004).

Emphasizing the point raised earlier in the description of Figure 7 – Nested Complexity and Layers of Physical Subsystems – we argue that the visualization element of the CLIOS diagram is central. Part of the value of the CLIOS Process could be that of a common organizing framework that all of the various stakeholders, decisionmakers and policymakers (those located on the outside policy sphere) can use to specify their particular role relative to that of other organizations and institutions. In fact, while this paper has outlined the CLIOS Process, as it would be carried out by a single analyst, further development of the methodology could focus on participation by stakeholders and decisionmakers using the CLIOS Process as a collaborative group process (Mostashari, 2004). It is envisioned that the CLIOS Process could allow a forum where stakeholder concerns are systematically raised and elaborated upon by stakeholders, so that these concerns can be adequately addressed by decisionmakers and policy makers. In the context of the unsustainable patterns of metropolitan development that has taken place in California, Innes (1997) notes that “efforts to intervene have been made by one or another set of interests, each grasping the elephant by only one of its parts and misunderstanding the whole”. This is not uncommon in the policy world as a multitude of agents have an influence on a complex and integrated system. Perhaps clearer frameworks for understanding such complex systems could enable decisionmakers to see their function as “part of a complex system of linked factors in the physical environmental and the governmental context” (Innes, 1997).

9.2 Comparison with other Systems Approaches

Having outlined the steps in a CLIOS Process, we now step back and compare a CLIOS Process to other systems approaches, in order to identify its advantages, limitations, and scope of applicability relative to traditional system approaches. In terms of its advantages, we suggest that the CLIOS Process provides a new systems approach that represents the entire system – physical and institutional – as is relevant to the problem definition or multiple problem definitions that motivate the analysis. In representing the system

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11 These questions parallel many of the issues that arise in performing Integrated Assessments, which are intended to support more policy-defined scientific and technical assessments of complex issues (Dodder et al, 2000).
in its more comprehensive form, we explicitly include the policy world as a part of the system, recognizing that changes to existing policy structures are not only an option, but are often necessary in order to implement options to improve the system’s performance. We also emphasize the interactions between the policy system and the physical systems – both the impact of the policy sphere on the physical system, and impact of the physical system and its performance on the policy sphere.

The incorporation of the policy sphere, while allowing for a broader scope of analysis, necessitates that qualitative as well as quantitative factors are included in the analysis. While this differs sharply from many other systems approaches, learning to incorporate factors that cannot be easily quantified (or quantified at all) is a necessary step if systems thinking is to be extended to social and political systems. While some might argue that all social and political factors can be quantified in some manner, our view is that in many cases quantifying social and political factors may frame the analysis in terms that no longer have any useful meaning for decisionmakers and policymakers. In addition, the CLIOS representation, by essentially abandoning the often-ineffactual search for a system optimum, focuses instead on the tradeoffs and uncertainties that are more characteristic of the policymaking process.

The analyst is given substantial flexibility in deciding the amount of detail in which certain aspects of the system are described. This creates both benefits and potential problems. On the one hand, this flexibility allows the analyst to tailor the CLIOS Process to address the issues that provide the foundation for the analysis. For example, whether a component is developed into a separate subsystem or expanded, is driven by whether understanding the inner dynamics of that component is essential for identifying options for policy intervention. On the other hand, this tailoring of the CLIOS representation can make the outcome highly dependent upon the values and perspective of the analyst. In the CLIOS Process, our intent is to emphasize identifying system performance metrics that are relevant to the organizations on the policy sphere. This, we hope, would constrain the extent to which the analyst’s own bias enters into the representation of the system. Furthermore, by forcing the analyst to explicitly represent their characterization of the system diagrammatically, the process provides a transparency that allows potential users of the analysis to challenge any apparent biases. By providing a structured (literally step-by-step) process for undertaking the analysis, it not only minimizes the omission of salient factors, but also injects greater rigor and structure to the analysis.

Another challenge is in finding a balance between the capturing the detail and complexity of the CLIOS, and exceeding the cognitive limits of the analyst. The supporting diagrams can become extremely complicated, making analysis of feedbacks and tracing the linkages within and between systems intractable. We have introduced layering, nesting and expanding as possible tools to contain the complexity of an individual subsystem diagram, by enabling the analysts to look at a specific slice of the system (a single layer, a policy sphere, or an “expanded” component). But, we recognize the analyst must bring a system’s mindset and a discerning eye to identify important loops and interactions, even though freed from the need for quantification at the representation phase of the CLIOS Process.

While the CLIOS Process has evolved significantly from a conceptual framework to a new systems approach, this methodology continues to develop through application to various CLIOS examples. Given the continuing maturation of engineering systems as an emerging discipline, we propose that by clearly defining concepts, explicitly outlining analytical procedures, and applying these concepts and procedures to actual systems, engineering systems researchers can explicate existing debates and identify new topics for investigation. In this context, we hope that further application of the CLIOS Process can serve to provide new perspectives and insights on engineering systems problems, and that through this process, we can further refine the procedures contained in the CLIOS Process.
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Table 1: Scenarios Logics for Three Mexico City “Future Stories”

<table>
<thead>
<tr>
<th></th>
<th>Growth Unbound</th>
<th>Divided City</th>
<th>Changing Climates</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Economics</strong></td>
<td>✓ 4.5% national GDP growth</td>
<td>2.2% national GDP growth</td>
<td>3.5% national GDP growth</td>
</tr>
<tr>
<td></td>
<td>Strong growth in manufacturing</td>
<td>Growing share of non-financial (often informal) services</td>
<td>Higher growth in commercial &amp; financial services</td>
</tr>
<tr>
<td></td>
<td>Finance strong, but commercial services weaker</td>
<td>Modest manufacturing growth</td>
<td>Shift away from manufacturing</td>
</tr>
<tr>
<td><strong>Society</strong></td>
<td>✓ Income inequality worsened</td>
<td>Large informal sector</td>
<td>Improving income equality</td>
</tr>
<tr>
<td></td>
<td>Security remains problematic</td>
<td>Urban instability</td>
<td>Convergence in income across MCMA</td>
</tr>
<tr>
<td></td>
<td>Income inequalities persist</td>
<td>Civic participation vocal</td>
<td>Growing civic participation</td>
</tr>
<tr>
<td><strong>Urban Form</strong></td>
<td>✓ Low population growth</td>
<td>High population growth</td>
<td>Moderate population growth</td>
</tr>
<tr>
<td></td>
<td>Auto-dependent sprawl</td>
<td>Spread of urban area</td>
<td>Slowing sprawl and re-densification of city center</td>
</tr>
<tr>
<td></td>
<td>Suburban/office park development</td>
<td>Large portion of irregular households</td>
<td>Shrinking household size</td>
</tr>
<tr>
<td><strong>Technology</strong></td>
<td>Rapid turnover of technologies</td>
<td>Long lag time with US technologies</td>
<td>✓ Convergence with US tech.</td>
</tr>
<tr>
<td></td>
<td>Still lagging US standards on efficiency and emissions control equipment</td>
<td>Slow turnover of existing fleets and infrastructure</td>
<td>High investment in S&amp;T</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Rapid diffusion of international “best practices”</td>
</tr>
<tr>
<td><strong>Politics</strong></td>
<td>✓ Inter-jurisdictional conflict</td>
<td>Further fragmentation of political parties and highly competitive</td>
<td>Government intervention high in investment and enforcement</td>
</tr>
<tr>
<td></td>
<td>Government intervention low</td>
<td>Corruption high</td>
<td>Better accountability</td>
</tr>
<tr>
<td></td>
<td>Institutional reforms slow</td>
<td></td>
<td>Metro governance successful</td>
</tr>
<tr>
<td><strong>Environment</strong></td>
<td>Environmental issues not addressed</td>
<td>Social problems overshadow environmental issues</td>
<td>✓ Growing evidence of ‘heat island’ effects</td>
</tr>
<tr>
<td></td>
<td>Public apathy and resignation toward environmental agenda</td>
<td>Water becomes the critical environmental issue</td>
<td>Strong international and local action on the climate agenda</td>
</tr>
</tbody>
</table>

✓ Checkmarks indicate the two macro drivers that “drive” each future story.
Table 2. Testing Robustness of Options.

<table>
<thead>
<tr>
<th></th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Option 1</td>
<td>0</td>
<td>–</td>
<td>++</td>
</tr>
<tr>
<td>Option 2</td>
<td>+</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Option 3</td>
<td>+</td>
<td>0</td>
<td>+</td>
</tr>
</tbody>
</table>
APPENDIX
This appendix concentrates on elaborating upon each of the processes and tools displayed in Figure 9, 10 and 11. The appendix contains a brief explanation on each process or tool and how each is used.

A.1. TECHNICAL PERSPECTIVE

A.1.1. Systems Engineering

Systems engineering is a process for understanding a problem and creating a solution by looking at the problem in a top-down manner. This means that the problem is considered from the viewpoint of the entire system and is then broken down into a series of smaller and smaller sub-systems that are individually “solved” and then integrated together. While there are many variations of systems engineering, all variants essentially have two main parts: requirement generation and design solution. A fundamental concept of systems engineering is the belief that the process should be iterative – that is, as additional information is learned, the problem statement and design solution should change to reflect this new information. Another hallmark of systems engineering is the recognition that teams need to be interdisciplinary in nature to effectively solve problems.

The systems engineering process is often used to help make management and technical decisions about the system by presenting alternatives in the form of trade-offs. The three primary trade-offs that are often presented are in the form of technical performance, program cost and schedule. The difference between systems engineering and systems management is often blurred, as systems engineers and program managers are often the same individuals or organization.

Systems engineering was developed in the 1950’s with the advent of large technical projects. It was initially created for use in the aerospace domain for missile and spacecraft development, though it has spread in use to many other fields. After using systems engineering in the Apollo Program, systems engineering was applied to social issues such as poverty and urban design, with less success. Traditionally, systems engineering has dealt with technical systems.

A.1.2. Integrated Product and Process Development (IPPD)

IPPD is a refined form of systems engineering. The primary increment to systems engineering is the explicit recognition that the product and the process (manufacturability) by which the product will be produced need to be developed simultaneously. In this manner, the product and process design influence each other in an iterative manner.

A.1.3. Total Quality Management (TQM)

TQM expands upon systems engineering by explicitly considering factors beyond product or process that relate to developing a successful solution, such as management approaches, organizational culture and services. The driving goal of TQM is to satisfy the customer. This is accomplished through the integration and improvement of management practices, organizational culture, workforce moral, technical improvements and cost control.

A.1.4. Requirements Analysis and Management

Requirements are defined from the problem statement and encompass the set of functions that must be provided for in the system if the system is to be considered a success. Requirements state what has to be included in the system and how well the system must perform, but requirements do not state how the system is to accomplish what is laid out in the requirements.

Dodder, Sussman and McConnell
Requirement analysis and management deal with the process of developing, understanding and updating requirements as the program matures and additional information is known. As requirements are often set at the start of a project when little information is known, requirements that are set are often unrealistic and must be modified during the course of the project. The process of understanding what the requirements means is known as requirement analysis, while the entire process of understanding, updating and ensuring that requirements are being met is requirements management.

A.1.5. Benchmarking

Benchmarking is the process of identifying a comparable product, process, etc. and setting its performance as a standard to be met by one’s own product, process, etc. Typically, the product or process that serves as the benchmark is a recognized leader or excels in some way. The purpose of setting a benchmark is to improve performance by identifying a performance gap and then striving to close that gap. Benchmarking is often used to identify problems, understand the performance of a system better and set future goals.

A.1.6. Forecasting

Forecasting is the process of analyzing past and current data and making projections as to what events and trends will likely occur in the future. Forecasting is used to help understand what future needs will likely be based on what past experience has demonstrated. As the future is uncertain, forecasting is a tool that is used to help make decisions now that will last far into the future.

A.1.7. Technical Domain Analysis

Technical domain analysis refers to any type of technical analysis that is needed to understand a system. Examples are numerous and span the range of disciplines. Some examples include finite element analysis for stress and strain, computational fluid dynamics, electric circuit analysis, etc. The type of domain analysis that is needed is highly dependant on the nature of the project.

A.1.8. Scenario Analysis

Scenario Analysis is a tool used to help understand future uncertainties and how these uncertainties will affect the design and performance of the system. Scenario analysis consists of two parts: generation of an internally consistent story and quantitative description of the story line. Scenario analysis is often used in conjunction with forecasting and sensitivity analysis to project future trends that are then used to analyze system performance. Normally, systems that have robust performance, meaning that the system performs well over a variety of possible futures, are desirable.

Scenario analysis is often used in multiple capacities. In a purely analytical sense, scenario analysis is used to help understand how the system performs and create design solutions. Scenario analysis can also be used in more of an implementation setting, where different implementation strategies are created and then played out against scenarios to help determine the effectiveness of the implementation strategies.

A.1.9. Sensitivity Analysis

Sensitivity analysis is a tool to help determine and understand how sensitive a system is to changes in specific parameters. Different parameters individually or in groups are changed and the effect that this change has on system performance is then observed. In an iterative process, the system design is modified to accommodate, reduce or increase system sensitivity, depending on the specifics of needs of the program.
A.1.10. Trade-Off Analysis

Trade-off analysis is used to help understand the set of design choices that must be made, presented as a set of possible exchanges. Trade-offs can be made either between system performance, cost and schedule or trade-offs can be made within one of these, such as different performance trade-offs. Trade-offs are usually presented to management or policymakers, especially when the decisions coming from a trade-off will substantially affect the system.

A.2. ECONOMIC PERSPECTIVE

A.2.1. Discounted Cash Flow Analysis (DCF)

DCF is used to normalize a series of financial outlays and incomes over time. The normalization is the discounting of future cash flows expressed as present day value. DCF can be used to reduce a series of cash flows down to a single number. This number is commonly used to compare cash flows of different projects for the purpose of making decisions about where to expend resources. Commonly, projects with a higher present value will receive higher priority for resource allocation.

A.2.2. Benefit-Cost Analysis (BCA)

Benefit-Cost Analysis, or Cost-Benefit Analysis, is used to compare costs and benefits of systems. Simply, in BCA all costs and all benefits are summed separately and then compared. If the benefits are larger than the costs, the project is deemed worthwhile. Projects can also be compared according to their ratio of benefits to costs. BCA is most commonly expressed in monetary terms. Over time, expansions to BCA have been made that include difficult to quantify and value factors, such as the value of a statistical life, which makes use of BCA often highly contentious with different interest groups arriving at vastly different conclusions using the same analysis tool. Another difficulty with BCA is that in the summing of total benefits and costs, the distribution of those benefits and costs is ignored. However, this distribution of winners and losers from a change to the system is important to implementation. Therefore, it should be coupled with processes and tools from the social and political perspective. BCA is used to understand the costs and benefits associated with a system and is commonly also used as a decision tool that management can use to determine whether or not a project should receive resources.

A.2.3. Game Theory

Game theory is a tool used to help understand and anticipate how players in a game will react and behave given different conditions. Assuming that players are rational, opposing players can analyze anticipated opponent behavior to craft a dominant strategy that will maximize their performance relative to that of the opponent. Game theory is often used to try and understand the behavior of other people and other organizations in a systematic manner, for example, whether the outcome of the “game” will be conflict or cooperation, an important consideration in policy analysis.

A.2.4. Decision Analysis

Decision Analysis is a tool to help systematically identify and understand different system alternatives and the decisions that must be made to enable the alternatives. Decision analysis is presented in a tree format, where the user follows the flow of the tree until a branch is encountered, where branches represent decision points. Often, decision analysis is quantified, with expected costs or benefits of each decision outcome represented. When different alternatives are selected by chance as opposed to
decisions, probabilities are often assigned to each outcome possibility. Decision analysis is a tool that is used both in system analysis and in decision making.

A.2.5. Real Options Analysis (ROA)

ROA is similar to decision analysis in that different alternatives, or options, are presented to the decision maker. The mathematics behind ROA is based on the valuation of financial options. A key difference in the mathematics between ROA and decision analysis is that ROA does not rely on knowing probabilities of events or the risk appetite of the decision maker.

A.2.6. LBO et al.

Various methods to build, operate, buy, lease and transfer systems exist that allow large systems to be funded, built and operated by private industry. Traditionally, only public sector organizations have had the resources and the risk appetite to construct large scale systems. With decreases in public funding available, new public-private partnership arrangements have been developed to help private funding sources bring large scale systems to market. While these various public-private partnerships are used to implement large scale systems, the type of public-private partnership that is chosen or designed will have a large influence on the eventual design of the system. This is because the public private partnership will specify funding, which is often non-separable from the performance considerations of the system.

A.3. SOCIAL, POLITICAL AND ORGANIZATIONAL PERSPECTIVE

A.3.1. Negotiations

Negotiation is a process embarked upon by various stakeholders to reach an agreement that is mutually acceptable by all parties. Often, negotiations must be ongoing to maintain an agreement, especially as the environment or stakeholders change. Negotiations are usually conducted at the end of analysis and have as the goal the implementation of some system solution to a recognized problem. Different stakeholders will bring different sets of analysis to the negotiations to strengthen their position. Looking ahead to negotiations – the type of negotiations that are expected to be encountered or the anticipated strategy of opponents in negotiations – will influence the type of analysis that is required.

A.3.2. Stakeholder Analysis

Stakeholder analysis is used to identify stakeholders and stakeholder interests and positions (which are not one and the same). The purpose of the analysis is to help ensure that all relevant stakeholders have been identified, including non-present, or not-yet-identified stakeholders, and understanding their concerns well enough to include them in the system design. Stakeholder analysis can be used not only to identify the different concerns that need to be included in the system analysis and design, but it can also be used as an implementation tool. By explicitly including stakeholders in the analysis, their support can often be obtained, which makes implementation of the system easier to do in the future.

A.2.3. System Dynamics

System Dynamics is a tool for systematically analyzing and understanding a system. System dynamics has been especially useful at uncovering, understanding and modeling non-intuitive processes that occur in a system, such as time delays and stock and flow interdependencies. System dynamics usually includes a simulation of the system that models the stocks and flows that drive system behavior.

A.2.4. Delphi Process
The Delphi Process is a tool used to help understand problems and make decisions. Originally, the Delphi Process was used to try and understand new and complex systems which had not been previously studied. The Delphi Process used a series of interviews and surveys of experts in related fields and compiled their opinions to help understand the new system. As it has evolved the Delphi Process has been used on a smaller scale to help understand existing systems. In these cases, people associated with the system are asked to submit their opinions on the system in an anonymous fashion. The anonymity involved is designed to help elicit the truth about the system. The results of the Delphi Process are often used to both understand the system and then implement decisions concerning future choices associated with the system.