THE CLIOS PROCESS

SPECIAL EDITION FOR THE EAST JAPAN RAILWAY COMPANY

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FOREWORD TO THE SPECIAL EDITION FOR JR EAST

This special edition of the CLIOS Process Teaching Note has been issued as part of a cooperative research project between the East Japan Railway Company (JR East) and the Massachusetts Institute of Technology (MIT). The purpose of the project is to apply the CLIOS Process in the context of JR East's high-speed rail (HSR)-related international opportunities.

The CLIOS Process has been developed at the Massachusetts Institute of Technology (MIT) over a long period of time, to study what we call Complex Sociotechnical Systems. In its first decade of existence, the CLIOS Process has continuously evolved; further, there have been many applications of the process in different contexts. In fact, each application of the process has added to the viability of the CLIOS process and contributed to its evolution and improvement.

Now, JR East's search for international opportunities opens the door to a new kind of application of the CLIOS Process. On one hand, JR East's potential clients -- countries and regions -- are interested in HSR and may consider *strategic alternatives* to enhance the performance of their system. On the other hand JR East may undertake some *actions* depending upon their client's selection of strategic alternatives (e.g. a particular network configuration for their HSR system). Thus, JR East and their clients co-evolve: JR East actions can influence the client, which in turn selects strategic alternatives that may suggest further actions by JR East. In this sense, JR East and its clients co-evolve via the interplay of client selection of strategic alternatives and JR East's corresponding actions. This is a new and exciting application of the CLIOS Process that can have special value for JR East as it considers its way forward in the international HSR world.

In 1991, when JR East endowed a professorship at MIT, the idea was to establish a relationship between a world-class railway and a world-class education and research university. This relationship has proved to be mutually advantageous. This new project is intended to break new ground in the relationship, by providing research that can be of value to JR East in their international endeavors and also advance the intellectual capital at MIT through a unique extension of the CLIOS Process.

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Mr. Masaki Ogata (left), JR East Vice-Chairman, presents to Prof. Claude Canizares (right), MIT's vice president for research and associate provost, a model of JR East's newest Shinkansen bullet train, the Falcon, at the Twentieth Anniversary Celebration of the JR East Professorship at MIT. (Photo: Jameson Toole, 2011)

Cover photo: JR East President Masatake Matsuda (left), Mr. Arimori, Director of JR East Research and Development (far left), and a translator (middle) in a conversation with Prof. Sussman (right).

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

When we try to pick out anything by itself, we find it hitched to everything else in the universe

John Muir

EXECUTIVE SUMMARY

Complex, Large-scale, Interconnected, Open, Sociotechnical (CLIOS) Systems are a class of engineering systems with wide-ranging social and environmental impacts. They are comprised of both a physical and an institutional system. They exhibit nested and evaluative complexity, and require interdisciplinary approaches for their study and intervention.

The CLIOS Process is thus an organizing mechanism for understanding a CLIOS System's underlying structure and behavior, identifying and deploying strategic alternatives for improving the CLIOS System's performance, and monitoring the performance of those strategic alternatives.

The CLIOS Process consists of three stages that cover a descriptive and a prescriptive treatment of the CLIOS System:

1. *Representation* of the CLIOS System structure and behavior
2. *Design, Evaluation, and Selection* of CLIOS System strategic alternatives
3. *Implementation and Adaptation* of the selected strategic alternatives

Moreover, it is an iterative process that allows for continuous learning about the system by both studying and intervening in the system.

The study of CLIOS Systems requires the use of a variety of models and frameworks, with quantitative engineering and economic models being used for the physical domain, and qualitative frameworks for understanding institutional, organizational and stakeholder behavior being used for the institutional sphere. An important aspect of the CLIOS Process is the integration of the analyses of the physical domain and institutional sphere, and the development of strategic alternatives for both.

The CLIOS Process is modular and flexible, and can be thought of as a Christmas tree and its ornaments; the tree represents the overall process and the ornaments represent the specific tools that one can use for specific steps in the overall process. While the CLIOS Process has a specific macro-structure, its inherent flexibility allows different analysts to tailor the process to their specific needs.

Our intent with the CLIOS Process is to: (1) provide a structure for undertaking the analysis, (2) increase the amount of rigor and validity in the analysis, and (3) facilitate the identification of alternatives that are relevant to the actors on the institutional sphere.

We suggest that the CLIOS Process provides an innovative systems approach that represents the entire system – physical and institutional – in an integrated form. The CLIOS Process explicitly includes the institutional world as part of the system, recognizing that changes to existing institutional structures are not only a strategic alternative, but are often necessary in order to implement other strategic alternatives to improve system performance.

PREFACE: CLIOS SYSTEMS

The purpose of this paper is to serve as an introduction to the CLIOS Process and to guide interested students, researchers, and analysts on how to successfully apply it in ways that both structure and add value to their analysis.

This document is structured as follows:

In the **Preface,** we discuss Critical Contemporary Issues (CCIs), their relation to Complex Sociotechnical Systems (CSSs), and the need for and the value of a CLIOS Process.

In **Chapter 1-5,** we detail the CLIOS Process step-by-step: **Chapter 1** gives an overview of the CLIOS Process, **Chapters 2-4** show its three stages, and **Chapter 5** describes its iterations.

Finally, in the appendixes, we present:

- **Appendix A:** Glossary
- **Appendix B:** List of potential models and frameworks that can be used to address various aspects of the system's analysis on an as-needed basis
- **Appendixes C and D:** Two examples of applications of the CLIOS Process
- **Appendix E:** Discussion of CLIOS Process within the Context of Systems Approaches
- **Appendix F:** List of applications of the CLIOS Process to date

i. Critical Contemporary Issues and Complex Sociotechnical Systems

We first begin by defining two interlinking concepts: Critical Contemporary Issues (CCIs) and Complex Sociotechnical Systems (CSSs).

Critical Contemporary Issues:

Critical Contemporary Issues (CCIs) are a variety of issues that we face in contemporary society, which are very expensive on many dimensions and have substantial impact on the human condition on this planet.

Examples of CCIs include productivity; competitiveness; economic development; sustainability, including energy/environment/air quality/global climate change; urban form (e.g., the mega-cities of the developing world and sprawl in the developed world); social equity; environmental justice; quality of life; congestion/mobility/accessibility; security; technology development and deployment; and doubtless many others.

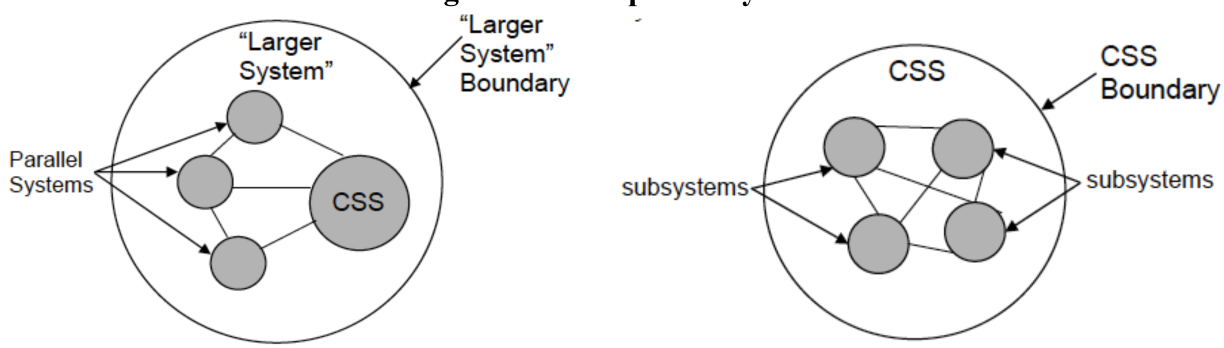
As one looks at this list, one recognizes that these are hardly disconnected. For example, if one looks at energy and the environment, one can tie it to mobility and how we are going to create an energy system that allows us to retain mobility—and the economic development it enables -- without having profoundly negative effects on the environment. So these issues all interconnect with each other.

Virtually all CCIs, we argue, have a Complex Sociotechnical System (CSS) at its core and share the characteristic of requiring *interdisciplinary* approaches – approaches that do not come neatly boxed in traditional disciplines but rather are integrative in nature. If we are going to deal with these CCIs, we're going to need to understand CSSs and how we can use CSSs as a way of thinking about issues we are so appropriately concerned about.

Complex Sociotechnical Systems:

First, let's look at an intuitive definition of a "*system*". Essentially the idea is having interconnected components and subsystems that exhibit a behavior not exhibited by the components and subsystems. Often they are structured hierarchically. Usually, the systems we are interested in interact with their environment; they provide input to the environment and receive input from the environment; they are often stochastic in character; they are often nonlinear; feedback is critical both internally within the system and with the external environment. Figure 1 shows a representation of systems.

Figure 1: Examples of Systems



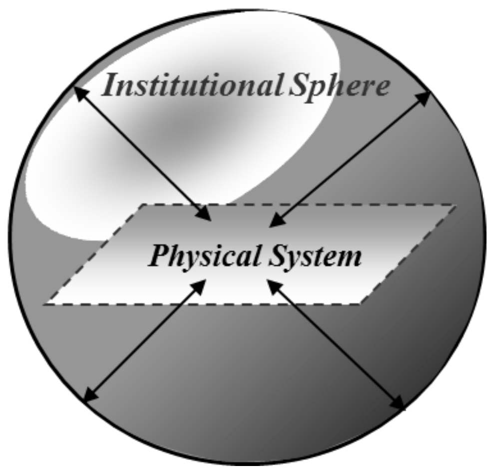
The word "s*ociotechnical*" lends itself to a relatively intuitive definition as well. Sociotechnical systems contain important technology subsystems and components that help control the system and are central to their performance. At the same time, sociotechnical systems have societal, political, and economic relevance and impact, that is, they are connected quite directly to the social context within which we operate. So, in sociotechnical systems, both the technical aspects and the social context within which the systems are operating play a central role, unlike in purely technical or social systems.

Various kinds of "*complexity*" emerge in the context of sociotechnical systems. This is why we call them Complex Sociotechnical Systems (CSSs). A system is complex when it is composed of a group of interrelated components and subsystems, for which the degree and nature of the relationships between them is imperfectly known, with varying directionality, magnitude, and time-scales of interactions. While there are several types of complexity (see Sussman, 2002; Lloyd, 2002), we are primarily concerned with four types for CSSs:

- **Structural Complexity** occurs due to the large number of components in a system and the network of interconnections between them.
- **Behavioral Complexity** exists when system performance is difficult to predict, even if we understand the behavior of individual parts. This type of behavior emerges due to the manner in which sets of components interact.

- **Evaluative Complexity** reflects the fact that in a multi-stakeholder environment we have competing perspectives about what good performance actually means. Different stakeholders value system performance in different ways. What may be good performance to one stakeholder may not be good performance to another stakeholder.
- **Nested Complexity** is the notion that we have a system with a complex *physical domain*, but surrounded by what we call the *institutional sphere*, complex in its own right, which has the relevant organizations and stakeholders on it (Figure 2). The physical domain follows quantitative principles that can be approximated by engineering and economic models, while the institutional sphere requires methodologies usually more qualitative in nature and often more participatory, such as evaluation of stakeholder perspectives and organizational analysis. We therefore have "nested complexity" when the physical domain is being affected or managed, loosely speaking, by a complex organizational and policymaking system. Understanding nested complexity is a necessary step in moving towards better integrating institutional design with technical design.

Figure 2: Nested Complexity



Both evaluative complexity and nested complexity are characteristic of sociotechnical systems, which make our job all the more difficult.

Beyond Study to Design of CSSs – We Are Not Simply Observers:

Those characteristics of CSSs require a specialized structure to study them. However, we are not simply observers trying to understand how the CSS works (although that is clearly an important aspect) and perhaps predict how it might work under other circumstances (although that is necessary as well). We are ultimately interested in improving the performance of the CSS, that is, in designing them, in doing interventions that make the world a better place.

We are interested in CSSs that are *purposeful*, namely, there is some goal that we want to achieve through the CSS. When we talk about *design* of CSS, we go beyond merely observing and representing the system. We have a normative perspective. We need to understand what good performance means, and given *evaluative complexity*, good performance may be very difficult to define categorically, given the sometimes divergent views of different stakeholders.

Then beyond the normative view, we have a prescriptive view: how do we make our CSS actually perform better? Now that we have decided (with some difficulty) what better performance means, how do we actually take actions to improve system performance? And here *nested complexity* rears its head since the organizations on the institutional sphere may well resist any change they do not see as in their interest. Developing a process to study and design CSS that exhibit these kinds of complexities is the topic of this paper.

ii. CLIOS Systems and Strategic Alternatives

The CLIOS Process provides a way to describe, understand, study, and ultimately, to improve the performance of a wide range of CLIOS Systems, where CLIOS Systems stand for Complex Large-scale Interconnected Open Sociotechnical Systems. The term "CLIOS System" was conceived as a way to capture the salient characteristics of a class of engineering systems with wide-ranging economic, social, political and environmental impacts that are of growing interest to researchers, decision makers, policy makers and stakeholders. Examples of CLIOS Systems are the air traffic control systems, the global energy/climate system, the National Missile Defense system, and the eBay online trading system (Magee and de Weck, 2002; Zuckerman, 2002). The boundaries of CLIOS Systems are often defined by the CCI and problems that emerge within these CSS and by the means available to the decision makers to affect the system.

CLIOS Systems exhibit three additional characteristics to CSS. CLIOS Systems are:

- **Large-Scale:** CLIOS Systems have impacts that are large in magnitude, and often long-lived and of "large-scale" geographical extent.
- **Interconnected:** CLIOS Systems are often interconnected with *other* sociotechnical systems.
- **Open:** CLIOS Systems explicitly include social, political, and economic aspects (Sussman, 2000) beyond the technical or "engineered" system; we are concerned about system performance on these dimensions.

The CLIOS Process is structured not only to support analysis, but guide users in their efforts to change, affect or otherwise intervene in the system, in order to address the problem (or CCI) that motivated the analysis in the first place. To do this, the CLIOS Process uses strategic alternatives:

- **"Bundles" of Strategic Alternatives:** The changes we consider to improve the performance of the CLIOS System. The creative part of the CLIOS Process is in designing a set of such alternatives and selecting among them. It often takes imagination and insight into the CLIOS System under consideration to develop useful and feasible strategic alternatives. Yet, rarely will we implement a single strategic alternative. Usually we select a set of strategic alternatives for simultaneous or phased implementation. We call these sets "bundles."

iii. The Need for the CLIOS Process

The primary motivation for this paper is the authors' perception that there is a need for a new process for both analyzing and managing the complex sociotechnical systems that are at the core of many of society's most intractable contemporary problems. Its value lies in its clearly structured process for approaching problems related to CLIOS Systems, starting the user at the very basic and simple description of the system, and leading the user step by step through a learning process of increasing complexity and depth. The CLIOS Process can lead the user from problem and goal identification to implementation and adaptation of strategic alternatives, with an explicit systems approach to both analyzing and addressing problems.

The behavior of CLIOS Systems is difficult to predict and often counterintuitive (i.e., exhibiting behavioral complexity) because of the many subsystems involved, the uncertainty in the behavior of the subsystems and their interactions, and the degree of human agency involved. This holds true even when subsystem behavior is readily predictable. One of the unique contributions of the CLIOS framework is it provides a set of tools for learning how to visualize, think about, discuss, and debate solutions for CLIOS Systems in a structured, but flexible and modular format. The representation phase of the CLIOS Process is critical in this respect. As an analogy, engineering drawings are fundamental to the creative process of engineering design, when one is engineering objects or devices or machines, ranging from simple gears to bridges to a space station.[1] For CLIOS Systems, similar "tools of visualization" are needed to build intuition and systems thinking for students and analysts.

We further argue that there is a need for a framework that is capable of capturing the complexity of these sociotechnical systems, while at the same time allowing analysts to incorporate qualitative and institutional factors. Developing quantitative models that will predict the performance of the physical domain can be very difficult and costly. Looking to the institutional sphere, increasingly sophisticated systems models have evolved to incorporate economic, social, and political interactions with the physical domain (Marks, 2002). Yet, the ability to fully 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). The CLIOS Process provides a structured process for the analysis of both the physical and institutional aspects of the system.

Finally, the CLIOS Process enables analysis in order to better understand the system, but also provides a structured process for "intervening in" and changing the system in order to improve outcomes or performance. The CLIOS Process is used for the design and implementation of strategic alternatives that are intended to enhance the performance of the CLIOS system. These strategic alternatives can take the form of changes to the subsystems in the physical domain, or changes to the related organizations and their inter-relationships on the institutional sphere.

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[1] See D. Newman (2002) on principles of engineering drawing for undergraduate engineering students. For a historical discussion of the role of engineering drawings as a "tool of visualization" for engineers, to support intuition and nonverbal thinking, see E. Ferguson (1992).

iv. The Value of the CLIOS Process

The CLIOS Process is valuable for both analyzing and changing/improving systems where existing methodological approaches such as cost-benefit analysis, simulation modeling, and stakeholder analysis fail to capture relevant and salient issues either on the technical/engineering or social/political side of the problem. It is particularly useful for dealing with problems for which the system boundaries may not be immediately evident.

Furthermore, the CLIOS Process is "discipline-neutral," in that the users do not require training in any specific disciplinary methodologies to successfully apply the CLIOS Process. However, users can and should incorporate specific methodologies (including some of the more advanced models and tools described in Appendix B) at specific steps in the process. What the CLIOS Process *does* require is a strong systems-thinking approach by the individual or group undertaking the analysis.

As suggested above, the CLIOS Process can be carried out either by individuals or by groups. Potential users of the CLIOS Process include the following:

- ***Students/Researchers:*** The CLIOS Process has been used for class projects – at both the graduate and undergraduate level – as a pedagogical tool, training students to approach and analyze engineering systems holistically.[2] It has also been used as a research framework for master's theses and doctoral dissertations for understanding systems that can be characterized as CLIOS Systems.[3] These theses have not only applied the CLIOS Process, but have illustrated the modularity of the CLIOS Process itself. Indeed, several students have extended and deepened the CLIOS Process in order to better understand their own CLIOS systems.
- ***Decision Makers:*** In addition to its research and pedagogical role, the CLIOS Process can also be employed by public or private sector decision makers, with responsibility for one or more components of a subsystem, to change and improve the system.
- ***Stakeholders:*** Citizens, private sector actors, non-profit organizations and advocacy groups that are affected for good or ill by the CLIOS System, can also use the CLIOS Process in a more participatory format to attempt to influence its performance. In CLIOS terms, both decision makers and stakeholders "populate" the institutional sphere.
- ***Experts/Analysts:*** Individuals or groups that provide analysis and recommendations to decision makers and stakeholders are the fourth group of potential users of the CLIOS Process. These experts/analysts may be a part of the CLIOS System (i.e., as employees of an organization on the institutional sphere) or retained to study the CLIOS System as consultants (and therefore do not "populate" the institutional sphere, but provide advice to decision makers or stakeholders that do "populate" the institutional sphere).

Part of the value is that all of these individuals and groups can work together on the CLIOS Process. For clarity, this paper outlines and describes the CLIOS Process as though it were being carried out by a single analyst. Yet, in practice, participation by stakeholders and decision makers using the CLIOS Process as a collaborative group process will (or should) occur

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[2] Moses (2006), for example, stresses a holistic approach as "fundamental" to Engineering Systems.

[3] Kometer (2005), Ward (2005), Mostashari (2005), and Osorio-Urzua (2007) are some examples.

(Mostashari, 2005). It is envisioned that the CLIOS Process could create a forum where stakeholders systematically raise and elaborate upon their concerns, so that these concerns could be adequately addressed by decision makers and policymakers, without losing the understanding of the systems as a whole. For example, in the context of the unsustainable patterns of metropolitan development, 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 individual subsystems in a larger, complex and interconnected system, thus leading to unintended consequences on the other subsystems. Clearer frameworks for understanding systems holistically could enable decision makers to better see their function as "part of a complex system of linked factors in the physical environmental and the governmental context" (Innes, 1997). We suggest that the CLIOS Process supports this effort.

1. OVERVIEW OF THE CLIOS PROCESS

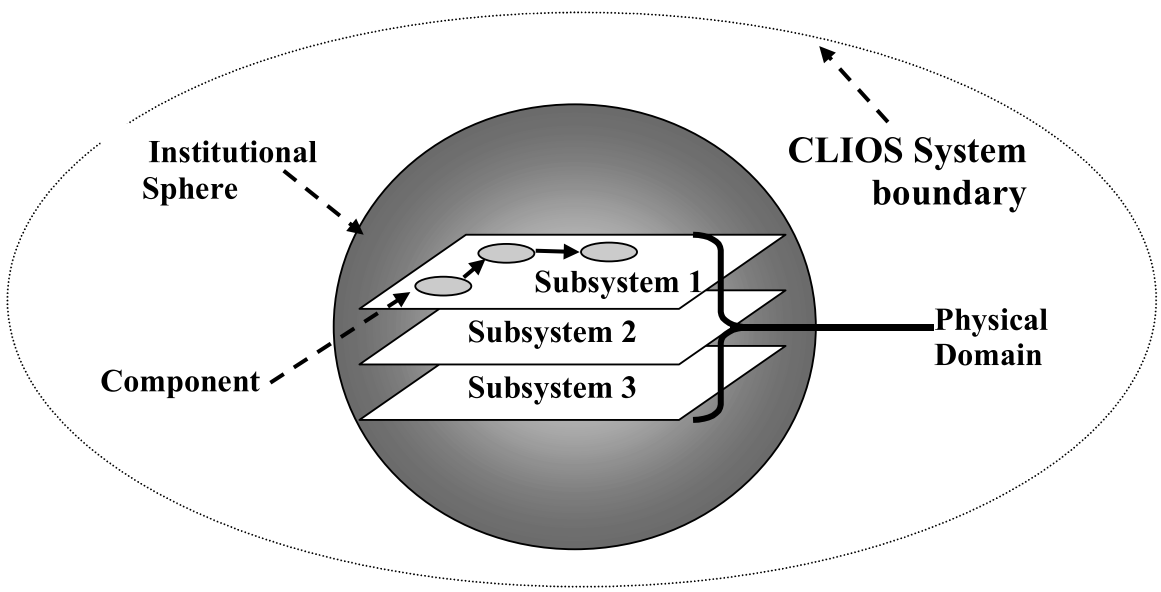
The CLIOS Process is composed of three stages divided into twelve steps. At the core of the CLIOS Process is the concept of CLIOS System Representation, an organizing mechanism for mapping out the system's underlying structure and behavior.

In the CLIOS Process, we think of a CLIOS System as consisting of a physical domain embedded (conceptually) in an institutional sphere. The CLIOS Process explicitly includes the institutional world as part of the system, recognizing that changes to existing institutional structures are not only a strategic alternative, but are often necessary in order to implement other strategic alternatives to improve system performance.

Therefore, when we speak of a CLIOS System, we refer both to the physical and the institutional aspects of the system; we include both domains. An important aspect of the CLIOS Process is the integration of the analyses of the physical domain and institutional sphere, and the development of strategic alternatives for both.

We suggest that the CLIOS Process provides an innovative systems approach that represents the entire system – physical and institutional – in an integrated form.

Figure 3: A CLIOS System Representation: A Physical Domain Embedded in an Institutional Sphere



1.1. The Three Stages of the CLIOS Process

The three stages of the CLIOS Process are (1) Representation; (2) Design, Evaluation, and Selection; and (3) Implementation and Adaptation.

1) **Representation:** The CLIOS System representation is created and considered in terms of both its structure and behavior. We also establish preliminary goals for the CLIOS System, i.e., in what ways do we want to improve its performance.

2) **Design, Evaluation, and Selection:** Strategic alternatives for performance improvements to the physical domain and institutional sphere are designed, evaluated and finally some are selected.

3) **Implementation and Adaptation:** Implementation plans for the physical domain and the institutional sphere are designed and refined.

Between Stages 1 and 2, there is a key transition from a descriptive treatment (trying to understand) to a prescriptive treatment of the system (trying to intervene, change, or improve).

An overview of the three stages is shown in Table 1.

Table 1: Summary of the Three Stages of the CLIOS Process

Treatment	Stage	Key Ideas	Outputs
Descriptive	Representation	▪ Understanding and visualizing the structure and behavior ▪ Establishing preliminary goals	System description, issue identification, goal identification, and structural representation
Prescriptive	Design, Evaluation, & Selection	▪ Refining goals aimed at improvement of the CLIOS System ▪ Developing bundles of strategic alternatives	Identification of performance measures, identification and design of strategic alternatives, evaluation of bundles of strategic alternatives, and selection of the best performing bundle(s)
	Implementation & Adaptation	▪ Implementing bundles of strategic alternatives ▪ Following-through – changing and monitoring the performance of the CLIOS System	Implementation strategy for strategic alternatives in the physical domain and the institutional sphere, actual implementation of alternatives, and post-implementation evaluation

In using the CLIOS Process, the analyst will often need to pose questions at each stage similar to those shown in Table 2 below:

Table 2: Sample Questions to Be Answered in Each CLIOS Process Stage

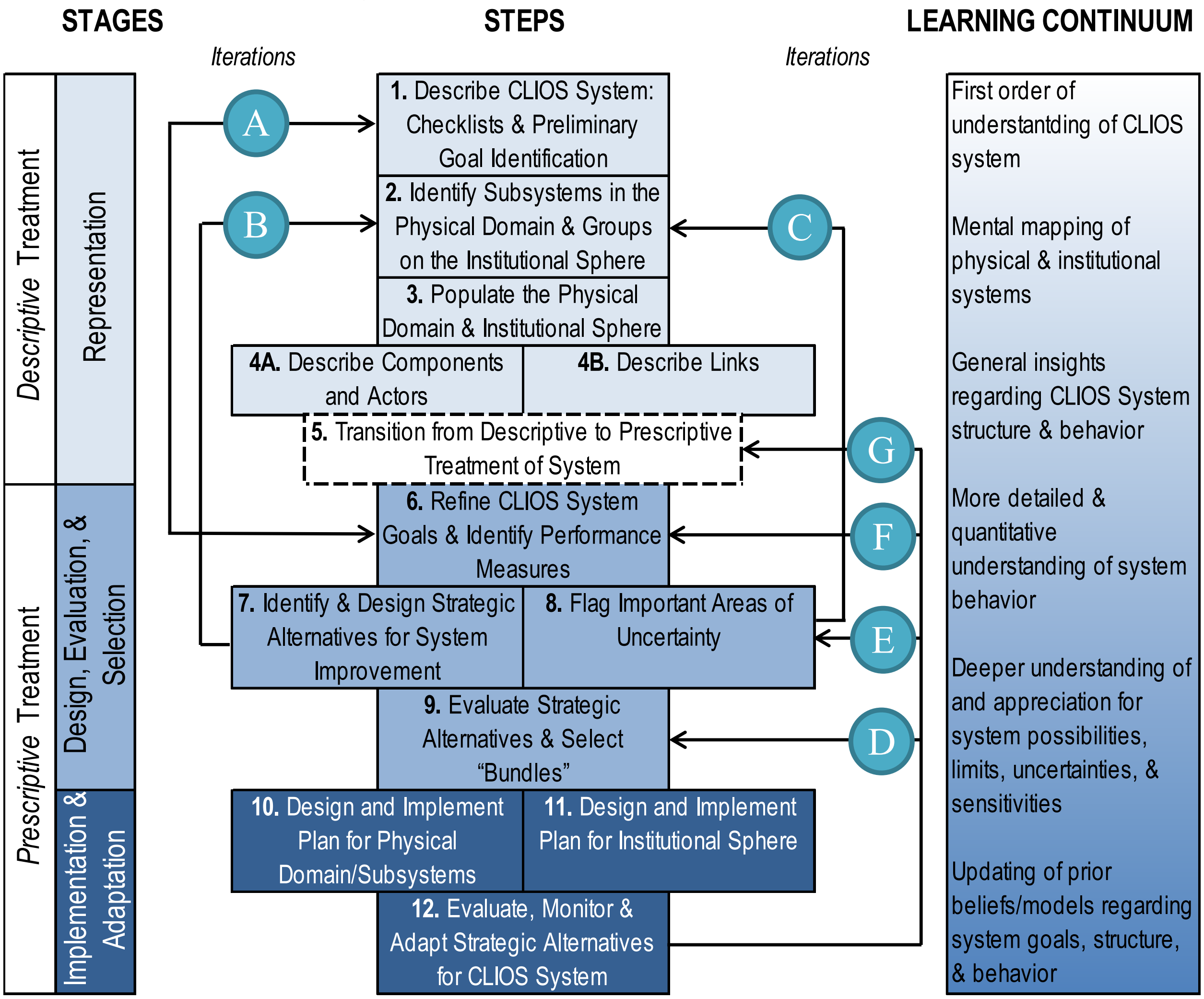
REPRESENTATION	Regarding the representation of the *structure* of the CLIOS System we can ask questions such as the following: ▪ Can we break out the physical domain into relatively independent subsystems? ▪ What are the technical, economic, and social aspects of each subsystem? ▪ What are the main components of each identified subsystem? ▪ How do the physical subsystems relate to the institutional sphere? ▪ What are the main actor groups and who are the key individual actors/organizations on the institutional sphere that impact the physical domain or are affected by it? Regarding the representation of the *behavior* of the CLIOS System, we can ask: ▪ What is the degree and nature of the connections between subsystems? ▪ Are the connections weak or strong? ▪ Are there important feedback loops connecting subsystems? ▪ What insights can we gain into emergent behavior? In both 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.
DESIGN, EVALUATION, & SELECTION	In this stage, we look at both how different strategic alternatives change system performance as well as preferences of different stakeholders. ▪ How is performance measured for the entire CLIOS System as well as for the physical subsystems? ▪ How do key stakeholders and decision makers measure or rank different types of performance? ▪ What are the tradeoffs among the various dimensions of performance (e.g. cost vs. performance) ▪ What strategic alternatives can lead to improved performance? ▪ How can we combine or "bundle" strategic alternatives to improve the system? ▪ Which bundle is selected for implementation?
IMPLEMENTATION & ADAPTATION	Finally, we can ask the following: ▪ How do these performance improvements actually get implemented, if at all? ▪ What compromises have to be made in the name of implementation? ▪ What actors/organizations on the institutional sphere have an influence on the parts of the system targeted for intervention? How are these actors/organizations related to each other? ▪ Do the types of policies made by different organizations on the institutional sphere reinforce or counter each other? ▪ Under the current institutional structure, can organizations manage the system to achieve target levels of performance?

In summary, the first stage is used to understand structural, behavioral, nested, and evaluative complexity; the second stage is used to create and evaluate strategic alternatives for improving system performance; and the final stage brings various alternatives for the physical and institutional systems together to form and implement a feasible strategy or plan for improving the CLIOS System.

1.2. The Twelve Steps in the CLIOS Process

The three stages of the CLIOS Process are divided into twelve steps, as shown in Figure 4. The steps are color-coded to indicate the corresponding stage. Step 5, the final step on the representation stage, indicates the key transition from a descriptive to a prescriptive treatment of the system.

Figure 4: Overview of the CLIOS Process



Many of the steps in the CLIOS Process are concurrent. For example, one identifies and describes both the components and the links between those components at the same time (Steps 4A and 4B). Also, as one identifies and analyzes strategic alternatives to change the CLIOS System (Step 7), additional uncertainties may begin to surface (Step 8). (In other words, as one thinks about how to "tinker with" the system, it often becomes clear that one does not fully understand the ways that the whole system will react in response to this "tinkering," both in the short and long run.) Finally, one of the differences of the CLIOS Process from other system approaches is that the strategic alternatives for implementation may include changes to both the physical domain (Step 10) and institutional sphere (Step 11), which are concurrent.

While we show the CLIOS Process as a set of ordered steps, it is an iterative process and not a rigid, once-through process. As we go through the steps of the CLIOS Process, we highlight several important points where iteration back to earlier steps can occur (having labeled some of these iterations as A, B, and so on, for reference).

1.3. Learning about CLIOS Systems

The CLIOS Process is also set up as an approach to learn about CLIOS Systems. This provides a structure of analysis that enables continuous learning for individuals and groups. As illustrated in Figure 4, the understanding of the CLIOS System should evolve as the analysts carry on the CLIOS Process. Moreover, because this is an iterative process, even during the "prescriptive" treatment (Stages 2 and 3), the "descriptive" understanding (Stage 1) of the system can change. The analysts can update their understanding of the system structure and behavior, decide how to better "bound" the system, and appreciate its key uncertainties, as they assess different possibilities for improving the system. However, the important decision of stopping the iteration of the CLIOS Process is at the discretion of the analyst.

1.4. Tailoring the CLIOS Process

The CLIOS Process is a *modular* and *flexible* process that can be supported by additional tools and methods of analysis.

As a useful analogy for understanding the *modularity* of the CLIOS Process, one can say that the CLIOS Process is structured like a Christmas tree. Its overall structure allows for quantitative ("models") and qualitative analytical tools ("frameworks"), which are suitable for each stage/step, to be "attached" to the CLIOS Process like ornaments on a tree.

How one decides to decorate the tree depends on the particular CLIOS System in question, the motivation for the analysis and the level of analytical sophistication desired. The selection and use of these tools will also depend upon the training and background of the individual or group undertaking the CLIOS Process, the data available, and the amount of time that can be dedicated to the CLIOS Process, among other factors. For this reason, we suggest that it is a *flexible* process.

Appendix B presents an overview of various tools (or "ornaments") and how these tools can be selected to "hang on to the CLIOS Process Christmas tree."

2. STAGE 1 OF 3: REPRESENTATION

The CLIOS Process begins with a representation of the CLIOS System. The CLIOS System representation is an organizing mechanism for mapping out the system's underlying structure and behavior. It also establishes preliminary goals for the CLIOS system.

In Steps 1 through 4, we present *one approach* to complex system representation, which uses a combination of diagrams and text to capture the critical aspects of the CLIOS System and presents them in an easy-to-comprehend format. It is, by no means, the only way, or maybe even the best way for all CLIOS Systems, but this approach has proven useful in the CLIOS System representations that have been conducted to date. It is left to the discretion of the users to decide which approach is more appropriate for their objectives, and we encourage the continuous development of new tools for system representation.

STEP 1 of 12: Describe CLIOS System: Checklists and Preliminary Goal Identification

In Step 1, we create three checklists that serve as a high-level examination of the CLIOS System and implicitly bound the CLIOS System, at least preliminarily.

1) A **characteristics** checklist that may relate to: (a) the temporal and geographic scale of the system, (b) the core technologies and systems, (c) the natural physical conditions that affect or are affected by the system, (d) the key economic and market factors, (e) important social or political factors or controversies related to the system and (f) the historical development and context of the CLIOS System.
2) An **opportunities, issues, and challenges** checklist that contains aspects of the CLIOS System for which we may seek constructive improvements through strategic alternatives in Stage 2.
3) A **preliminary system goals** checklist, which often relates to the opportunities, issues and challenges found in the second checklist.

As we develop the CLIOS System representation, we can return to these checklists to identify any major issues that have been omitted. The checklists are not definitive, though, as the boundaries of the CLIOS System are expected to expand and/or contract as the CLIOS Process advances and focuses more clearly.

The checklists should address the question: "what is it about the system that makes it interesting?" (Puccia & Levins, 1985). To answer this question, one can draw upon a wide range of sources: academic articles and books, popular press, reports published by government, business, non-governmental organizations, etc. Understanding the historical context and development of the system can also be useful for insights regarding current issues, challenges, and recurring themes or issues. For example, earlier attempts to change and improve the system, whether successes or failures, can highlight certain structures or dynamics within the system. It is particularly useful if the analyst has previous experience with the CLIOS System under study, or with other related systems, and can bring that experience.

The checklists should also capture the concerns and needs of a broad set of stakeholders, including policy makers, system managers and operators, customers and so forth. One has to ask

"What are the management and policy questions that need to be addressed?" When the CLIOS Process is carried out by a group, the representation stage is used to create a common understanding of the system that will allow a reasonable discussion. Some agreement on the issues and goals will facilitate the design and implementation of strategic alternatives for system performance improvements in later stages.

STEP 2 of 12: Identify Subsystems in the Physical Domain and Actor Groups on the Institutional Sphere

In Step 2, we organize our ideas about how the CLIOS System works by outlining the general structure of the CLIOS System: a physical domain (made up of subsystems) embedded in an institutional sphere (Figure 3). Here, subsystems refer to major parts of the physical domain. We visualize the subsystems as being divided into distinct layers, but with interconnections between the subsystems.

We determine:

1) Which **major subsystems** make up the physical domain
2) Who the **main actor groups** are on the institutional sphere
3) How they **relate** to one another on a macro-level

One useful way to identify these subsystems and actor groups is by grouping the issues identified in Step 1 into different categories. Another approach is to organize the subsystems according to their common technological characteristics, functions or how they fulfill the needs of the various actor groups on the institutional sphere.

For Identifying Subsystems in the Physical Domain:

We parse the physical domain into **subsystems**, map out the structure of those subsystems (which can be envisioned as layers), and finally identify the key linkages between subsystems. This is a difficult process, but worthwhile in that many of the insights into the structure and behavior of the CLIOS System will come through, while thinking about how it can be subdivided into the different layers.

For Identifying Actor Groups on the Institutional Sphere:

We divide the institutional sphere into general categories, or **actor groups**, such as government agencies, private sector firms, citizen groups, independent expert/advisory entities and so forth. This can be derived from the checklists in terms of who manages the system, who is affected by it, who attempts to influence it and, in general, who worries about it.

Relationship between the Physical Domain and the Institutional Sphere:

At this point, the analyst should start thinking how the major actor groups on the institutional sphere interact with the subsystems on the physical domain. If the relationships are unclear or not too relevant, perhaps the candidate subsystems or actor groups should be revisited.

STEP 3 of 12: Populate Subsystems and Actor Groups

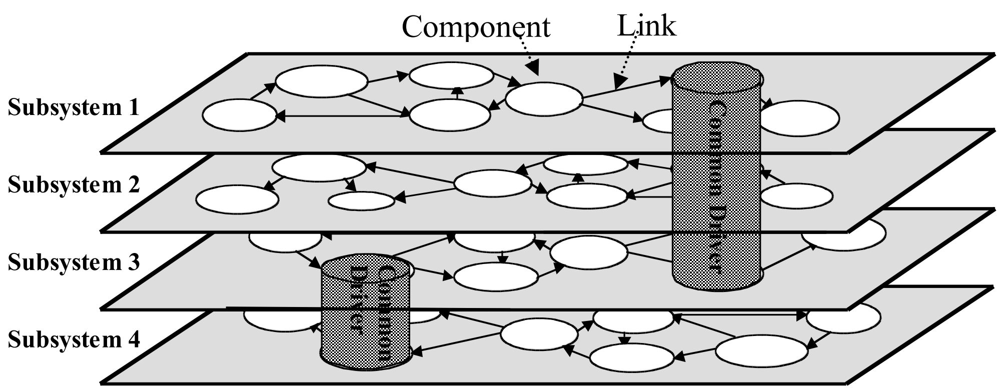
In Step 3 we populate (1) the subsystems in the physical domain and (2) the actor groups on the institutional sphere identified in Step 2.

Populating the Subsystems in Physical Domain:

For the graphical representation of subsystems, we employ **system diagrams,** a type of illustration used in systems sciences. System diagrams have components and relations depicted by nodes and lines, respectively, in a network-like diagram (see Figure 5).[4]

We populate the physical domain with the salient **components** in each subsystem and the **links** indicating influence of components on each other. When a component appears in more than one subsystem, it is called a **common driver**, and serves as a gear between subsystems. (We will discuss the different types of components and links in Step 4.)

Figure 5: Subsystem Diagrams



Populating the Institutional Sphere:
We populate the institutional sphere with individual **actors** within each of the major actor groups identified in Step 2, and show the links between them. In order to represent the institutional sphere conveniently, we flatten the sphere onto a two-dimensional plane similar to a subsystem diagram.

Cognitive Limits of Subsystem Diagrams:

Subsystem diagrams have a cognitive upper bound to the number of components that can be represented while still providing an opportunity for insight for the user. From the authors' experiences, a single subsystem diagram should contain 10-15 components, but that number depends on the preferences of the analyst. Sometimes, though, remaining within this cognitive limit can result in oversimplification of the system – that is, too few components that are too "macro" in nature to be of value, leaving some of its subsystems poorly represented.

One technique that can be used for increasing the resolution of the system representation without creating overcrowded diagrams is expanding or zooming in. Expanding focuses on critical components and magnifies their functions into separate diagrams for more detailed study. Expanding, however, also has cognitive limits.

[4] We recommend the construction of subsystem diagrams, but by no means deem this as the sole or the optimal method for all CLIOS Process applications. Alternatively, the user could use a matrix representation (e.g., Design Structure Matrix DSM) or a prose to describe the CLIOS system. The nomenclature that is introduced here, however, can be useful for communication purposes as a common language irrespective of which representation method is used.

STEP 4 of 12: Describe Components, Actors, and Links

In Step 4, we describe in detail the components, actors, and links identified in Step 3.

STEP 4A: Describe Components and Actors

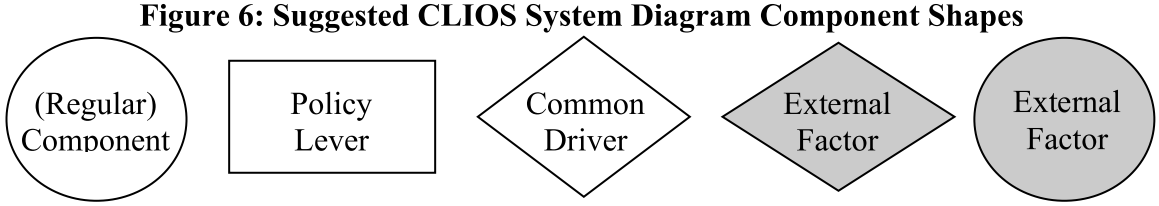
Describe Components in the Physical Domain:

In Step 4A, we characterize more carefully the nature of individual components within the physical domain. We note that components need not be well-defined physical entities, and can refer to concepts such as "congestion" or contain complex internal structures such as "economic growth". However, components may only appear in the physical domain and not on the institutional sphere.

Each component is described in a few sentences and classified according to four categories:

1) **(Regular) Components** (from now on, simply "**Components**", indicated by circles as in Figure 6) are usually the most common in the subsystems in the physical domain.
2) **Policy Levers** (indicated by rectangles) are components within subsystems in the physical domain that are most directly controlled or influenced by the actors on the institutional sphere. They are the points of "contact" between the institutional sphere and the physical domain.
3) **Common Drivers** (indicated by diamonds) are shared components across multiple and possibly all subsystems in the physical domain. They emerge from the process of dividing the physical domain into separate subsystems and usually "drive" the behavior of more than one of the subsystems. The common drivers are important both for understanding the structure and behavior of the CLIOS System in Stage 1 as well as for implementing changes to the system in Stages 2 and 3 of the CLIOS Process. They may constitute major sources of uncertainty, since they impact the physical domain at several different subsystems.
4) **External Factors** (indicated by shading, a color, rather than a shape) are exogenous to the physical domain. By definition, they are external, and cannot be a policy lever, but they appear in the physical domain either as a component or a common driver.

Figure 6: Suggested CLIOS System Diagram Component Shapes



Deciding on the inclusion or exclusion, an accurate definition, and the classification of a component is not trivial and requires a serious thought process from the analyst.

Describe Actors on the Institutional Sphere:

In describing the actors on the institutional sphere, we can identify important characteristics, such as their power or mandate over different parts of the physical subsystems, their interests in the subsystems, their expertise and resources and their positions with regards to different potential strategic alternatives. This, however, should be a short description.

STEP 4B: Describe Links

In Step 4B, parallel to Step 4A, we characterize the nature of the several kinds of links. Our framework for thinking about and describing the links in the CLIOS System has three classes of links:

1) **Class-1 Links:** Between components within a subsystem in the physical domain. Generally, these can be analyzed using engineering- and microeconomics-based methods, and will often be quantifiable.
2) **Class-2 Links:** (Also called **projections**) between components in a subsystem in the physical domain and actors on the institutional sphere. Quantitative analyses are less useful for these links, since human agency and organizational and stakeholders' interests come into play as they attempt to induce changes in the physical domain.
3) **Class-3 Links:** Between actors on the institutional sphere. Understanding these links requires methods drawing upon theories of organizations, institutions, politics and policy.

While the interactions within the physical domain and within the institutional spheres more readily fall under the domain of more traditional disciplinary perspectives, we would argue that the interactions between the institutional sphere and physical subsystems are more interdisciplinary and of particular 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).

The links in the CLIOS System representation will be largely qualitative and should be described in terms of important characteristics like:

- Directionality of influence and feedback loops (one-way or bi-directional)[5]
- Magnitude of influence (big/important/strong, average or small/marginal/weak impacts on the adjoining components)
- Sign of the influence (positive or negative)
- Timeframe of influence (short-, medium-, or long-term lags)
- Functional form of the influence (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 of the effect of one component upon another (including uncertainty in all of the above characteristics)

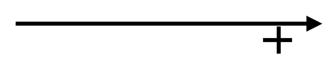
[5] We suggest that feedback loops in which one component has a feedback loop directly back onto itself would not be used in a CLIOS System representation. Instead, the intervening components need to be identified, to provide insight into the chain of causality that creates this feedback.

Different types of links can be identified based on what "goods" they carry from one component/actor to another. These include:

- **Causal:** Causation between two components, two actors, or a component and an actor
- **Informational:** Information/decision flow between two actors or two components
- **Financial:** Flow of financial resources between two actors
- **Control:** Usually associated with relations among organizations/institutions, and between organizations and the physical domain; can be advisory or hierarchical
- **Mass Transfer:** Flow of materials between two components
- **Energy Transfer:** Flow of energy between two components

Figure 7 shows some suggested link shapes for the CLIOS diagrams.

Figure 7: Examples of Possible Link Shapes for CLIOS Diagrams

LINK	SHAPE
Class-1 link (between *components* of physical subsystems) Class-3 link (between *actors* on the institutional sphere)	
Class-2 link ("projections" between the institutional sphere and the physical domain)	
Weak	
Average	
Strong	
Bi-directional	
Positive (*increase* in component A results in *increase* in component B)	
Negative (*increase* in component A results in *decrease* in component B)	

STEP 5 of 12: Transition from Descriptive to Prescriptive Treatment

Step 5 marks a key transition from a descriptive to prescriptive treatment of the system, necessary for Stages 2 and 3 of the CLIOS Process.

By the end of Step 4, we should have developed a good understanding of the general structure of the CLIOS System and characterized relatively well the behavior of components, actors, and links. At this moment, a CLIOS System representation could look like the example in Figure 8.

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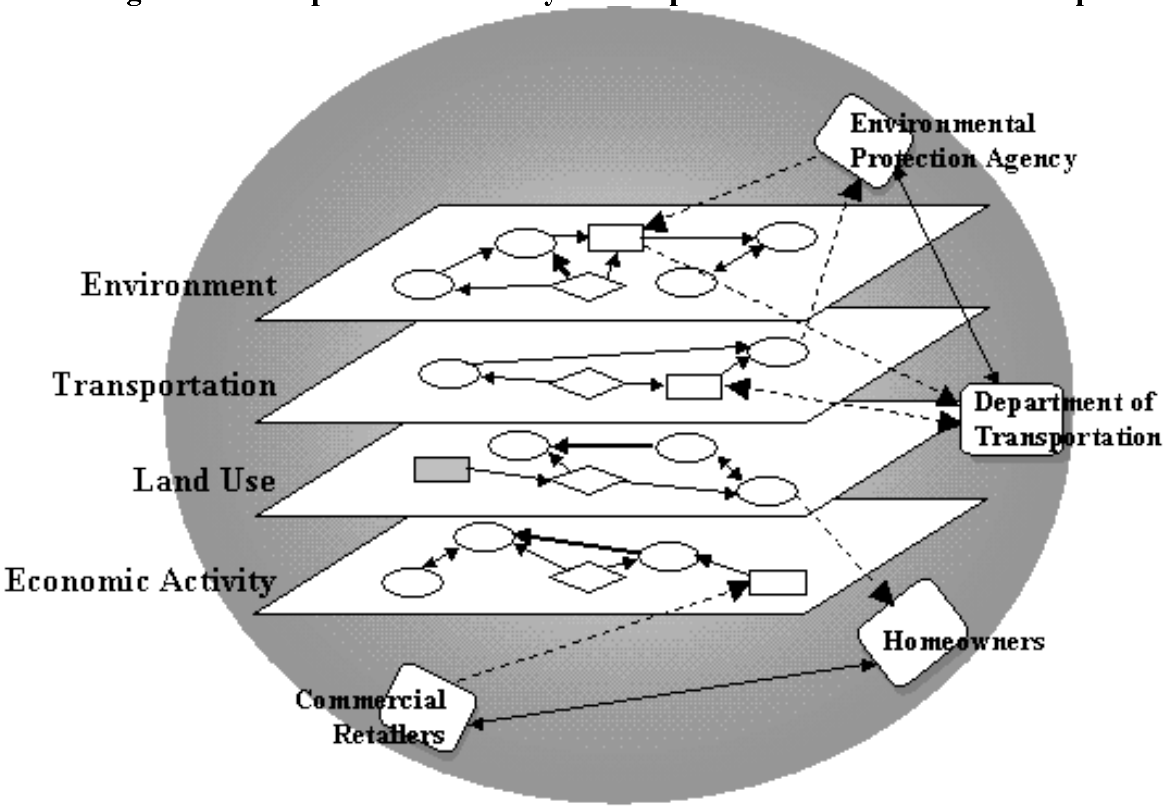
Figure 8: Example of a CLIOS System Representation at the End of Step 4



With this information, we can now gain a better understanding of the overall CLIOS System behavior, and where possible, counterintuitive or emergent system behavior. In Step 5, we trace through the system at its different levels and identify sources of important system behavior by asking the following types of leading questions:

1) With respect to **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 strongly non-linear and/or irreversible in their impact? Finally, can strong positive or negative feedback loops be identified?
2) Looking at **class-2 links or projections**, can we identify components within the physical domains that are influenced by many different organizations in the institutional sphere? If so, are the organizations pushing the system in the same direction, or is there competition among organizations in the direction of influence? Alternatively, do some organizations on the institutional sphere have an influence on many components within the physical domain?
3) Within the **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 institutional sphere? What is the hierarchical structure of the institutional sphere, 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 several organizations that all influence the same subsystems within the physical domain?

In Step 5, 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.

Here we also begin to develop a **catalogue of issues** and **possible strategic alternatives** for the CLIOS System. The idea is that certain 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. Thinking carefully through these questions can generate some insights regarding how to improve the system, some of the key uncertainties, and possible implementation issues that may arise.

Choosing and Developing a CLIOS Representation:

The exact shape or notation for components and links, or the level of detail in describing the CLIOS System, is solely the decision of the analyst. What is most important is that the analyst *does* follow a systematic process of thinking through and attempting to classify the components and links in the system. In that manner, the analyst will learn more about the CLIOS system under study, and gain intuition regarding its structure and behavior, which is a goal of Stage 1. *The diagrams are not as important as the thinking that went into making the diagrams!* To quote Edward Tufte, "The act of arranging information becomes an act of insight".

A new user of the CLIOS Process may find it hard to scale and bound the CLIOS system. Thus, Box 1 provides some useful heuristics about working with the CLIOS Process.

Box 1: A Note on Heuristics for Scaling and Bounding the CLIOS System

As we introduce the basic concepts of the CLIOS Process' representation stage in general terms, there are many specific questions the user might ask. Where is the boundary of the CLIOS System? How does one break up the physical domain into subsystems? When should a component in a physical subsystem be expanded into subcomponents? Similarly, when should an organization on the institutional sphere be broken up into sub-organizations?

These are all difficult questions and *there is no single right answer* to them. As Maier and Rechtin note, system analysis is more of an art rather than science; hence, analysts are expected to use heuristics and their experience to make these choices. A second reason is that any answer to these is dependent on the scale and scope at which we want to consider the CLIOS System and indeed that can change as the analysis advances. These changes are indicative of shifting mental models and possibly precursors to important insights (Figure 4).

That being said, we describe some heuristics that can support these decisions. However, caveat emptor – as with all heuristics, they can be contradictory, not universally applicable, and certainly the list is not exhaustive.

1. *The analysis needs to take into account the actual scale of the system (spatial and temporal), and the magnitude and scope of its impacts, physical, economic, political or social.* This will not only determine where the system boundaries are drawn, but also which subsystems and components will be included.
   - *Components are the units of analysis for the appropriate level of detail – scale – of the system.* For a general transportation system example, vehicles are components and would probably not be analyzed further.
   - *The scale of the system is determined by whether any meaningful additional insight can be gained through further analysis.* There is no need to break down cars into auto parts even if these may play a role in the system (e.g. catalytic converters for reducing pollutants) unless additional insight is gained by doing so.

2. *The boundary of a CLIOS System is also determined by what the analyst considers as feasible strategic alternatives.* Therefore some macro-level economic and social factors may well fall outside the boundary of the system but would be part of the "relevant environment," affecting and in some cases affected by the CLIOS System. As will be discussed later, scenario building will be one tool to think systematically about these linkages between the CLIOS System and the relevant environment.

3. *Ideally, system boundaries should not reflect ideological convictions and preconceived mental models of the analyst*. This is a key reason that a team with members with differing mental models, rather than a single analyst, should ideally work on the CLIOS Process.

4. *External factors usually influence the CLIOS System unidirectionally.* For a typical urban transportation system, the global economy (an external factor) affects the local economy (a system component and probably a common driver). No component in the urban transportation system can meaningfully affect the global economy and the global economy is too massive to be affected by the local economy of a typical urban area.

5. "*Think outside of the box.*" Innovative solutions usually lie out of conventional boundaries. Avoiding restrictive boundary setting may facilitate better strategic alternatives.
   - *Start by representing the big picture.* Detail can be added as needed as the CLIOS Process proceeds by using techniques such as expanding or by adding subsystems as necessary.
   - *System boundaries can be altered as the CLIOS Process unfolds.* It is usually easier to narrow the boundaries than it is to expand them, so think broadly at the outset.

3. STAGE 2 OF 3: DESIGN, EVALUATION, AND SELECTION

After considering the structure and behavior of the CLIOS System during the representation stage, Stage 2 (Steps 6 through 9) focuses on refining the goals and performance measures of the system and designing, evaluating, and selecting bundles of strategic alternatives for improving both the physical domain and the institutional sphere.

STEP 6 of 12: Refine CLIOS System Goals and Identify Performance Measures

In Step 6, we refine the preliminary goals developed in Step 1, and use them to determine a desired future state of the CLIOS System and corresponding performance measures.

At the beginning of Step 6, the needs and perspectives of the stakeholders and the opportunities and issues of the CLIOS System should become clearer. They can now be used to refine the preliminary goals from Step 1 into a concise, normative view of a **desired future state** of the system. This concrete vision can then be used to identify **performance measures** that mark the progress from the current to the desired future state. Usually, these performance measures would be properties of components in the physical domain.

Performance measures for CLIOS Systems 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. This is a case of the *evaluative complexity* inherent in CLIOS Systems: Good performance depends heavily upon the viewpoint of the various stakeholders.

We also select and validate the appropriate models to evaluate the current state of the system, which will subsequently serve as a basis for comparing strategic alternatives. The models can be the quantitative analog of the qualitative representation built in the representation stage, or can be constructed from scratch simply using insights from the qualitative representation.

Two basic model categories can be used: **case-specific** (i.e., models that track limited facets of the CLIOS System on the component or subsystem level) and **system-wide** (i.e., models that aim to describe interactions at the CLIOS system level, such as a system dynamics simulation). Ideally, the system-wide models should integrate inputs from the independent models in a system representation consistent with the qualitative insights that are gained from Stage 1.

STEP 7 of 12: Identify and Design Strategic Alternatives

With refined goals and performance measures from Step 6, we can ask in Step 7 *how* CLIOS System performance can be improved through strategic alternatives.

Performance improvements through strategic alternatives can take three forms:

1) **Physical:** Changes involving direct modification of components in the physical domain, which often lead to more technology-driven strategic alternatives relating directly to the physical domain.

2) **Policy-driven:** Changes involving the policy levers in the physical domain influenced by the institutional sphere. These rely on incentives or disincentives such as taxes, subsidies,

voluntary agreements, and restrictions on certain behaviors need to be considered in order to achieve changes in the physical domain. Implicit in these types of alternatives is usually an assumption about how a policy change, initiated by actors on the institutional sphere, will cascade through the physical domain, and what changes in the performance measure will occur. Following this process can also reveal where strategic alternatives of this kind are counterproductive, diminishing the performance in other parts of the system.

3) **Actor-based:** Architectural changes of the institutional sphere either within actors or between actors. We evaluate the institutional arrangements that govern the management of the CLIOS System and then devise strategic alternatives that change these arrangements. The institutional sphere can be investigated to highlight the interventions that need to be made on the institutional sphere to accomplish those changes to the physical domain.

This is a creative step in the CLIOS Process where imagination in developing strategic alternatives is to be valued and out-of-the-box thinking and brainstorming is often a key to success. Considering what kinds of strategic alternatives have worked well in similar CLIOS Systems can be helpful. This step is meant to bring out a wide range of (even if only remotely reasonable) alternatives. Broad and creative thinking is valued here.

STEP 8 of 12: Flag Important Areas of Uncertainty

A parallel activity to Step 7 is to look for uncertainties in the anticipated performance of the CLIOS System in Step 8.

In identifying the important uncertainties, one can rely on the insights gained in Stage 1 and Step 6, in which we looked for chains of strong interactions, areas of conflict between stakeholders, or emergent behavior resulting from feedback loops.

The common drivers, given their importance to the performance of a CLIOS System, are another key area that can affect CLIOS System uncertainty. Since these factors can simultaneously influence different subsystems in different ways, the overall impact of the common drivers can be difficult to ascertain. Sensitivity analysis exercises can be useful here. These common drivers can have a particularly strong influence on the physical domain in the long-run evolution of the CLIOS System.

Finally, while flagging important areas of uncertainty, we should also consider the impact of external factors, such as macroeconomic growth, and national and international political trends that link a CLIOS system to an even broader system. For this reason, we need to use models and frameworks for understanding uncertainty in open systems.

STEP 9 of 12: Evaluate Strategic Alternatives and Select "Bundles"

In Step 9, the individual strategic alternatives that were generated in Step 7 are evaluated using the models developed in Step 6 or additional models if need be. Also, we can return here to the insights gained in Stage 1.

Usually, each alternative is examined with regards to how it impacts the CLIOS System, especially for the performance areas that it was designed for. The case-specific models are usually adequate for this evaluation.

If the strategic alternative is causing the intended performance measures to deteriorate, then the strategic alternative usually should be withdrawn from further consideration (or perhaps modified). Further, even for strategic alternatives that are narrowly targeted on specific subsystems or components, the systemic impacts of all strategic alternatives need to be considered, particularly if specific alternatives targeting one performance measure can spillover to other performance measures producing unintended consequences. The value of flexibility in the strategic alternative design, as identified in Step 8, should also be considered at this point.

Given system complexity, it would be unusual for a single strategic alternative to be deployed and meet all the CLIOS System goals. However, by combining strategic alternatives into **bundles**, the analyst may accomplish two objectives:

1) One can mitigate and/or compensate for negative impacts. Given the interconnectedness of the CLIOS System, improvements along one dimension of performance may degrade performance in other areas of the system. Therefore, one should look for alternatives that can either attenuate those negative impacts, or compensate those actors and stakeholders on the institutional sphere that are negatively impacted, by including strategic alternatives that address their needs, even though these alternatives might not have made the initial cut.
2) Different combinations of strategic alternatives can improve the **robustness** of the overall bundle. We here define robustness as the ability of bundles of strategic alternatives to perform reasonably well under different futures. Seeking a robust bundle is a different approach than that of identifying a so-called "optimal" bundle, which may only perform optimally under a constrained set of conditions. In fact, we argue that achieving "optimal performance" is an unrealistic goal for a CLIOS System. Given the range of performance measures involved, different stakeholder views and trade-offs needed to obtain the necessary support for implementation, simply finding a feasible bundle (one that works and can be implemented) may be an achievement in itself.

One way of displaying robustness is with a matrix like that shown in Table 3. The columns represent different futures and the rows represent bundles of strategic alternatives. In this way, we can see how the bundles perform compared across a range of futures.

Table 3: Performance of Bundles across Different Futures

	Future 1	Future 2	Future 3
Bundle 1	+	–	++
Bundle 2	+	++	+
Bundle 3	+	0	+

Where we see positive outcomes in each of the futures (Bundle 2, in the example), that bundle is then considered robust. In this case, the choice is straightforward. However, if choosing between Bundle 1 and 3, this would depend upon the desire to avoid negative outcomes, in which case Bundle 3 would be preferable, even though Bundle 1 performs well in two out of the three futures, and extremely well in one of the futures. In further developing and refining both strategic alternatives and implementation plans, as will be described below, the focus should be on combining strategic alternatives that can make bundles more robust and implementable across the entire set of possible futures.

We note that implicit in characterizing the overall "performance" of a bundle, is weighing the various "performance measures" identified earlier. Evaluative complexity suggests that different stakeholders will see this weighing differently. So, while for illustrative purposes we refer to overall "performance," we should realize that agreeing on it will often be non-trivial in practice.

4. STAGE 3 OF 3: IMPLEMENTATION AND ADAPTATION

Once a bundle of promising strategic alternatives is selected in Stage 2, the next crucial (but often overlooked) action is to design a plan for implementation in Stage 3.

Many 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 the recommended actions, or how the political realities will affect the actual deployment. Thus, the concurrent Steps 10 and 11 are meant to address this common shortcoming.

Step 10 focuses on how to implement the strategic alternatives that are related to the physical domain, while Step 11 focuses on how to implement the strategic alternatives on the institutional sphere. While we separate the two steps to emphasize the need to consider both areas, ideally the two steps will create a common implementation plan where the strategic alternatives for the physical domain and those for the institutional sphere are mutually supportive.

Akin to project management, but at a higher level, the implementation plans developed in Steps 10 and 11 would often include deployment budget/financial requirements, actor champion and contingency planning in case some strategic alternatives fail or are not implemented on time.

STEP 10 of 12: Design and Implement Plan for Physical Domain

Step 10 concentrates on the physical and policy-driven types of strategic alternatives in the physical domain, which are part of the bundle of strategic alternatives selected in Step 9.

In developing the implementation plan, it is important to consider first how each strategic alternative fits with the others:

- Are they independent or are some prerequisite for the success of the others?
- Are there enough resources to proceed with all strategic alternatives or do additional fund-raising mechanisms need to be considered?
- Is the projected time horizon for achieving the CLIOS System goals reasonable based on the ability to implement each alternative?
- How is implementation affected by failures in meeting the targets of specific strategic alternatives?

An additional consideration when creating a plan is focusing on all the performance measures and the trade-offs among them. Neglecting certain performance measures, especially those measures which are highly valued by certain actors on the institutional sphere, can make the bundle deployment 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 System representation to identify which actor is going to implement, monitor and enforce which strategic alternative (i.e., who will be the champion for each strategic alternative), as well as who has the potential to impede its implementation.

STEP 11 of 12: Design and Implement Plan for Institutional Sphere

In Step 11, we design a plan for implementation of actor-based strategic alternatives, which are part of the bundle of strategic alternatives selected in Step 9.

When creating such a plan, due consideration should be given to the actors' individual and collective goals. By studying actors on the institutional sphere to assess how each strategic alternative affects their interests, one can try to identify both the proponents and opponents of various strategic alternatives. One can also consider the building of coalitions that will overcome resistance created from the opponents.

Notwithstanding, a well-crafted implementation plan for the institutional sphere may work against the goals of some 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, 2000), and we need to be realistic in our time frames for improving our CLIOS System when changes to the institutional sphere are among our strategic alternatives.

STEP 12 of 12: Evaluate, Monitor, and Adapt Strategic Alternatives

Once bundles of strategic alternatives have been implemented in Steps 10 and 11, the final step is to monitor and observe outcomes, both in the short and long run.

In particular, one should be careful to identify any unanticipated side effects such as degradation in the performance of one subsystem due to strategic alternatives targeted at improving a different subsystem. Indeed, creating the capability to monitor key aspects of the CLIOS system, its subsystems, and their components can and should be included as part of the plan for implementation in Steps 10 and 11.

Step 9 and Step 12 should be considered as complements of one another. While Step 9 represented the *ex-ante* evaluation of how well bundles of strategic alternatives *should* perform, Step 12 represents the *ex-post* evaluation of how well those bundles *did* perform.

5. THE ITERATIONS IN THE CLIOS PROCESS

While we explained the CLIOS Process as a set of ordered steps, it is an iterative process and not a rigid, once-through process. In this chapter, we explain eight major points where iteration back to earlier steps can occur, as depicted in Figure 4. However, these are not the only possible points for iteration, and there are other possible points of iteration.

A. Steps 6 and 1, and vice versa:

In Step 1, some preliminary system goals are identified as the overarching description of the CLIOS System is developed. However, these goals will be revisited in greater depth in Step 6. This occurs in Stage 2, after the CLIOS System representation has been developed, and the user better understands the system. Specifying system goals via performance measures (in Step 6) may lead one to revisit the system goals as originally conceived (in Step 1). *Note that this iteration is bidirectional.* Upon reaching Step 6, another review of the checklists in Step 1 will ensure that no relevant characteristics, opportunities, issues and challenges have been omitted from the analysis.

While on Step 6, one may find that difficulties in defining performance measures that capture all of the phenomena of interest lead one to revisit Step 1, to challenge the initial description, preliminary goals, and boundaries of the CLIOS System.

B. Steps 7 and 2:

When evaluating strategic alternatives (Step 7), one can revisit the CLIOS representation beginning with Step 2, in which the subsystems in the physical domain and major actor groups on the institutional sphere are first identified. As one considers strategic alternatives, it may be necessary to modify some of the earlier CLIOS representation to include additional actors or components, or even subsystems and actor groups, that were originally left out and that may be necessary to achieve specific performance measures and attain CLIOS System goals.

C. Steps 8 and 2

As uncertainties are identified (Step 8), it may be necessary to reconsider the boundaries of the CLIOS System and how the subsystems in the physical domain and groups on the institutional sphere appear in the CLIOS representation (Step 2). It may be that subsystems are characterized in ways that do not help the analyst understand and deal with the key uncertainties. One may also find that important groups on the institutional sphere were missing or poorly characterized. Therefore, revisiting the diagrams in Steps 2 and onward may be useful for better understanding uncertainties.

D. Steps 12 and 9

If the strategic alternatives failed to achieve improved system performance, one can return to Step 9, and reevaluate the individual strategic alternatives, or consider different bundles of options that can overcome any problems with the original bundles that were implemented. For example, if a bundle of options worked relatively well, but did not meet their expected performance measures, one can consider adding additional strategic alternatives to improve their performance through supporting strategic alternatives. One may also find that evaluation methods applied in Step 9 were poor, and explore other methods for evaluating strategic alternatives.

E. Steps 12 and 8-7

One can use information gleaned from successful (or unsuccessful) implementation of strategic alternatives to inform Steps 7 and 8. For example, close observation of outcomes will resolve many of the initial uncertainties in terms of how the system will respond to different interventions, both in the physical domain and on the institutional sphere. This information can also inform choices regarding future strategic alternatives. After implementing strategic alternatives and evaluating their outcomes, an analyst can decide whether and how to design new strategic alternatives or simply modify strategic alternatives which were already considered.

F. Steps 12 and 6

We can also use knowledge gained after the implementation of bundles of strategic alternatives to once again refine CLIOS System goals and performance measures. For example, it may be that there were fundamental disagreements among decision makers and stakeholders on the performance measures – disagreements that did not become clear until strategic alternatives were actually implemented. This type of information – carefully gathered after interventions – can be extremely valuable in designing future strategic alternatives.

G. Steps 12 and 5

Again, Step 5 is where the user makes the critical transition from a descriptive treatment to a prescriptive treatment of the CLIOS System. It is also the point at which one can consolidate knowledge and emerging insights regarding the structure and behavior of the system. Thus, this iteration suggests that one has completed the entire CLIOS Process and returns to reiterate the prescriptive stages. This "second time through" the process should reflect a much deeper understanding of and appreciation for system possibilities, limits, uncertainties, and sensitivities, and an updating of prior beliefs/models regarding system goals, structure, and behavior (see Learning Continuum in Figure 4). Of course, one's perception and understanding of the system may have shifted so fundamentally that it may even be worthwhile to return to Step 1, and repeat the representation stage of the CLIOS Process.

As noted above, these are not the only points of iteration. One could return to the initial CLIOS System representation and assess whether certain aspects of the system were missing or poorly represented at this stage. Looking first at the physical domain, one could ask if there was any unanticipated emergent behavior that altered the performance of the system or if any of the links were mis-specified or functioned differently than expected. One may learn the most from failures in achieving desired goals and performance measures. The lack of performance improvement could indicate a failure to understand the actors on the institutional sphere and interactions among them, or poorly designed plans for implementation.

6. CONCLUSION

This completes our discussion of the basic CLIOS Process. We hope you will find it of value in studying complex sociotechnical systems and seeking means to improve their performance in ways that are implementable. While we have come to the end of our description of the CLIOS Process, we emphasize one last time the fact that the user will doubtlessly have the need to iterate back through the process multiple times as understanding that conditions change.

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Appendix A: Glossary

The reader may find most of the concepts of the CLIOS Process in this glossary. Some definitions end with a set of related concepts for clearer associations.

- **Actor:** An institutional stakeholder in the CLIOS representation. (See *Institutional Sphere.*)
- **Actor Groups:** General categories that comprise the institutional sphere.
- **Bundle:** A set of strategic alternatives for simultaneous or phased implementation. (See *Strategic Alternative.*)
- **CLIOS Process:** A three-staged process to study and design CLIOS systems.
- **CLIOS System:** Complex, large-scale, interconnected, open, sociotechnical system. (Relate to CCIs.)
- **CLIOS System Representation:** An organizing mechanism for mapping out the system's underlying structure and behavior.
- **Common Driver:** Components that are shared across multiple subsystems of the physical domain and serve as a gear between subsystems. (See *Physical Domain.*)
- **Complex (System):** A system composed of a group of interrelated components and subsystems, for which the degree and nature of the relationships between them is imperfectly known, with varying directionality, magnitude and time-scales of interactions. (See *Complexity*.)
    - **Complexity, Behavioral:** When predictions of system outputs or behavior are difficult and often counterintuitive (also referred to as dynamic complexity).
    - **Complexity, Evaluative:** When different stakeholders value different aspects of system performance in different ways, making decision-making difficult. What may be good performance to one stakeholder, may not be good performance to another stakeholder.
    - **Complexity, Nested:** When the physical domain is nested within and being affected by a complex organizational and policymaking system.
    - **Complexity, Structural:** When a system consists of a large number of interconnected parts (also known as combinatorial or detail complexity).
- **Component:** The basic unit that makes up a subsystem in the CLIOS representation. (See *Physical Domain.*)
- **Critical Contemporary Issues (CCIs):** A variety of issues that we face in contemporary society, which are very expensive on many dimensions and have substantial impact on the human condition on this planet.
- **Descriptive (Treatment):** Trying to understand and describe. (Contrast with *Prescriptive*.)
- **Driving Force:** A key factor driving the outcome of the CLIOS system.
- **Emergence:** A specific example of behavioral complexity in which the laws or rules governing the behavior or individual components are simple, but the patterns of overall behavior that result are complex and usually surprising (Holland, 1998).
- **External Factor:** A component outside the boundaries of the CLIOS system that usually influence the CLIOS System unidirectionally. (See *Component*.)
- **Flexible (Process):** Adaptable to the many factors on which the analysis depends. (See *Modular.*)

- **Framework:** A qualitative tool of analysis for understanding institutional, organizational and stakeholder behavior, usually used for the institutional sphere. (Contrast with *Model*.)
- **Institutional Sphere:** The set of actors and organizations (i.e. the institutional stakeholders) that influence and affect (and are affected by) the physical domain. (Contrast with *Physical Domain*.)
- **Interconnected (System):** Linked to other systems.
- **Interdisciplinary (Approach):** An approach that does not come neatly boxed in traditional disciplines but rather is integrative in nature.
- **Link:** A direct oriented connection between two components or a component and an actor.
    - **Link, Class-1:** A connection between two components in the physical domain.
    - **Link, Class-2:** A connection between a component in the physical domain and an actor on the institutional sphere.
    - **Link, Class-3:** A connection between two actors on the institutional sphere.
- **Model:** A quantitative engineering and economic tool of analysis, usually used for the physical domain. (Contrast with *Framework*.)
    - **Model, Case-specific:** Models that track limited facets of the CLIOS System on the component or subsystem level.
    - **Model, System-wide:** Models that aim to describe interactions at the CLIOS system level.
- **Modular (Process):** Allowing for models and frameworks to be attached to the stages of the process. (See *Flexible.*)
- **Open (System):** Including social, political and economic aspects beyond the technical or "engineered" system.
- **Physical Domain:** The set of all subsystems of the CLIOS representation without considering the institutions. (Contrast with *Institutional Sphere*.)
- **Policy Lever:** A component within the physical domain that is most directly controlled or influenced by decisions taken by the actors on the institutional sphere. (See *Component.*)
- **Prescriptive (Treatment):** Trying to intervene, change, or improve. (Contrast with *Descriptive*.)
- **Robustness:** The ability to perform reasonably well under different futures.
- **Sociotechnical (System):** Including both technology and the social context within which a system is operating.
- **Strategic Alternatives:** changes intended to enhance the performance of the CLIOS system. (See *Bundles.*)
    - **Strategic Alternatives, Physical:** Changes involving direct modification of components in the physical domain
    - **Strategic Alternatives, Policy-driven:** Changes involving the policy levers in the physical domain, which are influenced by actors on the institutional sphere.
    - **Strategic Alternatives, Actor-based:** Architectural changes of the institutional sphere either within actors or between actors.
- **Subsystem:** a major part of the physical domain.
- **System:** A set of interconnected components and subsystems that exhibits a behavior not exhibited by the components and subsystems.

Appendix B: CLIOS Processes and Tools

THE CLIOS PROCESS AS A CHRISTMAS TREE

To effectively utilize the CLIOS Process, additional existing tools and processes must be employed. Given that the steps state *what* task should be completed but do not explicitly describe *how* (in particular after step 5), the "how" is accomplished through the use of specific processes and tools that vary to suit the taste or needs of the user in a particular project. This is why 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, and the structure of the tree (the CLIOS Process itself) being constant.

It is likely that analyzing a CLIOS system 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 system, 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 chose their processes and tools, while remaining conscious of where their work fits within the overarching structure.

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 system will involve nested complexity, processes and tools that help analyze and shape both the physical domain and the institutional sphere are necessary.

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 system. 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.

HANGING THE ORNAMENTS ON THE CLIOS "CHRISTMAS TREE"

Figure B.1 shows how various tools and processes in different domains are mapped onto the CLIOS Process. Two different perspectives, technical/ economic and social/ political/ organizational, were chosen because the processes and tools are often different in each[6]. The technical/ economic perspective is a general category containing processes and tools, such as those based in science, engineering, finance, accounting, and econometrics. The social/ political/ organizational perspective includes several domains, such as management, politics, and administrative science[7].

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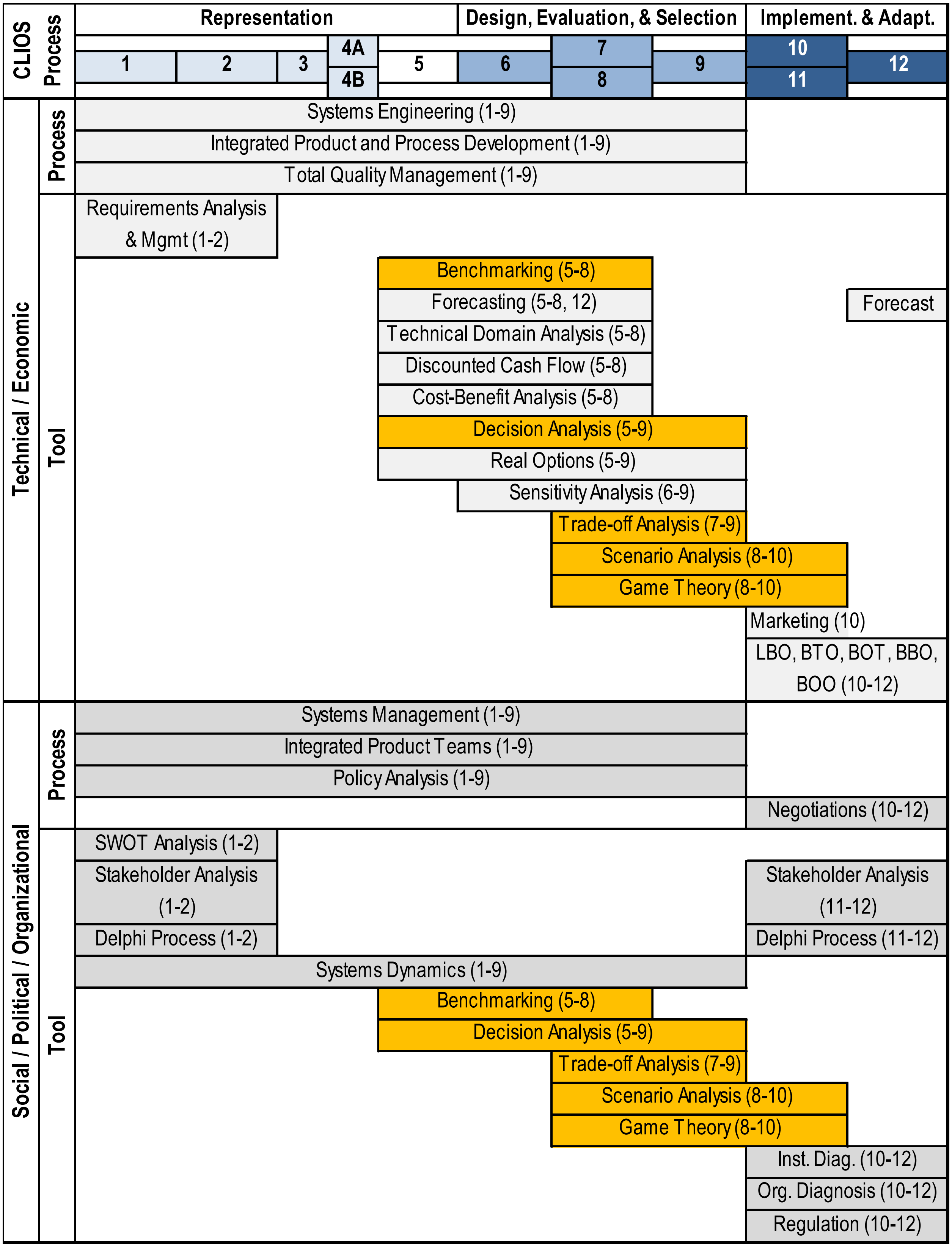
[6] While each perspective is substantially different from the other, it is recognized that there is some overlap. Some tools may appear in both perspectives, but their usage and utility to users is often different when employed in each perspective.

[7] It can be argued that additional perspectives or a finer division between perspectives should be presented. While both points have merit, for the purpose of this paper of explaining how different processes and tools hang on the CLIOS Process, the two perspectives used here are deemed sufficient

Figure B.1 Mapping Technical/ Economic, and Social/ Political/ Organizational Tools and Processes onto the CLIOS Process



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.

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. In general, however, processes denote a set of steps stating what should be done while tools provide the specific means for accomplishing the tasks denoted in processes.

TECHNICAL/ ECONOMIC PERSPECTIVE

Processes

Systems Engineering (Steps 1-9)

Systems engineering is a process for understanding a problem and creating a solution by looking at the problem in a top-down manner. The problem is considered from the viewpoint of the entire system and is then broken down into a series of 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.

Integrated Product and Process Development (IPPD) (Steps 1-9)

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.

Total Quality Management (TQM) (Steps 1-9)

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.

Tools

Requirements Analysis and Management (Steps 1-2)

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.

Requirements analysis and management deals 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 the requirements is known as requirement analysis, while the entire process of understanding, updating, and ensuring that requirements are met is labeled as requirements management.

Benchmarking (Steps 5-8)

Benchmarking is the process of identifying a comparable product, process or entity and setting its performance as a standard to be met by one's own product, process, or entity. Typically, the product, process or entity 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.

Forecasting (Steps 5-8, 12)

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.

Technical Domain Analysis (Steps 5-8)

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, and many more. The type of domain analysis that is needed is highly dependent on the nature of the project.

Discounted Cash Flow Analysis (DCF) (Steps 5-8)

DCF analysis 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 net present value (NPV) will receive higher priority for resource allocation.

Cost-Benefit Analysis (CBA) (Steps 5-8)

CBA is used to understand and compare the costs and benefits associated with a system, and it is commonly used as a decision tool for investing in a project. In CBA, all costs and all benefits are summed separately and then compared. If the benefits are larger than the costs, or the ratio of benefits to costs is larger than 1, the project is deemed worthwhile.

CBA is most commonly expressed in monetary terms, but, over time, expansions to CBA include difficult-to-quantify-and-value factors, such as the value of a statistical life. This makes the use of CBA often highly contentious with different interest groups arriving at vastly different conclusions using the same analysis tool.

Another difficulty with CBA 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.

Decision Analysis (Steps 5-9)

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.

Real Options Analysis (ROA) (Steps 5-9)

ROA is similar to decision analysis in the sense 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.

Sensitivity Analysis (Steps 6-9)

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.

Tradeoff Analysis (Steps 7-9)

Tradeoff analysis is used to help understand the set of design choices that must be made, presented as a set of possible exchanges. Tradeoffs 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. Tradeoffs are usually presented to management or policymakers, especially when the decisions coming from a tradeoff will substantially affect the system.

Scenario Analysis (Steps 8-10)

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.

Game Theory (Steps 8-10)

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.

Marketing (Step 10)

Marketing is the process of communicating the characteristics of a product or service (or a strategic alternative) to customers in order to effectively place and sell that product.

Lease, Build, Operate et al. (Steps 10-12)

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.

SOCIAL, POLITICAL AND ORGANIZATIONAL PERSPECTIVE

Processes

Negotiations (Steps 10-12)

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.

Tools

Stakeholder Analysis (Steps 1-2, 11-12)

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.

Delphi Process (Steps 1-2, 11-12)

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.

System Dynamics (Steps 1-9)

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.

Appendix C: Example of High-speed Rail in the Northeast Corridor

This appendix contains an application of the CLIOS Process to the transportation system in the Northeast Corridor of the U.S. (NEC), adapted from: Sussman, J.M., Archila, A.F., Carlson, S.J., Peña-Alcaraz, M., & Stein, N.E.G. 2012. Transportation in the Northeast Corridor of the U.S.: A Multimodal and Intermodal Conceptual Framework. http://web.mit.edu/hsr-group/documents/jiti.pdf

This study used the CLIOS Process coupled with scenario analysis and flexibility analysis in a modular fashion.

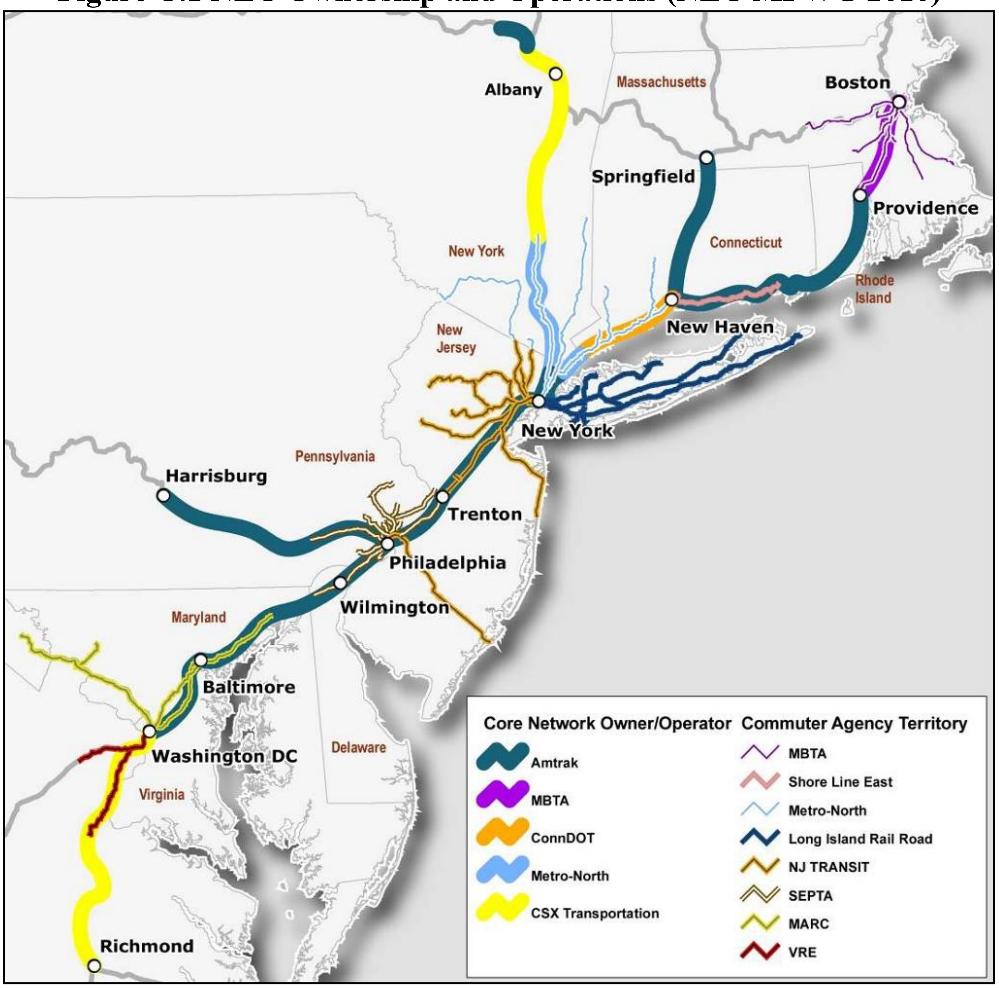
Although the development of this study was highly iterative, the version presented here is the final cut presented by the researchers.

STAGE 1 of 3: REPRESENTATION

Stage 1 focuses on the structure and behavior of the CLIOS System. This section presents a brief pass over the Steps. For a thorough explanation, the reader is directed to Sussman et al. (2012), Chapter 1.

Step 1 of 12: Describe the NEC CLIOS System: Checklists and Preliminary Goal Identification

Figure C.1 NEC Ownership and Operations (NEC MPWG 2010)



Characteristics Checklist:

- The NEC is the most densely settled region in the richest country in the world
  - 55 million people
  - $2.6 trillion economy, 20% US GDP
- 457 miles on the NEC spine, from Boston, MA to Washington, DC
- Multi-state (12 States and the District of Columbia), multi-use (freight and passenger), multi-operator (1 intercity, 8 commuter, and 7 freight operators), and multi-owner (4) corridor
- Congestion on roads, airports and rails
- Aging infrastructure

Opportunities, Issues, and Challenges Checklist:

- Cities at distances where HSR is competitive with air travel (<500 miles) and with mass transit systems in place
- Population growth
- Increasing travel demand
- Economic recovery since 2009
- Climate change adaptation and mitigation
- Constraints on investment
- Criticism to Amtrak, the National Railroad Passenger Corporation
  - Poor level of service but increasing ridership and revenues
  - Problematic implementation of HSR service
- Possible private participation
- HSR as a national priority in 2009

Preliminary System Goals:

- An intermodal, multimodal, and sustainable transportation system
- Strategic goals of the U.S. Department of Transportation: safety, state of good repair, economic competitiveness, livable communities, and environmental sustainability

Step 2 of 12: Identify Subsystems in the Physical Domain and Groups on the Institutional Sphere

The physical domain was divided into five subsystems:

- Transportation
- Energy / Environmental
- Land use
- Economic activity
- Multi-modal transportation

The institutional sphere was divided into three groups:

- Government
- Private sector
- Transportation users

Step 3 of 12: Populate Subsystems in the Physical Domain and Actor Groups on the Institutional Sphere

Steps 3 and 4 are shown both in diagrammatic, text, tabular, and matrix ways.

The 5 subsystems in the physical domain were populated with 52 components as follows:

- **Transportation subsystem (16 components):** transportation demand, transportation service, trip attributes, modal split, network usage, transport revenues, energy output, air emissions, transportation infrastructure, congestion, fuel cost and availability, transport funding and investment, transport operations subsidy, fuel tax, weather, and global fuel prices
- **Energy / Environmental subsystem (13 components):** energy output, air emissions, land usage, economic activity, other environmental impacts, energy generation infrastructure, energy transmission infrastructure, human health & environmental sustainability, energy investment, energy policies, environmental policies, weather, and energy sources
- **Land use subsystem (14 components):** energy output, land usage, economic activity, environmental policies, transportation demand, transportation service, land demand, land costs, land supply, demographics, physical characteristics of land, land accessibility, land use policies, and natural characteristics of land
- **Economic activity subsystem (15 components):** transportation demand, energy output, transportation service, land usage, economic activity, private investment, firm's costs & capacity, foreign investment, demand for goods & services, labor, capital, federal and state fiscal policies, taxes, foreign economies, and macroeconomic factors
- **Multi-modal transportation subsystem (15 components):** modal split, trip attributes, network usage, transport revenues, private investment, transportation linkages, transportation nodes, transportation vehicles, transportation frequency, transportation capacity, transportation coverage, transportation connectivity, transport funding and investment, taxes, and inter-modal transportation integration policies.

The reader may notice that some components appear in various subsystems. The full description of components is presented in Step 4.

The 3 groups on the institutional sphere were populated with 23 actors as follows:

- **Government (14 actors):** State governments, local governments, USEPA, US Department of Commerce, US Department of Energy, USDOT, FRA, FTA, FHWA, FAA, Amtrak, commuter rail agencies, and urban public transportation organizations
- **Private sector (6 actors):** freight railroad companies, intercity bus operators, trucking industry, aviation industry, private consortiums, and private land owners
- **Transportation users (3 actors):** commuters, intercity travelers, and freight users

In addition, the authors linked the several components in preliminary subsystem diagrams.

Step 4 of 12: Component, Actor, and Link Descriptions

Step 4A: Describe Components and Actors:

Table C.1 shows the description of components and their classification as common drivers, "regular components, policy levers or external factors. Table C.2 shows the description of actors.

Table C.1 Description of Components in the Physical Domain

COMMON DRIVERS (11)	
Transportation Demand	Combination of O-D patterns and volumes. It includes both the aggregate and disaggregate demand
Transportation Service	Transportation operations. It includes frequency, reliability, and quality of service
Trip Attributes	Includes in-vehicle travel time, waiting time at stops, transfer time, walking time, safety, security, reliability and comfort
Modal Split	Share of the transportation demand per mode
Network Usage	Usage volumes per mode, subject to capacity constraints
Transport Revenues	Revenues obtained from providing transportation services
Energy Output	Mode, amount availability, reliability and cost
Air Emissions	Both greenhouse gases and NOx
Land Usage	Specifies location, quantity, and type of land
Economic Activity	Vector of GDP, GDP per capita, and income distribution
Private Investment	Private investment in all sectors of the economy including transportation
"REGULAR" COMPONENTS (25)	
Transportation Infrastructure	Infrastructure, signals, ROW, stations, etc.
Congestion	All kinds of congestion (road, rail, air)
Fuel Cost and Availability	Includes gasoline, diesel, and jet fuel prices
Energy Generation Infrastructure	The physical infrastructure required to generate electricity (all methods)
Energy Transmission Infrastructure	The physical infrastructure required to distribute electricity
Human Health & Environmental Sustainability	Considers human health effects and long-term environmental sustainability
Other Environmental Impacts	Water pollution, nuclear waste, habitat destruction, and additional environmental impacts not captured in the other components
Demographics	Statistical characteristics of population
Land Demand	Specifies the quantity, type, and desired location of land
Land Costs	Results from the interactions between land supply and demand
Land Supply	Quantity and type of land available at a given location
Physical Characteristics of Land	Physical and artificial characteristics of land
Land Accessibility	Refers to the ability of goods, services, energy, etc. to reach the land
Firm's Costs & Capacity	The firm's production and cost functions

Foreign Investment	Similar to private investment, but specifically considering foreign sources
Demand for Goods & Services	The quantity of goods and services that primarily individuals demand
Labor	Quantity, type, and cost of labor. Saturation (employment) level
Capital	Includes type, quantity, and cost of capital
Transportation Linkages	The physical infrastructure between nodes for all modes (e.g. track)
Transportation Nodes	Physical terminal/station infrastructure for all modes
Transportation Vehicles	Refers to vehicles operated by all modes of transportation (e.g. cars, buses)
Transportation Frequency	The service plan of the operators
Transportation Capacity	The number of people or amount of goods that can be transported per mode per unit of time
Transportation Coverage	The number of people or the amount of goods that is in close proximity to a mode
Transportation Connectivity	The concept of how well the modes are connected
POLICY LEVERS (10)	
Transport Funding & Investment	Federal and state funding and investment
Transport Operations Subsidy	How much the government chooses to subsidize transportation operations
Fuel Tax	Excise fuel tax. Fixed since 1991
Taxes	Includes business and personal taxes
Energy Investment	Monetary investment in energy
Energy Policies	Environmental and technical policies
Environmental Policies	US EPA's regulations
Land Use Policies	Primarily state and local policies
Federal & State Fiscal Policies	Allocation of expenditures
Inter-Modal Transportation Integration Policies	How well transportation agencies/operators interact between modes and how well infrastructure is able to serve multiple modes
EXTERNAL FACTORS (6)	
Weather	Weather and environmental conditions. It is also a common driver
Natural Characteristics of Land	Includes slope, type of soils, climate conditions, etc.
Global Fuel Prices	The market price of petroleum products
Energy Sources	Wind, solar, water, nuclear, coal or gas availability
Macroeconomic Factors	Economic factors largely outside of government control
Foreign Economies	Foreign economic factors largely outside of government control

Table C.2 Description of Actors on the Institutional Sphere

GOVERNMENT (14)	
Congress	Senate and House of Representatives
State Governments	8-9 States and the District of Columbia. (MA, RI, CT, NY, NJ, PA, DE, MD, VA)
Local Governments	Municipal governments, county governments, metropolitan planning organizations and regional councils
US Environmental Protection Agency (EPA)	In charge of developing and enforcing environmental regulations in the U.S.
US Department of Commerce	Promotes job creation, economic growth, sustainable development and improved standards of living for the U.S.
US Department of Energy	In charge of the energy, environmental and nuclear challenges of the U.S.
US Department of Transportation	A cabinet-level agency in charge of transportation in the U.S. It comprises several sub-agencies, including FRA, FTA, FAA, and FHWA
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
FHWA	Federal Highway Administration
FAA	Federal Aviation Administration
Amtrak	The National Railroad Passenger Corporation, the solely intercity rail passenger operator in the NEC
Commuter Rail Agencies	8 commuter agencies in the NEC: MBTA, SLE, MNR, LIRR, NJT, SEPTA, MARC, and VRE
Urban Public Transportation Organizations	MBTA in Boston, MTA in New York, SEPTA in Philadelphia, and WMATA in Washington, D.C.
PRIVATE SECTOR (6)	
Aviation Industry	Includes both airlines that operate over the NEC and airports that operate in its boundaries
Intercity Bus Operators	Boltbus, Greyhound, Peter Pan Bus, DC2NY, Vamoose Bus, Megabus, Washington Deluxe, Eastern Travel, New Century, Fung Wah Bus and Lucky Star Bus
Private Consortiums	Consortiums that could finance, design, build, operate and/or maintain NEC high-speed rail
Freight Railroad Companies	7 freight railroads have trackage rights over some portion of the NEC
Trucking Industry	Private trucking companies that ship to and from areas along the NEC
Private Land Owners	Private landowners of potential right-of-way
TRANSPORT USERS (3)	
Commuters	Users of NEC completing short trips, who primarily use commuter rail services
Intercity Passengers	Users of the NEC completing long trips (>75 miles)
Freight Users	Commercial and industrial users along the NEC that rely on the freight railroads and trucks to ship and deliver their goods and products

The corresponding subsystem diagrams are shown in Figures C.2-C.7. Usually, the graphical representation is accompanied by a short description. We include only the description of the transportation subsystem as an example. The reader may find the remaining descriptions in Sussman et al. (2012), Chapter 1.

Figure C.2 CLIOS Representation of the NEC

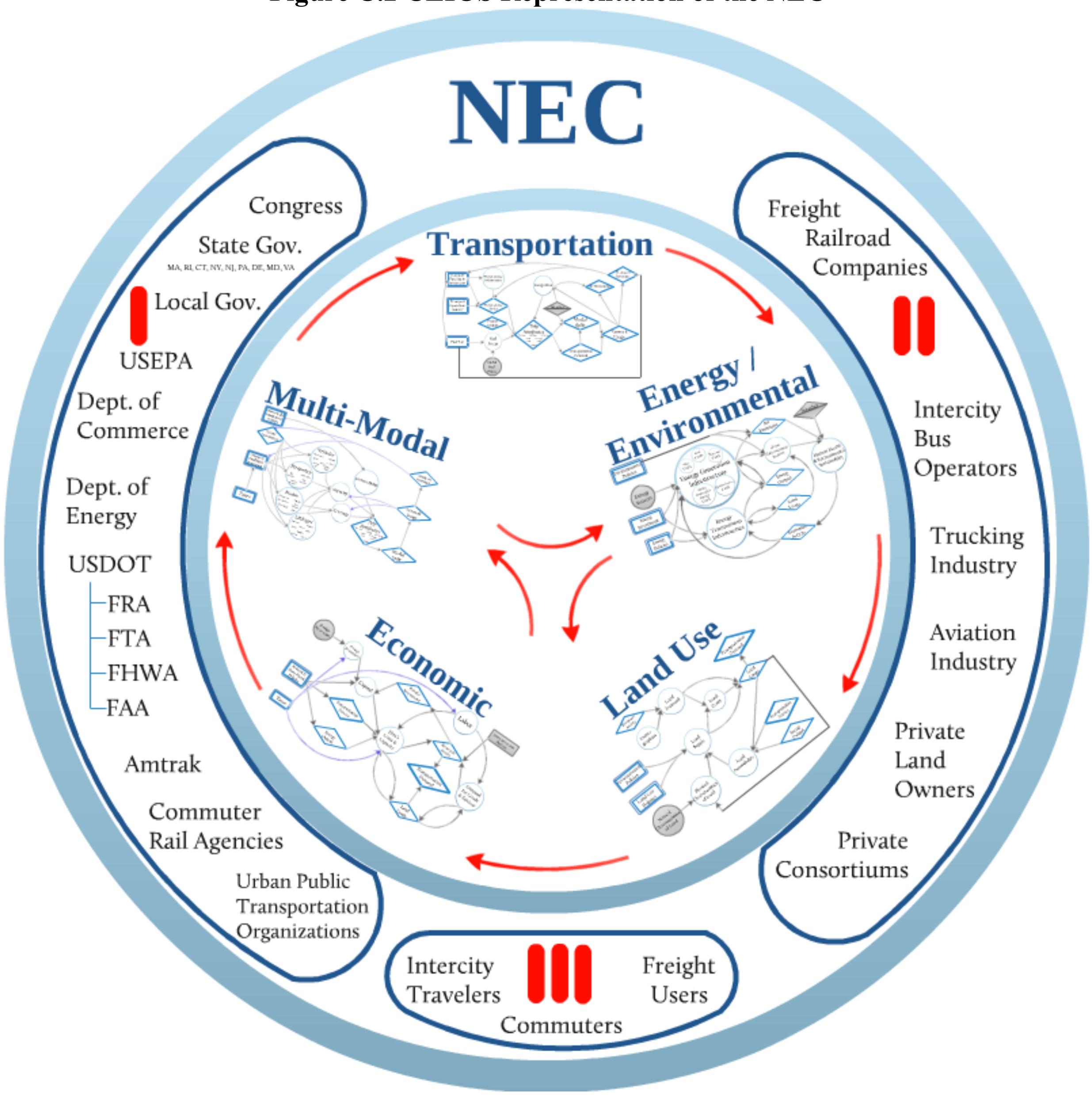
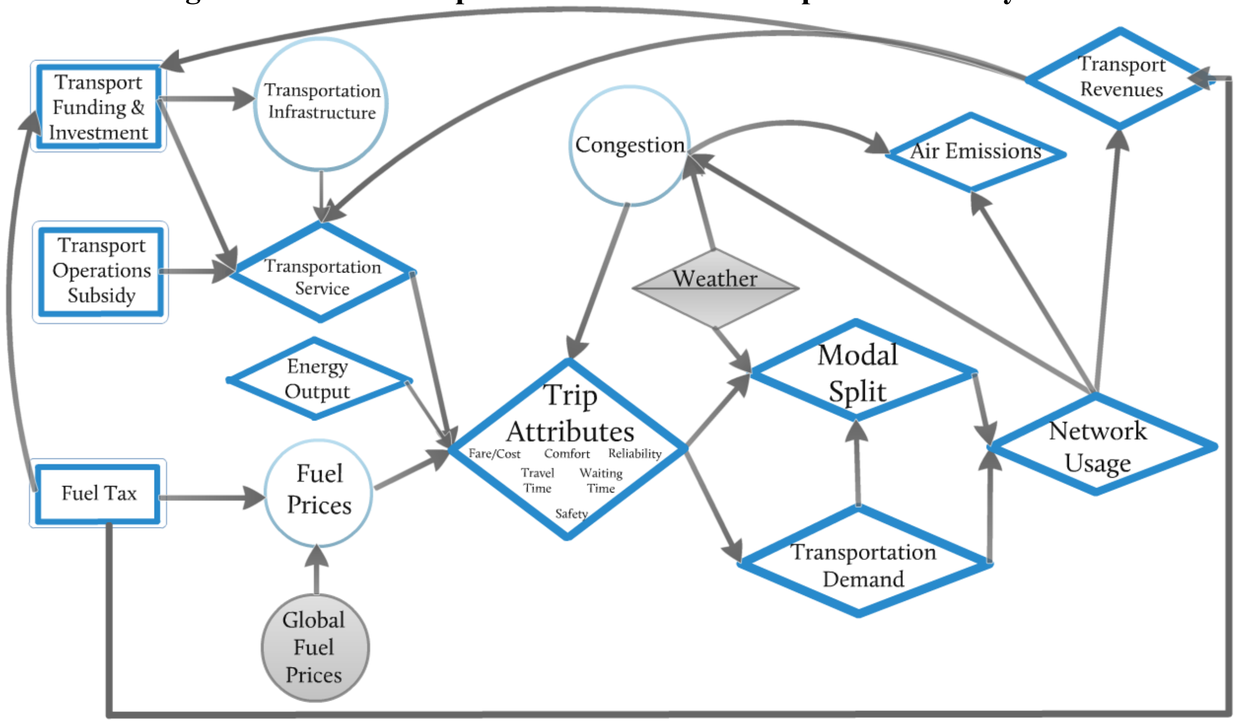


Figure C.3 CLIOS Representation of the Transportation Subsystem



Box C.1 Description of the CLIOS Representation of the Transportation Subsystem

"Transportation Demand is initially an output of the land use and the economic subsystems, namely, a derived demand of the activities' distribution and the levels of economic activity. Next, the Modal Split results from the Transportation Demand and certain Trip Attributes per mode – travel time, waiting and/or transfer time, costs or fares, safety, reliability and comfort– which results in an induced Transportation Demand. Weather (an external factor) further impacts the decisions on the transportation mode, both on a seasonal and on a daily basis. In this way, weather could explain systematic differences in mode choice during the summer and the winter months or random differences in mode choice due to sudden weather changes or adverse conditions."

"Subsequently, Transportation Demand and Modal Split determine the Network Usage for each mode, which results in certain levels of Transport Revenues, Air Emissions and Congestion. Extreme climate conditions also increase the Congestion levels, which consequently increase Air Emissions (greenhouse gases, NOx, SOx, particulate matter, VOCs and ground-level ozone, for example) and cause deterioration to Trip Attributes: increasing travel times and unreliability, decreasing comfort and safety of trips. The sensitivity to congestion is different for each transportation mode."

"Some of the Transport Revenues are destined to Transport Funding and Investment, which then determines the levels of maintenance and improvements of the Transportation Infrastructure. Transport Funding and Investment as well as Transport Revenues are strongly dependent on the excise Fuel Tax. An additional recipient of Transport Revenues and Transport Investment is Transportation Service, which also benefits from a state of good repair… for the Transportation Infrastructure. Usually for mass transit systems, an additional Subsidy is given to cover operational costs."

"Then, Transportation Service, Energy Output… and Fuel Prices influence the relative Trip Attributes as described before. Energy Output is especially important in setting the travel costs for public transportation, whereas Fuel Prices play a major role both for private and public vehicles. Fuel Prices are sensitive to variations in external factors, such as the Global Fuel Prices, or governmental policies, such as the Fuel Tax."

(Sussman et al. 2012, Chapter 1, p. 4-5)

Figure C.4 CLIOS Representation of the Energy/Environmental Subsystem

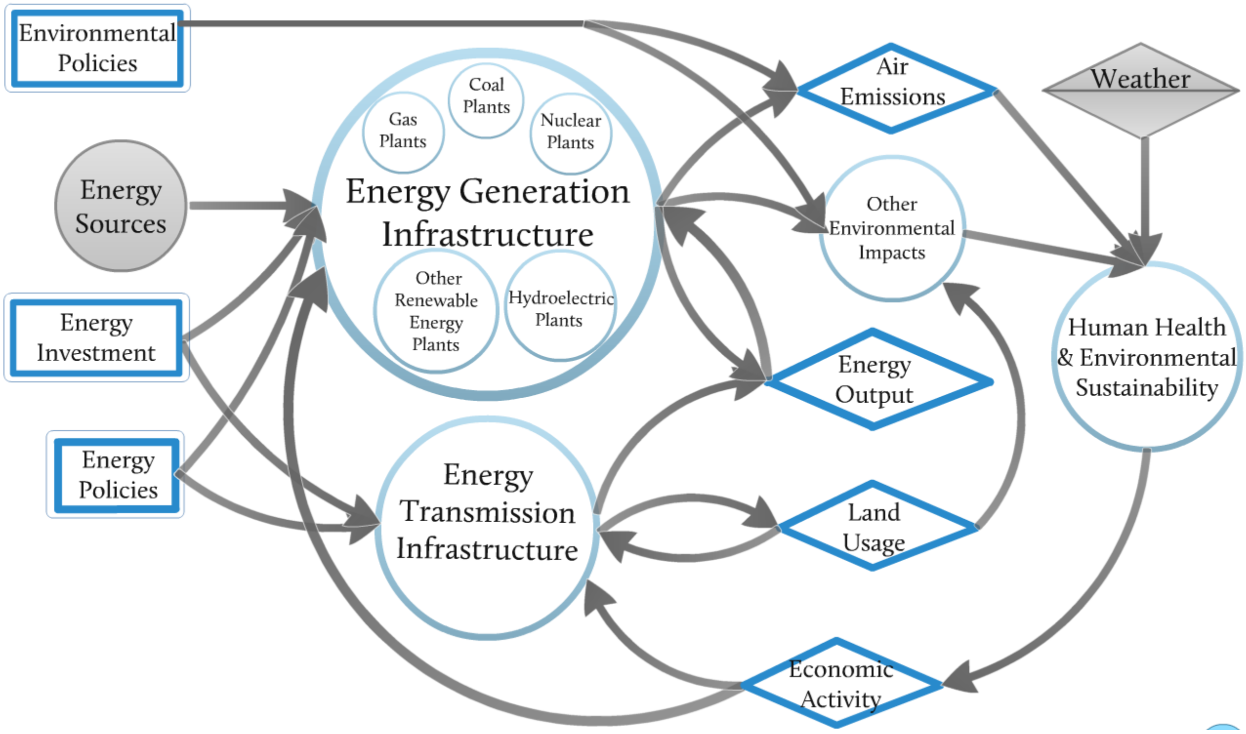


Figure C.5 CLIOS Representation of the Land Use Subsystem

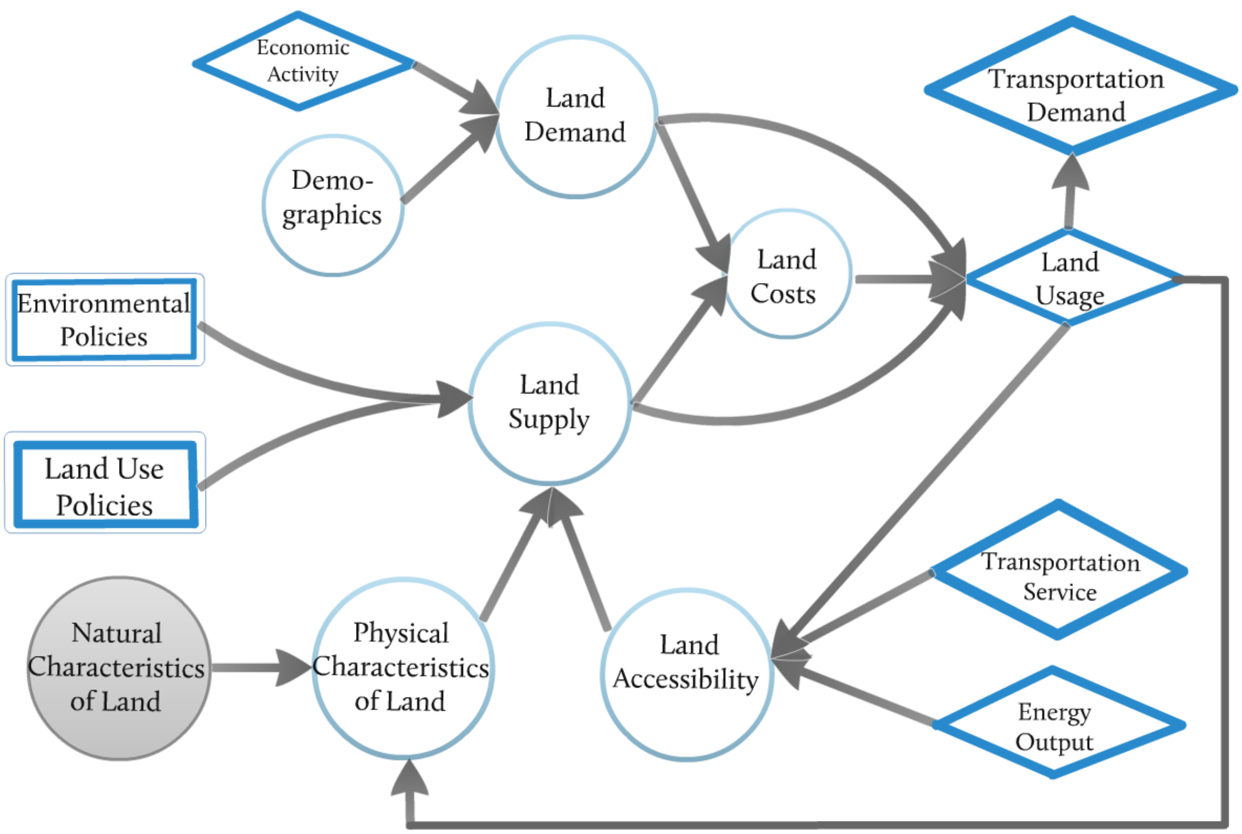


Figure C.6 CLIOS Representation of the Economic Subsystem

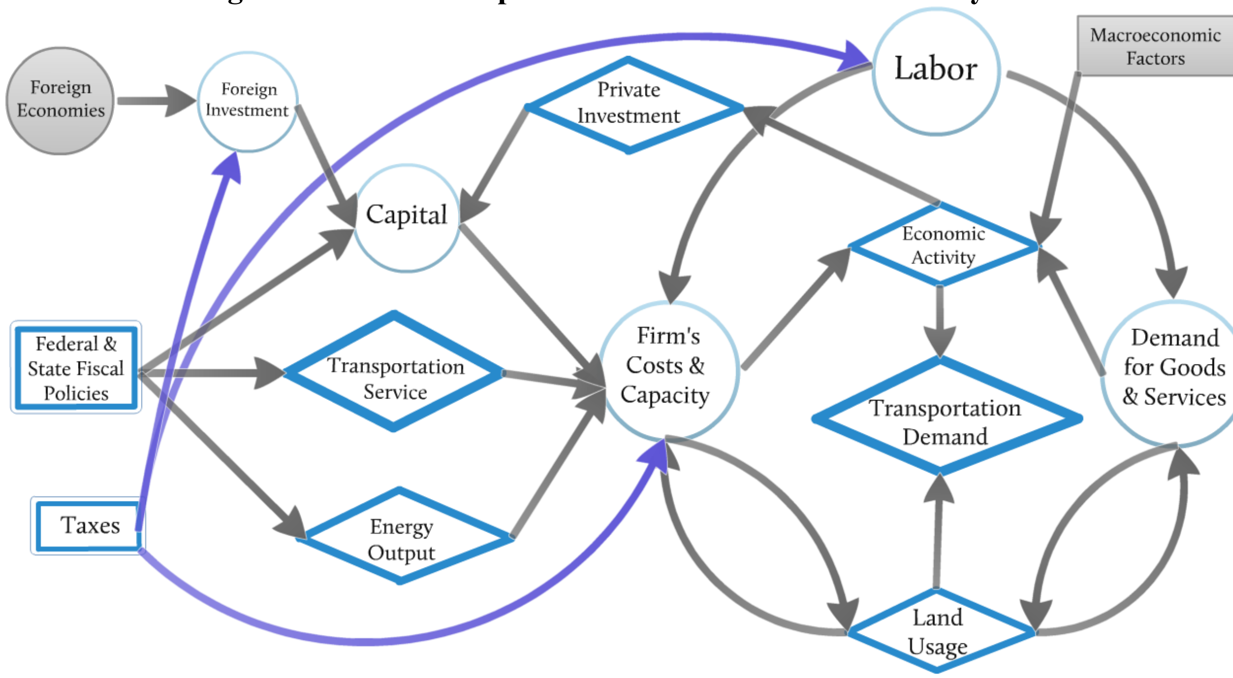
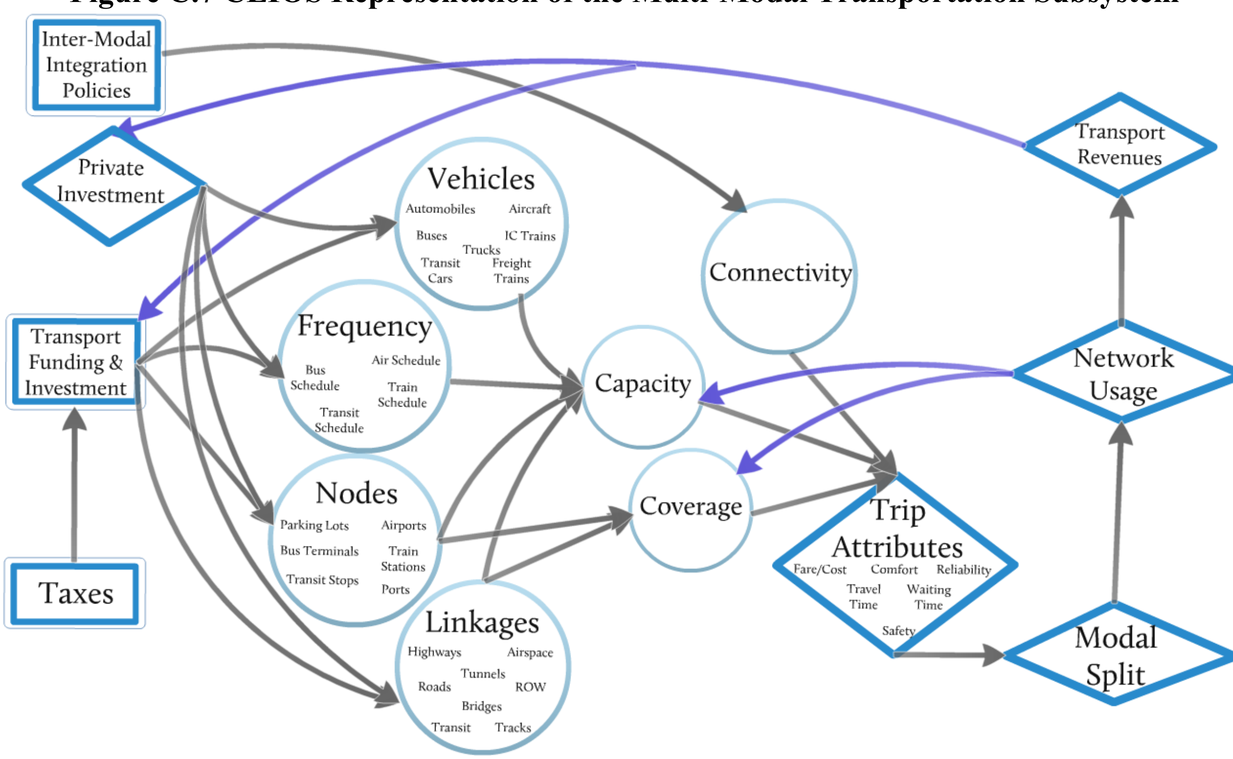


Figure C.7 CLIOS Representation of the Multi-Modal Transportation Subsystem



Step 4B: Describe Links

Table C.3 shows the description of the 103 links identified in the subsystem diagrams (class-1 links). Figure C.8 shows how the actors connect with components (class-2 links). The authors did not consider class-3 links.

Table C.3. Description of Links in the Physical Domain (Class-1 Links)

From	To	Characteristics & Magnitude	Linkage
Transportation Demand	Modal Split	Travelers choose among modes based upon their individual preferences (average, variable-effects)	Causal
Transportation Demand	Network Usage	Network usage is directly proportional to transportation demand (strong, positive)	Causal
Energy Output	Trip Attributes	Improved energy output impacts positively some trip attributes, e.g. cost and reliability (average, positive)	Causal
Transportation Service	Trip Attributes	Improved transportation service enhances trip attributes for a given mode, e.g. more frequent service diminishes waiting time (strong, positive)	Causal
Modal Split	Network Usage	A greater share of transportation demand per mode increases the network usage per mode (strong, positive)	Causal
Trip Attributes	Transportation Demand	An induced demand results from improved trip attributes (average-weak, positive)	Causal
Trip Attributes	Modal Split	Improved trip attributes increase the share of a specific transportation mode (strong, positive)	Causal
Network Usage	Air Emissions	As network usage increases, there are more air emissions. However, the proportionality of the relationship depends on the network usage per mode (strong, positive)	Causal
Network Usage	Transport Revenues	As network usage increases, transport revenues increase, given that the marginal revenue exceeds marginal cost (strong)	Causal
Network Usage	Congestion	As network usage increases, congestion will also increase, although the proportionality of the relationship depends on the modal split and the available capacity (average, positive)	Causal
Transport Revenues	Transportation Service	In general, increases in transportation revenues will allow for transportation services to be improved, but it is subject to the decision of the firm (weak-average, none or positive)	Causal
Transport Revenues	Transport Funding and Investment	An increase in transportation revenues will encourage more transportation investment, but it is subject to the decision of the institutional actor (average, none to positive)	Causal
Transportation Infrastructure	Transportation Service	Improving transportation infrastructure allows for better transportation service, but the decision to improve	Causal

		transportation service is subject to other conditions (strong, none to positive)	
Congestion	Trip Attributes	An increase in congestion has a negative impact on trip attributes (average, negative)	Causal
Fuel Prices and Availability	Trip Attributes	Improvements to fuel prices and availability (e.g. a decrease in cost and an increase in availability) improves trip attributes (average, positive)	Causal
Transport Funding and Investment	Transportation Service	Increased transportation funding and investment allows for improved transportation service (average, positive)	Causal
Transport Funding and Investment	Transportation Infrastructure	Increased transportation funding and investment improves levels of maintenance and enhancements to transportation infrastructure (strong, positive)	Causal
Transport Operations Subsidy	Transportation Service	Increased operating subsidies allows for improved transportation service; however, it is also a function of the management of the organization (strong, none to positive)	Causal
Fuel Tax	Transport Revenues	Increases to fuel taxes increases transportation revenues, assuming that fuel prices remain inelastic (strong, positive)	Causal
Fuel Tax	Fuel Prices	Increases to fuel taxes increases the PRICE of fuel (average, positive)	Causal
Fuel Tax	Transport Funding and Investment	Most of the transport funding comes from fuel taxes (strong, positive)	Causal
Weather	Modal Split	Poorer weather causes a shift from public to private transportation (average, variable effects)	Causal
Weather	Congestion	Poorer weather causes increased congestion (average, negative)	Causal
Global Fuel Prices	Fuel Prices	Increases in global fuel prices increases the PRICE of fuel (strong, positive)	Causal
Energy Output	Energy Generation Infrastructure	An increase in consumption encourages the development of more energy generation infrastructure. Providing more energy generation infrastructure increases the availability of energy, but has a variable impact on energy cost, depending on the cost of bringing these plants online and the regulatory environment (i.e. are prices fixed by a regulator) (bi-directional, average-strong, variable impacts)	Causal
Air Emissions	Human Health & Environmental Sustainability	An increase in air emissions has a deleterious effect on human health and environmental sustainability (strong, negative)	Causal
Land Usage	Other Environmental Impacts	Land usage has various impacts on other environmental impacts (average, variable)	Causal

Land Usage	Energy Transmission Infrastructure	Certain types of land usage requiring energy output can encourage the development of transmission infrastructure. Similarly, improvements to energy transmission infrastructure can encourage the development of land (bi-directional, average, generally positive)	Causal
Economic Activity	Energy Generation Infrastructure	An increase in economic activity encourages the development of energy generation infrastructure (average, positive)	Causal
Economic Activity	Energy Transmission Infrastructure	An increase in economic activity encourages the development of energy transmission infrastructure (average, positive)	Causal
Other Environmental Impacts	Human Health & Environmental Sustainability	An increase in other environmental impacts has a deleterious effect on human health and sustainability (average, negative)	Causal
Energy Generation Infrastructure	Air Emissions	An increase in energy generation infrastructure generally increases air emissions; however, the proportionality of the increase depends on the mix of energy sources used (average, positive)	Causal
Energy Generation Infrastructure	Other Environmental Impacts	An increase in energy generation infrastructure generally increases other environmental impacts; however, the proportionality of the increase depends on the mix of energy sources used (average, positive)	Causal
Energy Transmission Infrastructure	Energy Output	Improved energy transmission infrastructure provides better coverage and reliability of energy (strong, positive)	Causal
Human Health & Environmental Sustainability	Economic Activity	Healthy citizens increase the potential for economic activity inside a society. Environmental sustainability allows long-term economic activity (average, positive)	Causal
Energy Investment	Energy Generation Infrastructure	Energy investment is necessary in order to enhance energy generation infrastructure for any given mode (strong, positive)	Causal
Energy Investment	Energy Transmission Infrastructure	Investment in energy transmission infrastructure determines the actual distribution of the electrical grid (strong, positive)	Causal
Energy Policies	Energy Generation Infrastructure	Energy policies regulate the type and amount of energy generation (strong, variable effects)	Causal
Energy Policies	Energy Transmission Infrastructure	Transmission infrastructure is restricted to energy regulations, policies and standards (strong, variable effects)	Causal
Environmental Policies	Air Emissions	One mechanism for control of air emissions is environmental policies. More stringent environmental policies reduce allowed levels of air emissions (strong, negative)	Causal

Environmental Policies	Other Environmental Impacts	More rigorous environmental regulations diminish possible environmental impacts (strong, negative)	Causal
Weather	Human Health & Environmental Sustainability	Alterations of climate patterns affect our way of living and reshape the Earth's cycles. (strong, variable effects)	Causal
Energy Sources	Energy Generation Infrastructure	Available energy sources favor the selection of specific energy generation modes at a given site (strong, variable effects)	Causal
Energy Output	Land Accessibility	An improvement in energy output (i.e. greater availability and lower cost) available to a given parcel of land improves the accessibility of the land (average, positive)	Causal
Transportation Service	Land Accessibility	An improvement in transportation service (i.e. greater availability and lower cost) to a given parcel of land improves the accessibility of the land (average, positive)	Causal
Land Usage	Transportation Demand	Changes to land usage have a complex, but important impact on transportation demand. It sets off most of the O-D patterns (strong, complex)	Causal
Land Usage	Physical Characteristics of Land	An increase in human-made development alters the physical characteristics of land. Often these human impacts negatively impact the physical characteristics of the land; however, occasionally they can have a positive impact on the land if they are properly designed (strong, variable - often negative)	Causal
Land Usage	Land Accessibility	Current land usage feeds back into land accessibility definitions (average, variable effects)	Causal/ Constitutive
Economic Activity	Land Demand	An increase in economic activity increases the demand for land (average, positive)	Causal
Land Demand	Land Usage	The type of land demanded influences the type of land used (strong)	Informational
Land Demand	Land Costs	Assuming all else equal, an increase in land demand increases the cost of land (average, positive)	Causal
Land Costs	Land Usage	The cost of land influences the type of land usage (strong)	Informational
Land Supply	Land Usage	The nature of available land impacts the type of land usage (average)	Causal/ Informational
Land Supply	Land Costs	Assuming all else equal, an increase in land supply decreases the cost of land (average, positive)	Causal
Demographics	Land Demand	Demographics has an impact on the type of land demanded (average)	Informational
Physical Characteristics of Land	Land Supply	The physical characteristics of the land describe the land supply (average)	Constitutive

Land Accessibility	Land Supply	Accessibility is a characteristic of the land supply (average)	Constit utive
Environmental Policies	Land Supply	Environmental policies restrict how a parcel of land can be used (average-strong)	Informa tional
Land Use Policies	Land Supply	Land use policies restrict how a parcel of land can be used (average-strong)	Informa tional
Natural Characteristics of Land	Physical Characteristics of Land	Natural characteristics of the land define the initial characteristics of the land and constrain further physical changes to the land (strong)	Informa tional
Energy Output	Firm's Costs & Capacity	An improvement in energy output (i.e. an increase in availability and a decrease in cost) improves the capacity and cost functions of firms (average, positive)	Causal
Transportation Service	Firm's Costs & Capacity	An improvement in transportation service (i.e. an increase in availability and a decrease in cost) improves the capacity and cost functions of firms (average, positive)	Causal
Transport Revenues	Private Investment	An increase in transport revenues increases the likelihood of private sector involvement (average, positive)	Financi al
Land Usage	Firm's Costs & Capacity	An improvement in land usage (e.g. an increase in the availability of an appropriate land type and a decrease in costs) improves the capacity and cost of operation of a firm. Similarly, a change in the cost and capacity of the firm as a result of changes to land usage and other factors can cause it to relocate, and thus impact land usage. (weak, bi-directional)	Causal
Land Usage	Demand for Goods & Services	Specific land usage and O-D patterns may increase or decrease the need for services. If the demand for specific goods, services is sufficiently high, it could favor new land usage patterns, however, this would be on the long-term (weak on a time scale, bi-directional, complex)	Causal
Economic Activity	Transportation Demand	An increase in economic activity increases the demand for transportation (average, positive)	Causal
Economic Activity	Private Investment	An increase in economic activity encourages more private investment (average, positive)	Causal
Private Investment	Capital	An increase in private investment increases the availability of capital (average, positive)	Causal
Firm's Costs & Capacity	Economic Activity	The capacity of the firms sets an upper bound for the economic activity, while lower costs favor increments in production (average, positive)	Causal
Foreign Investment	Capital	An increase in foreign investment increases the availability of capital (average, positive)	Causal
Demand for Goods & Services	Economic Activity	Assuming all else equal, an increase in the demand for goods and services increases economic activity (strong, positive)	Causal

Labor	Firm's Costs & Capacity	An improvement in the availability and cost of labor improves a firm's cost and capacity (strong, positive)	Causal
Labor	Demand for Goods & Services	As a the wages and employment of labor increases, so does the demand for goods and services (average, positive)	Causal
Capital	Firm's Costs & Capacity	An improvement in the availability and cost of capital improves a firm's cost and capacity (strong, positive)	Causal
Federal and State Fiscal Policies	Energy Output	The way in which governments spend their energy budget sets boundaries to energy output (strong)	Causal
Federal and State Fiscal Policies	Transportation Service	Adequate allocation of government funds improves transportation service (average, complex)	Causal
Federal and State Fiscal Policies	Capital	More allocation of governmental funds increase access to capital (average, positive)	Causal
Taxes	Firm's Costs & Capacity	An increase in taxes increases the cost of operating a firm (strong, positive)	Causal
Taxes	Foreign Investment	Taxes pose restrictions to foreign investment (average, negative)	Causal
Taxes	Labor	An increase in taxes decreases the real income of individuals (strong, negative)	Causal
Foreign Economies	Foreign Investment	An improvement in foreign economies allows for an increase in foreign investment, but does not necessarily suggest that there will be foreign investments (average, unknown)	Causal
Macroeconomic Factors	Economic Activity	Economic activity is subject to and primarily defined by macroeconomic factors (strong, complex)	Causal
Network Usage	Transportation Capacity	Increases in network usage favor capacity enhancements (average, positive)	Informational
Network Usage	Transportation Coverage	Patterns of network usage serve as tool for decision-making on transportation coverage (strong, variable effects)	Informational
Private Investment	Transportation Linkages	Private investment enhances some of the transportation linkages: highways, roads, tunnels, bridges, transit lines, ROW, track or airspace. This occurs generally through PPP (weak, positive)	Causal
Private Investment	Transportation Nodes	More private investment improves transportation nodes, generally through PPP (weak, positive)	Causal
Private Investment	Transportation Vehicles	Private investment increases the number and quality of private transportation vehicles (strong, positive)	Causal
Private Investment	Transportation Frequency	Private investment alters some of the available transportation patterns (weak, variable effects)	Causal
Transportation Linkages	Transportation Capacity	Linkages are a key component of transportation infrastructure and capacity (strong, positive)	Constitutive

Transportation Linkages	Transportation Coverage	Greater transportation coverage is achieved through infrastructure enhancements, where linkages play a major role (strong, positive)	Constitutive
Transportation Nodes	Transportation Capacity	Nodes are a key component of transportation infrastructure and capacity (strong, positive)	Constitutive
Transportation Nodes	Transportation Coverage	Transportation nodes are especially relevant for public transportation and for rail/air transportation (strong, positive)	Constitutive
Transportation Vehicles	Transportation Capacity	Greater size and quantity of vehicles increase transportation capacity (average, positive)	Constitutive
Transportation Frequency	Transportation Capacity	Frequencies are relevant for transportation capacity in the public sector. Higher frequencies increase the capacity (average, positive)	Constitutive
Transportation Capacity	Trip Attributes	Greater capacity generally improves trip attributes, such as travel time, comfort, cost and safety (strong, positive)	Causal
Transportation Coverage	Trip Attributes	Better coverage improves some trip attributes, such as reliability, waiting time (average, positive)	Causal
Transportation Connectivity	Trip Attributes	Greater transportation connectivity improves trip attributes by allowing cooperation between modes (strong, positive)	Causal
Transport Funding and Investment	Transportation Linkages	Public investment enhances most of the transportation linkages and keeps them in a state of good repair (strong, positive)	Causal
Transport Funding and Investment	Transportation Nodes	Public investment improves and/or maintains most of the transportation nodes (strong, positive)	Causal
Transport Funding and Investment	Transportation Vehicles	Public investment increases the number and quality of public transportation vehicles (strong, positive)	Causal
Transport Funding and Investment	Transportation Frequency	Public investment alters some of the available transportation patterns (average, positive)	Causal
Taxes	Transport Funding and Investment	Taxes are the main source of the Highway Trust Fund and other public funds (strong, positive)	Causal
Inter-Modal Transportation Integration Policies	Transportation Connectivity	Transportation connectivity across modes is improved through policy alignments for each mode (strong, positive)	Causal

Matrix Representation

An alternative approach to the tabular description and graphical representation of the links is the matrix representation. Figure C.8 below shows how the actors connect with components (class-2 links), and whether the influence along these links flows from actor to component (A), component to actor (C), or whether the influence is bi-directional (B).

Figure C. 8 Matrix of Links between Actors and Components (Class-2 Links)
(Only components with class-2 links are shown)

COMPONENTS: Common Drivers; (Regular) Components; Policy Levers

#	ACTORS	1 Transportation Demand	2 Energy Output	3 Transportation Service	4 Modal Split	5 Air Emissions	6 Trip Attributes	8 Transport Revenues	9 Land Usage	10 Economic Activity	11 Private Investment	12 Transportation Infrastructure	13 Congestion	14 Fuel Cost and Availability	15 Other Environmental Impacts	16 Energy Generation Infrastructure	17 Energy Transmission Infrastructure	18 Human Health & Environmental Sustainability	19 Land Demand	24 Land Accessibility	25 Firm's Costs & Capacity	26 Foreign Investment	27 Demand for Goods & Services	28 Labor	29 Capital	30 Transportation Linkages	31 Transportation Nodes	32 Transportation Vehicles	33 Transportation Frequency	3 Transport Funding and Investment
	Government																													
1	Congress																					A								A
2	State Governments																					A								A
3	Local Governments								C	C																				A
4	USEPA					C									C															
5	US Department of Commerce										B											A								
6	US Department of Energy		C													C	C													
7	USDOT																													A
8	FRA																													A
9	FTA																													A
10	FHWA																													A
11	FAA																													A
12	Amtrak		C	A				C			A	A		C	A											A	A	A	A	A
13	Commuter Rail Agencies		C	A				C			A	A		C	A											A	A	A	A	A
14	Urban Public Transportation Organizations		C	A				C			A	A		C	A											A	A	A	A	A
	Private Sector																													
15	Freight Railroad Companies			A				C			A	A		C	A											A	A	A	A	
16	Intercity Bus Operators			A				C			A			C	A												A	A	A	
17	Trucking Industry			A				C			A			C	A												A	A	A	
18	Airline Industry			A				C			A	A		C	A												A	A	A	
19	Private Consortiums		C	A				C			A														A	A	A	A	A	
20	Private Land Owners															C	C													
	Transport Users																													
21	Commuters	A			A	C	C						C	C	C			C	A	C			A	A						
22	Intercity Travelers	A			A	C	C						C	C	C			C	A	C			A	A						
23	Freight Users	A			A	C	C						C	C	C				A	C	C									

Key
A: Actor influences component
B: Bi-directional influence
C: Component influences actor

As mentioned earlier, the authors did not consider class-3 links in their CLIOS System Representation.

Step 5 of 12: Transition from Descriptive to Prescriptive Treatment of System

Sussman et al. (2012) Chapter 4, developed extensions to the CLIOS Process representation to identify highly-leveraged points.

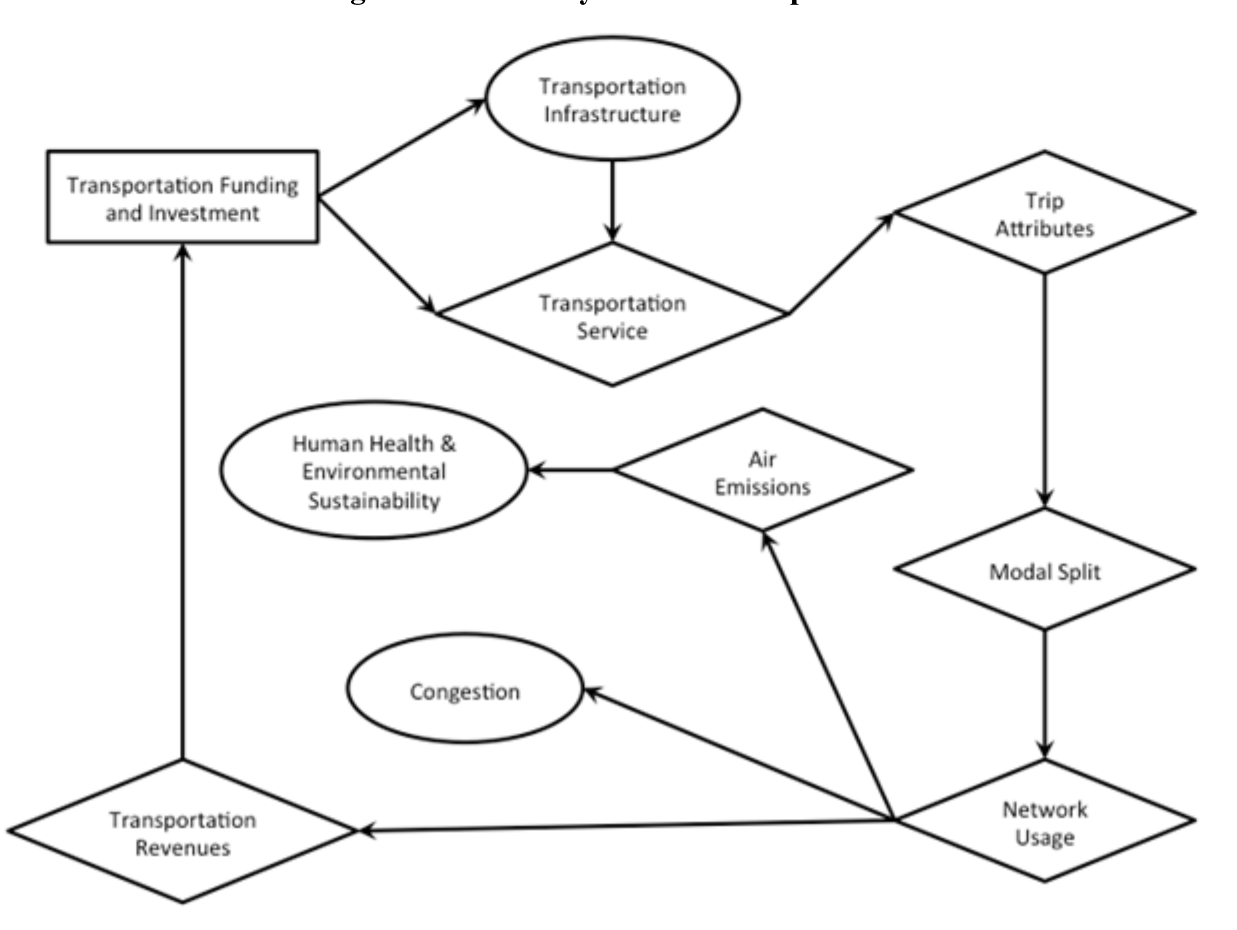
A connectivity matrix determines whether two components are connected and how many links are in the shortest path that connects them. In addition, the path-impact matrix shows how significant are the interactions along chains of links (paths) in terms of speed, strength and impact.

This allowed the authors to represent and understand the structural complexity of the CLIOS system, and provided a mechanism to prioritize areas of study and intervention.

In Sussman et al. (2012) Chapter 5, some high-impact paths and networks in the CLIOS Representation are analyzed in the context of broader transportation issues, thus changing from a descriptive to prescriptive treatment of the CLIOS System. These subnetworks also facilitate the subsequent analysis and design of strategic alternatives.

Figure C.9 shows an example of one of such high-impact networks derived from the analysis of the CLIOS System Representation:

Figure C.9 Basic Cycle - Central Spine Subnetwork



STAGE 2 of 3: DESIGN, EVALUATION, AND SELECTION

The goals of Stage 2 are to refine goals aimed at improvement of the CLIOS System, and to develop and select bundles of strategic alternatives.

Step 6 of 12: Refine CLIOS System Goals and Identify Performance Measures

After the CLIOS Representation is complete, the goals (G) and performance measures (PM) for the CLIOS System are refined and placed in three categories as follows:

Transportation System Performance:

Direct benefits to the transportation system and its users that would result from an investment:

- (G) Improve the mobility of transportation system users (passengers and freight)
  - (PM) Capacity, utilization, (best available) trip times, reliability
- (G) Return the transportation system to a state of good repair (SoGR)
  - (PM) Estimated backlog of repairs
- (G) Improve transportation system safety
  - (PM) A weighted average (based on the number of users per mode) of the fatality rates per mode
- (G) Efficiently use public investments to fund the transportation system
  - (PM) Cost-benefit ratio

External Impacts of the Transportation System:

Intended to gauge more broadly the sustainability of the transportation system considering the economy, environment and social equity:

- (G) Promote economic growth
  - (PM) Number of jobs/labor within reach of transportation, firm productivity, land value
- (G) Increase environmental sustainability
  - (PM) CO2 emissions, fuel consumption, land utilization
- (G) Ensure social equity
  - (PM) Spatial distribution and socioeconomic class of jobs

Organizational Structure Effectiveness:

Focused primarily on the implementation of HSR:

- (G) Develop an effective organizational structure
  - (PM) Project implementation time, ability to account and coordinate operations

The goals and performance measures presented here were simplified, but the reader may find a more thorough explanation in Sussman et al. (2012) Chapter 2.

Step 7 of 12: Identify and Design Strategic Alternatives for CLIOS System Improvement

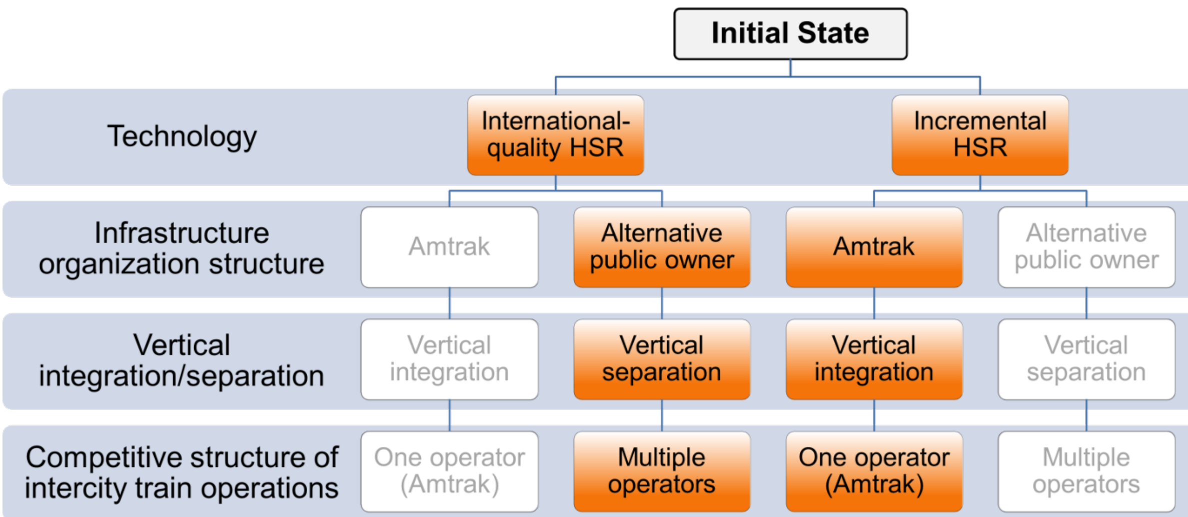
In Sussman et al. (2012) Chapter 3, four bundles of strategic alternatives are identified, and eventually, two are selected for further analysis.

The bundles comprise four decisions for simultaneous or phased implementation: (1) technology, (2) infrastructure organizational structure, (3) vertical integration/separation, and (4) competitive structure of intercity train operations.

- Technology involves the decision between an international-quality HSR --similar in service quality to the Japanese Shinkansen or French TGV on a dedicated track alignment-- and incremental HSR – gradual upgrades to the existing NEC alignment.
- The infrastructure organizational structure involves the decision between Amtrak and an alternative public ownership structure with private involvement.
- The third decision involves vertical integration --having ownership and management of infrastructure and train operations handled by one organization—and vertical separation-- having ownership and maintenance of infrastructure by one organization and train operations by one or several organizations.
- The competitive structure of intercity train operations involves the decision between one or multiple operators. It depends on previous decisions.

Eventually, two bundles of strategic alternatives were selected and labeled as *international-quality-HSR* and *incremental-Amtrak.* These are highlighted in Figure C.10

Figure C.10 Bundles of Strategic Alternatives



Step 8 of 12: Flag Important Areas of Uncertainty

In Sussman et al. (2012) Chapter 6, various areas of uncertainty and driving forces motivate the development of scenarios of analysis. Thus, *Scenario Planning* was a tool attached in modular fashion to the CLIOS Process, as an ornament on a Christmas tree.

The following driving forces of the system point to areas of uncertainty, in decreasing order of relevance:

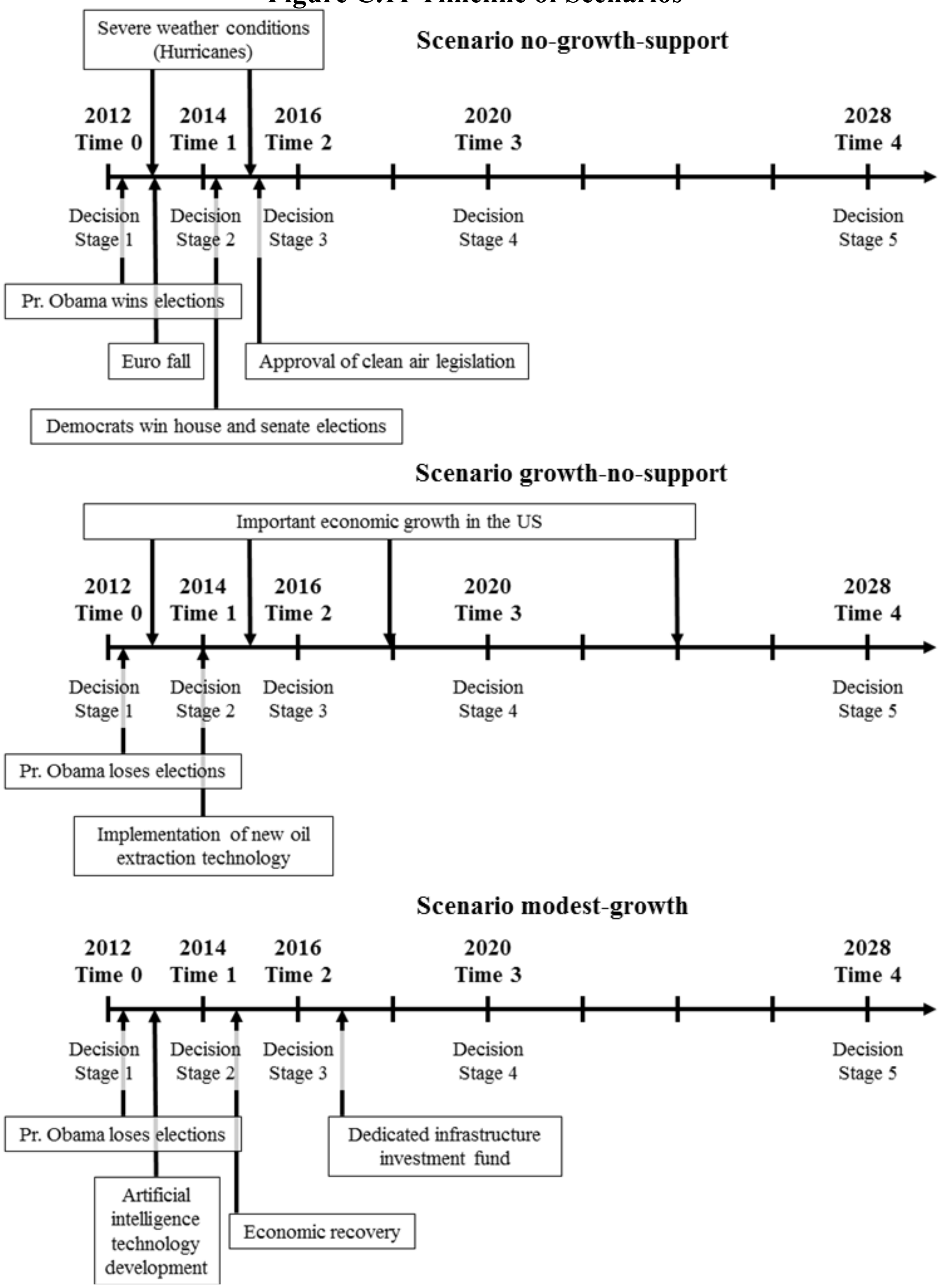
- Economic growth
- Political support
- Congestion
- Technological change
- Public perception
- Environmental change
- Energy
- Funding sources
- Multimodal cooperation

- Changes in land use
- Social attitudes toward the environment

Step 9 of 12: Evaluate Strategic Alternatives and Select Robust Bundles

Subsequently, three scenarios, spanning 16 years, were considered in the evaluation of the bundles of strategic alternatives. The scenarios were based on the uncertainty of economic growth and political support, the two major areas of uncertainty:

Figure C.11 Timeline of Scenarios



- **No-growth -- Support:** The U.S. experiences very slow economic growth, but at the same time HSR in the NEC has strong political support.
- **Growth -- No-support:** The U.S. experiences rapid economic growth, but there is little political support for HSR projects.
- **Modest support -- Growth:** Some years of medium economic growth as well as political support for HSR in the NEC.

Depending on the scenario, the bundles of strategic alternatives perform differently. International-quality HSR performs better in one scenario; incremental HSR performs better in another scenario; and, in a third scenario, none of the bundles are promising.

Table C.4 synthesizes the performance of the bundles.

Table C.4 Performance of Bundles of Strategic Alternatives

		Bundles	
		International-Quality HSR	**Incremental-Amtrak HSR**
Scenarios	**No-growth – Support**	• Difficult to achieve international-quality HSR • Increasing opposition to HSR due to lack of results	• Modest but tangible improvements along NEC • Stronger support to HSR
	Growth – No-support	• Not feasible • Commitment to car-based transport system (highways)	• Degradation of intercity passenger rail • Amtrak degradation Commitment to car-based transport system (highways)
	Modest Support – Growth	• Success of international-quality HSR • Transportation demand and benefits increase	• Modest but tangible improvements along NEC • Constrained NEC (in terms of capacity)

STAGE 3 of 3: IMPLEMENTATION AND ADAPTATION

The selected bundles of strategic alternatives are implemented in Stage 3.

Given that no bundle was clearly more robust than the other, *Flexibility Analysis* was used as a way of jumping between the international-quality and incremental-Amtrak HSR, in order to increase the expected value of the implementation. This kind of analysis was also attached to the CLIOS Process as an ornament on a Christmas tree.

In Sussman et al. (2012) Chapter 7, different kinds of flexibility are designed for the physical domain and the institutional sphere.

Step 10 of 12: Design and Implement Plan for Physical Domain/Subsystems

Technological Flexibility is the option (i.e., the right but not the obligation) to transition from implementing international-quality HSR to incremental HSR and vice-versa depending on future economic or political conditions.

Box C.2 Technological Flexibility

"If the incremental-Amtrak bundle were implemented, a flexible approach would focus on upgrades that would benefit both international-quality and incremental HSR systems. Some examples of these projects include expanding the capacity of New York Penn Station and its access tunnels and increasing the capacity of Boston South Station. In addition to upgrading the NEC infrastructure incrementally, the planning, permitting and design processes associated with international-quality HSR could be pursued. If this process were to start soon even if future funding is uncertain, implementing international-quality HSR would not be delayed (as much) by regulatory and design issues."

"If the international-quality-HSR bundle were chosen initially, flexibility could be designed-in by allowing the construction of the new alignment in phases. For example, a section from New York to Philadelphia could be constructed first, and HSR could run between the two cities. If demand were lower than expected, the infrastructure owner would not incur such big losses (as trying to build out the system all at once), as the infrastructure owner could stop construction of the new international-quality alignment on other links, North of New York or South of Philadelphia. There would still be inherent value to this construction, however, as trains would be able to run on the new alignment for part of the route (from Philadelphia to New York, for example), and thus trip time would be reduced (provided that the new train sets could operate on the new and existing system). If demand were higher than expected, then the new riders of the HSR system would represent a new stakeholder group who could push for the further expansion of the system."

(Sussman, J.M., Peña-Alcaraz, M., Carlson, S.J., Archila, A.F., & Stein, N.E.G. (2013). Analysis of High-Speed Rail Implementation Alternatives in the Northeast Corridor: the Role of Institutional and Technological Flexibility. 2013 Annual Meeting of the Transportation Research Board)

Step 11 of 12: Design and Implement Plan for Institutional Sphere

In parallel to Step 10, *Institutional Flexibility* would allow Amtrak to transition into a new organizational structure.

Box C.3 Institutional Flexibility

"Some of this [institutional] flexibility could be designed-in immediately, while some of it could be included at a later date. Additionally, some of the flexibility presented could also have inherent value, even if the flexibility is never exercised."

"There would be advantages and disadvantages to such a flexible approach. The first advantage is that Amtrak could begin upgrading infrastructure almost immediately (subject to availability of funding). At the same time, the flexibility in the approach would provide Amtrak and other decision-makers some ability to redefine their operation if they later choose to exercise that option. If an alternative public-ownership structure were pursued immediately, years might go by before any actual upgrades (incremental or otherwise) take place on the NEC. The second advantage is that the flexibility provides stakeholders the ability to compromise. Splitting Amtrak into separate entities acknowledges the views of both Amtrak supporters (as Amtrak will still exist) and detractors (as the flexibility provides some potential to reopen the debate about future institutional structure). Finally, the flexibility allows decision-makers gradually change the ownership structure of the NEC and test additional reforms without having to jump completely to a radically different ownership structure."

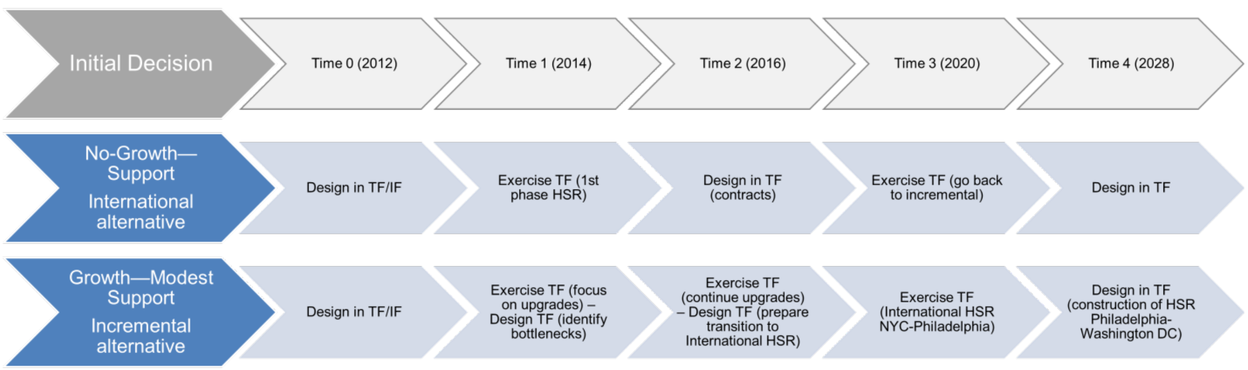
"There are some disadvantages to this approach, however. For example, although many of the proposals above have inherent value, designing-in flexibility adds cost. For instance, there is the added cost of separating the accounting of Amtrak into profit centers based on NEC operations that may not be needed if Amtrak is otherwise operating well (but it will substantially reduce the cost of implementing a new institution from scratch, in terms of time, political willingness, money, etc.). Note also that this research does not study whether Amtrak (or a private firm) has the expertise to construct and manage international-quality HSR in the NEC but simply recognizes the possibility of having different ownership formulas."

(Sussman, J.M., Peña-Alcaraz, M., Carlson, S.J., Archila, A.F., & Stein, N.E.G. (2013). Analysis of High-Speed Rail Implementation Alternatives in the Northeast Corridor: the Role of Institutional and Technological Flexibility. 2013 Annual Meeting of the Transportation Research Board)

Step 12 of 12: Evaluate, Monitor, and Adapt Strategic Alternatives for CLIOS System

With the flexibility in place and the right triggers, the decision-makers can adapt the CLIOS System to different realizations of the future. Figure C.12 shows how one would use flexibility to jump between bundles of strategic alternatives under different scenarios. While designing-in and executing flexibility has a cost, it may facilitate the implementation of the bundles by enabling adaptation under different scenarios, thereby improving performance.

Figure C.12 Performance of the Bundles with Flexibility



Appendix D: Example of Mexico City

This appendix presents an example of the application of the CLIOS Process through the analysis of transportation in Mexico City.

STAGE 1 of 3: REPRESENTATION
In this Stage, we represent the structure and behavior of the CLIOS System

Step 1 of 12: Describe the Mexico City CLIOS System: Checklists and Preliminary Goal Identification

In developing a CLIOS 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 growth 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 to 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, we identified several critical **goals** for the MCMA. These goals and brief descriptions of their rationale are outlined below.

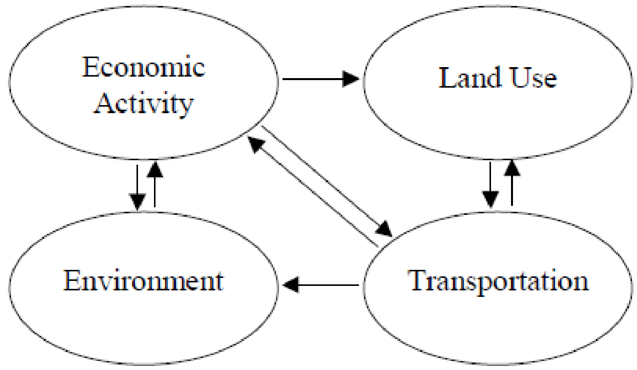
(a) Foster modal shares that improve both congestion and environmental quality, favoring modes with newer and cleaner fleets. Human health and quality of life are the key drivers for this goal.
(b) Manage congestion in a manner that will not induce additional traffic in a substantial way. Congestion 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.

Step 2 of 12: Identify Subsystems in the Physical Domain and Groups on the Institutional Sphere

The next step is 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 system, by grouping the issues highlighted above, the major physical subsystems would include the environment, land use, transportation, and economic activity (Sussman, 2002a), interacting as shown in Figure D.1.

Figure D.1: Relationships between Subsystems



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 decision makers and stakeholders on the outer policy sphere 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.

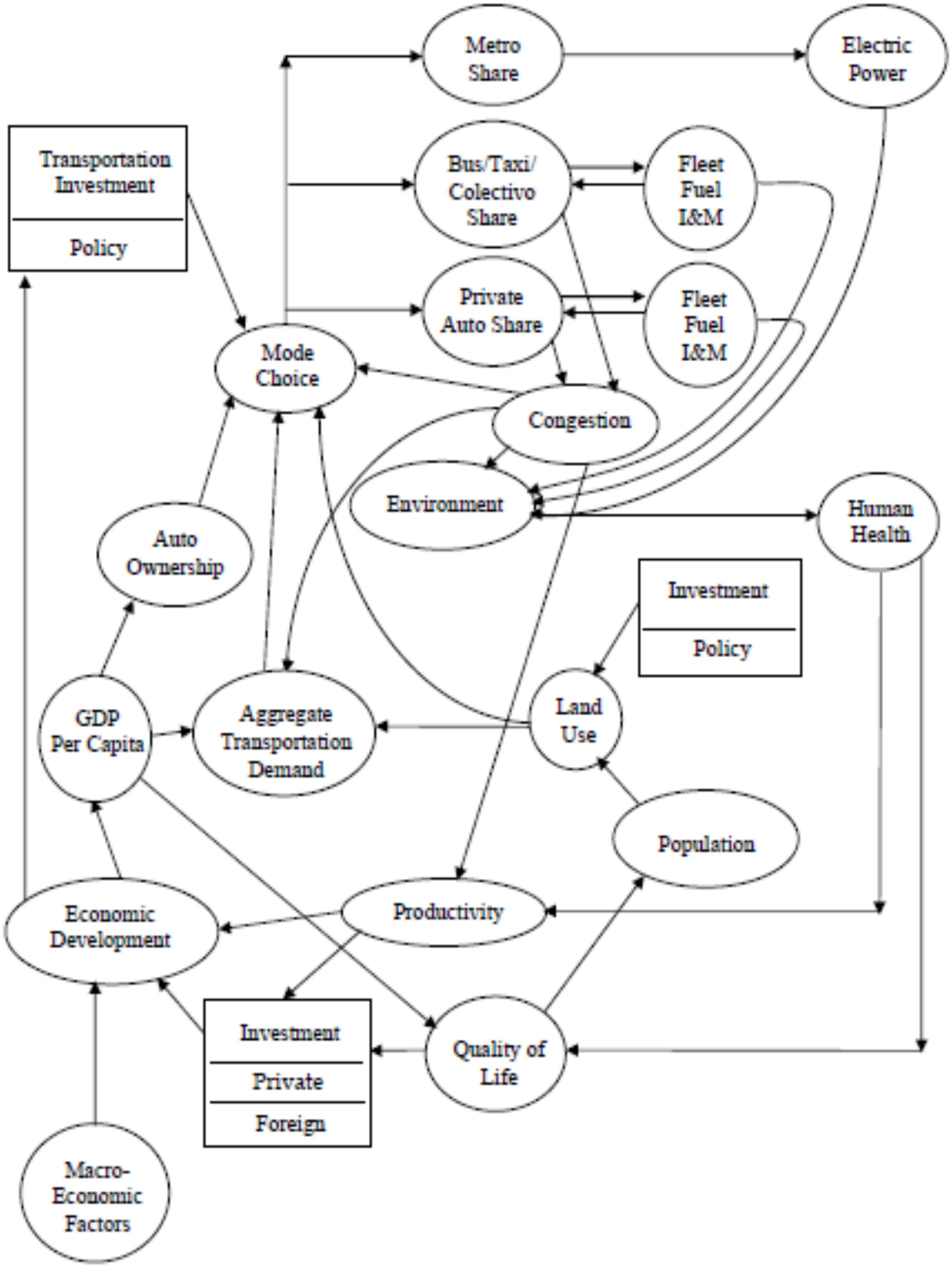
Step 3 of 12: Populate Subsystems in the Physical Domain and Actor Groups on the Institutional Sphere

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.

In Figure D.2 we present the passenger transportation subsystem diagram for the Mexico City case. This is developed here in its simplified form, but after further discussion of the CLIOS representation, we will return to the same diagram (in Figure D.4), representing it in its more complex form, and including the notation for "components" that will be described later.

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.

Figure D.2: Passenger Transportation Subsystem for Mexico City



Nesting

By nesting the systems (as shown in Figure D.1) the basic CLIOS diagram is separated into the inner physical system and outer policy sphere. While the policy sphere will include the usual actors – policymakers and decision makers 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.

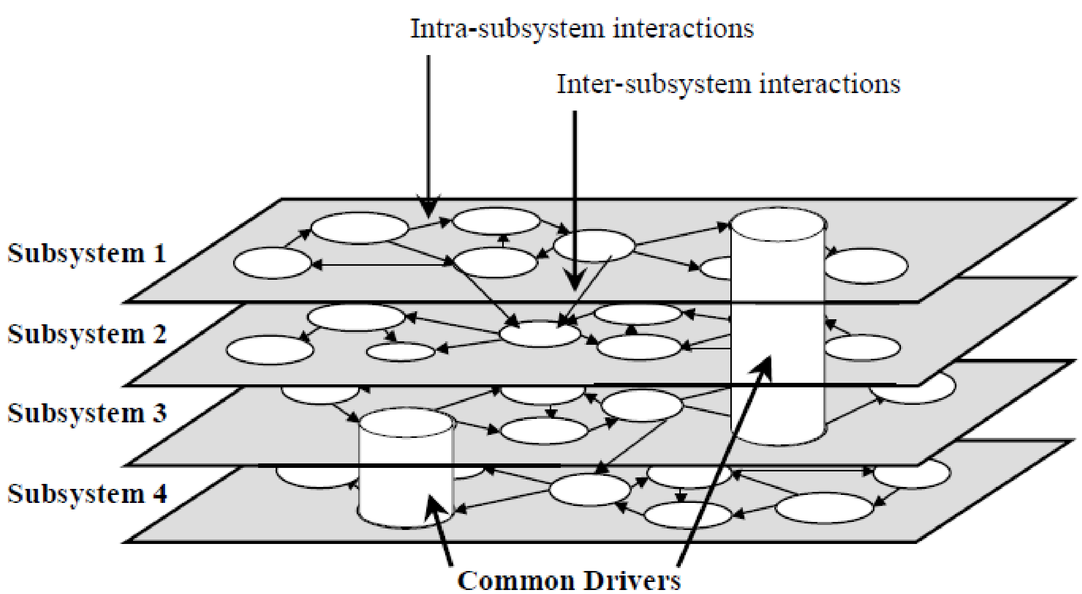
For the CLIOS representation shown in Figure D.2 for passenger transportation, nesting would be accomplished by linking the policy components of "investment" and "policy" decisions to policymakers, decision-makers and stakeholders on the policy sphere. Therefore, the policy sphere would need to include actors such as the Secretaries of Transportation for the Federal District and State of Mexico, financial institutions, private sector firms, and public transit operators.

Layering

We layer the physical domain into several separate but interrelated subsystems of a similar scale, as shown in Figure D.3. For definitional clarity, there is one physical "system", which is then layered into several physical "subsystems".

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 D.3, 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.

Figure D.3: Layered Subsystems with Common Drivers



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 para-transit 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, 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.

This separation into the policy and physical also requires that the analyst clarify the set of actual decision makers 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 institutional 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.

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.

Step 4 of 12: Describe Components in the Physical Domain and Actors on the Institutional Sphere

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.

Step 4A: Describing the Mexico City System Components

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.

Step 4B: Describe Links

Similarly, as the components were characterized and divided into different types, we also need to characterize the nature of the links.

Within the Mexico City CLIOS system, there is a range of characteristics across links that could be considered. However, for simplification, in the diagrams presented here, only direction and magnitude of influence are indicated.

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.

Step 5 of 12: Transition from Descriptive to Prescriptive Treatment of System

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 step is to use this information to gain a better understanding of the overall system behavior, and where possible, counterintuitive or emergent system behavior. 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.

STAGE 2 of 3: DESIGN, EVALUATION, AND SELECTION

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.

Step 6 of 12: Refine CLIOS System Goals and Identify Performance Measures

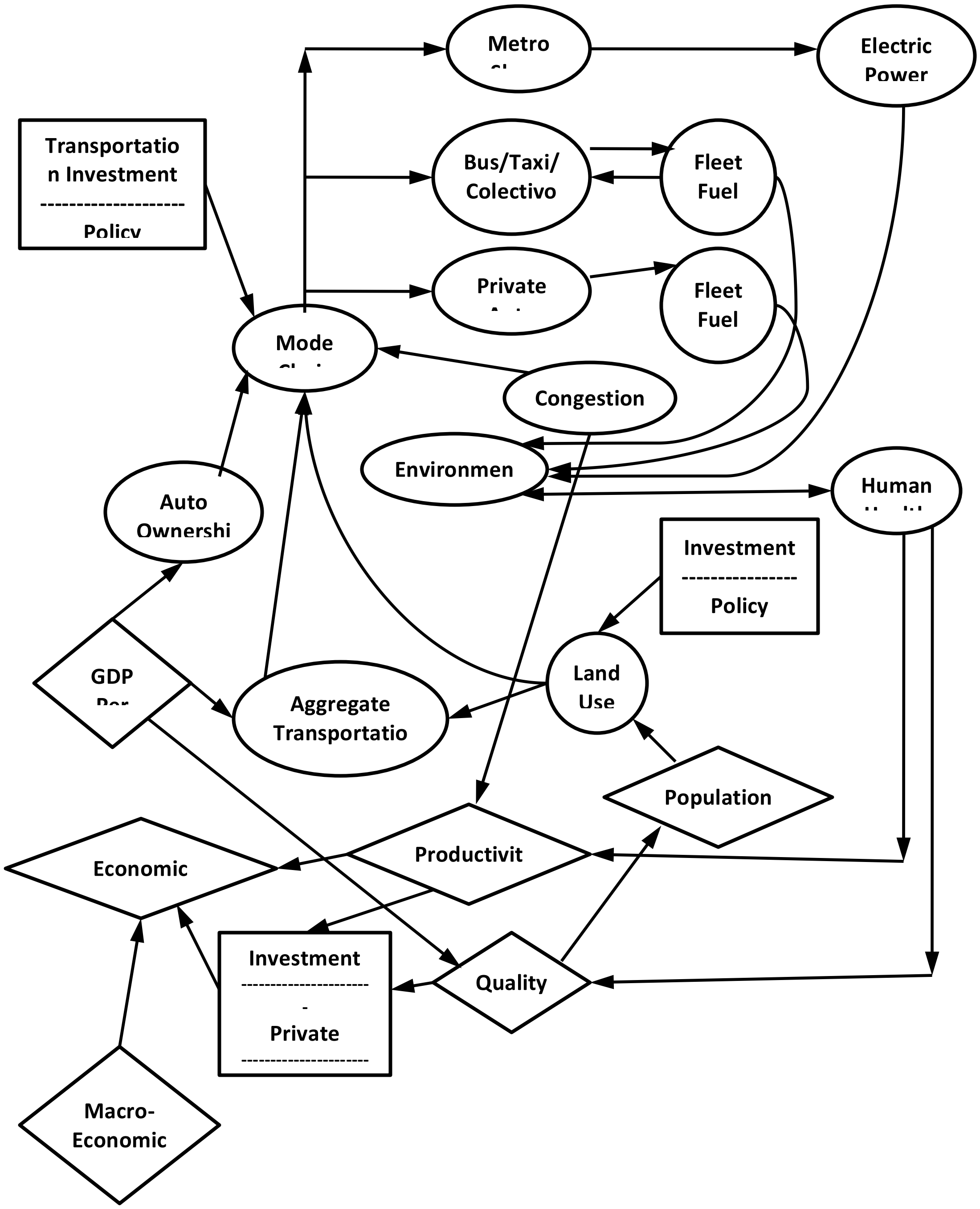
We first need to identify those system components that matter for the *performance* of a subsystem. Diagrammatically, we represent this for any of the system elements – components, common drivers, or policy levers – by a double line for the border.

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, decision makers, 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 Step 1, 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 Strategic Alternatives for CLIOS System Improvement" 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 of the passenger transportation subsystem. Figure D.4 represents the same system as in Figure D.2 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 D.4: Passenger Transportation Subsystem Using CLIOS Notation



Step 7 of 12: Identify and Design Strategic Alternatives for CLIOS System Improvement

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."

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.

Step 8 of 12: Flag Important Areas of Uncertainty

A parallel activity to the identification of strategic alternatives 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 system to an 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.

Understanding Uncertainty in Mexico City Using Scenarios

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 head of Shell's Scenarios Team, defined 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.

(e) Explore the implications of the scenarios for the decisions and focal issues identified earlier.[8]

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 D.1 summarizes the Mexico City scenarios or "future stories" according to the six common drivers.

[8] 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).

Table D.1: Scenarios Logics for Three Mexico City "Future Stories"

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

✓Checkmarks indicate the two macro drivers that "drive" each future story.

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

Step 9 of 12: Evaluate Strategic Alternatives and Select Robust Bundles

Robustness is defined as the ability of an strategic alternative to perform reasonably well under different scenarios of the future. This represents a different approach than that of identifying an optimal strategic alternative, which may only perform optimally under a constrained set of conditions. Given the range of performance measures involved, different stakeholder views, and trade-offs needed to obtain the necessary support for strategic alternative implementation, simply finding a feasible strategic alternative (one that works) may be the best expectation.

Implicit in this discussion is that the design and evaluation of policy strategic alternative 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 strategic alternative, understanding how those options impact the rest of the system, both quantitatively and qualitatively, is an essential part of the design and evaluation of strategic alternatives. Therefore, an evaluation of a strategic alternative 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.

STAGE 3 of 3: IMPLEMENTATION AND ADAPTATION

Step 10 of 12: Design and Implement Plan for Physical Domain/Subsystems

Once a set of promising policy options is identified, the next crucial (but often overlooked) step is to design a strategy for implementation. In the CLIOS Process, identifying a strategy for implementation requires taking the set of good strategic alternatives and identifying combinations of policy options that fit together in a comprehensive strategy.

By combining strategic alternatives, 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 strategic alternatives that can either attenuate those negative impacts, or compensate those actors and stakeholders on the policy sphere that are negatively impacted, by including policy strategic alternatives that address their needs, even though these strategic alternatives might not have made the initial cut in Step 9.

Second, different combinations for strategic alternatives can improve the robustness of the overall strategy. Given the uncertainties in the individual strategic alternatives, certain combinations of strategic alternatives can provide insurance against extreme changes or shocks to the system, such as major shifts in the common drivers. For example, a certain strategic alternatives 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 strategic alternatives, in conjunction with the strategic alternatives 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 strategic alternative, as well as who has the potential to impede its implementation. By looking along the policy sphere, to assess how each strategic alternative 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

Step 11 of 12: Design and Implement Plan for Institutional Sphere

The structure of the institutional sphere itself may affect the ability to implement a strategic alternative. 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.[9] Therefore, part of Step 11 should be to evaluate the institutional arrangements that

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[9] 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

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.[10]

Returning to the concept of nested complexity, institutional architecture is central to the CLIOS Process for several reasons.

First, by separating the institutional 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 institutional 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 Appendix B.

Mexico City provides a clear example of how changes in the physical domain 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 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).

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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.

[10] 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.

Step 12 of 12: Evaluate, Monitor, and Adapt Strategic Alternatives for CLIOS System

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)?

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_3), carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_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 of 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_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_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 system. Because cause and effect are not straightforward in a CLIOS system, 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).

Appendix E: CLIOS Process within the Context of Systems Approaches

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).[11]

Emphasizing the point raised earlier in the description of 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).

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

[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).

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 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 decision-makers and policymakers. In addition, the CLIOS representation, by essentially abandoning the often-ineffectual 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.

Appendix F: List of Applications of the CLIOS Process

Bunn, M. 2007. *Guardians at the Gates of Hell: estimating the risk of nuclear theft and terrorism – and identifying the highest-priority risks of nuclear theft*. Ph.D. Thesis, M.I.T. http://hdl.handle.net/1721.1/39006

Dodder, R.S. 2006. *Air quality and Intelligent Transportation Systems: understanding Integrated Innovation, Deployment and Adaptation of Public Technologies*. Ph.D. Thesis, M.I.T. http://hdl.handle.net/1721.1/37969

Dickmann, J.Q. 2009. *Operational flexibility on complex enterprises: case studies from recent military operations*. Ph.D. Thesis, M.I.T. http://hdl.handle.net/1721.1/52785

Mostashari, A. 2005. *Stakeholder-assisted modeling and policy design for engineering systems*. Ph.D. Thesis, M.I.T. http://hdl.handle.net/1721.1/31173

Sgouridis, S.P. 2005. *Integrating regional strategic transportation planning and supply chain management: along the path to sustainability*. Master's Thesis, M.I.T. http://hdl.handle.net/1721.1/58666

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