THE "CLIOS PROCESS"

A USER'S GUIDE

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

John Muir

SUMMARY

Complex, large-scale, interconnected, open, sociotechnical (CLIOS) Systems are a class of engineering systems with wide-ranging social and environmental impacts. Because of the many interacting subsystems, the uncertainty in subsystem behavior and interaction, and the degree of human agency involved, the behavior of a CLIOS System is difficult to predict and often counterintuitive. These attributes make it difficult to represent and study CLIOS Systems. We have developed a CLIOS Process to help study such systems. The CLIOS Process can be used as an organizing mechanism for understanding a CLIOS System's underlying structure and behavior, identifying and deploying strategic alternatives for improving the system's performance, and monitoring the performance of those strategic alternatives. Moreover, it is an iterative process that allows for continuous learning about the system by both studying and intervening in the system.

A key motivation behind the need for a CLIOS Process is the presence of "**nested complexity,**" which results when a physical domain is nested within and interacts with an institutional sphere, where both are complex. 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 consists of three **stages**:

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

The representation stage is primarily diagrammatic in nature. Diagrams are used to represent the structure and behavior of the CLIOS System by graphically illustrating the system components and interactions in the physical domain, on the institutional sphere, and between them. An accompanying text describing and explaining the CLIOS System diagrams is often helpful.

The CLIOS Process can be thought of as a Christmas tree and its ornaments; the tree represents the overall process and the ornaments represent the specific tools (e.g. benefit-cost analysis, probabilistic risk assessment, system simulations, stakeholder analysis, scenario planning, design structure matrices, etc.) that one can use for specific steps in the overall process. This paper describes the overall CLIOS Process and particular regimes of tools that can be used in the study of CLIOS Systems. The appendix highlights tools that can be used for more advanced analyses of CLIOS systems.

With the CLIOS Process, our intent is: (1) to 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. The CLIOS Process is designed to be a **modular process that can be customized and expanded as needed**.[1] While the CLIOS Process has a specific macro-structure, its inherent flexibility allows different analysts to tailor the process to their specific needs

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.

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. In **Section 1** we explain what we mean by a CLIOS System and indicate the situations for which the CLIOS Process would be most applicable. **Section 2** reviews some of the key concepts that are extensively used in the CLIOS Process. The CLIOS Process itself is explained step by step in **Sections 3 to 6**. Finally, the **Appendix** directs the reader to a number of potential models and frameworks that can be used to address various aspects of the system's analysis on an as-needed basis.

[1] For example, research is ongoing on (i) incorporating stakeholder perspectives throughout the CLIOS Process and (ii) developing and valuing flexible strategic alternatives.

1. INTRODUCTION

1.1. Our World is CLIOS

Our world is complex, large-scale, interconnected, open and sociotechnical (CLIOS). 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, decisionmakers, policy makers and stakeholders. The CLIOS framework provides a way to describe, understand, study, and ultimately, to improve the performance of a wide range of systems. Systems that can be described and analyzed as CLIOS Systems include 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 an existing or impending problem, such as the reduction of air pollutant emissions from transportation systems in megacities, or the transport and storage of spent nuclear fuel from nuclear power plants.

We begin by defining the primary characteristics of CLIOS Systems.

Complex: A system is "complex" when it is composed of a group of interrelated components and subsystems (those terms will be defined more rigorously later), 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 many types of complexities defined in the literature (Sussman 2002, Lloyd 2002), we are primarily concerned with four types of complexities for CLIOS Systems:

- *Structural Complexity* (also known as combinatorial or detail complexity) exists when the system consists of a large number of interconnected parts.

- *Behavioral complexity* (also referred to as dynamic complexity) exists when predictions of system outputs or behavior is difficult. This can be found even in systems with low structural complexity when their parts interact over time in closely-coupled feedback loops. Even if we understand the internal behavior of individual subsystems and components, our lack of understanding of the relationships between these components and subsystems leads to difficulties in making predictions of overall CLIOS System behavior. *Emergence* is 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).

- *Nested Complexity* is a concept that suggests a complex "physical/technical" system embedded within an institutional system (which we will later refer to as an institutional sphere). Moreover, the institutional system exhibits structural and behavioral complexity in its own right. The two-way interactions between the physical/technical and institutional systems create "nested complexity."

- *Evaluative Complexity* reflects the multi-stakeholder environment in which CLIOS Systems exist – different stakeholders value different aspects of system performance in different ways, making decision-making difficult. Simply put, what may be good performance to one stakeholder, may not be good performance to another stakeholder. Even if one could make good predictions about the behavior of the CLIOS System when strategic alternatives are implemented, evaluative complexity means it is still difficult to make a decision about what to do.

Large-Scale: CLIOS Systems have impacts that are large in magnitude, and often long-lived and of "large-scale" geographical extent. For this reason, as we argue later, CLIOS Systems are often related to Critical Contemporary Issues.

Interconnected: CLIOS Systems are often interconnected with *other* sociotechnical systems. As an example, one could point to the relationships between transportation systems, energy systems and the global climate system.

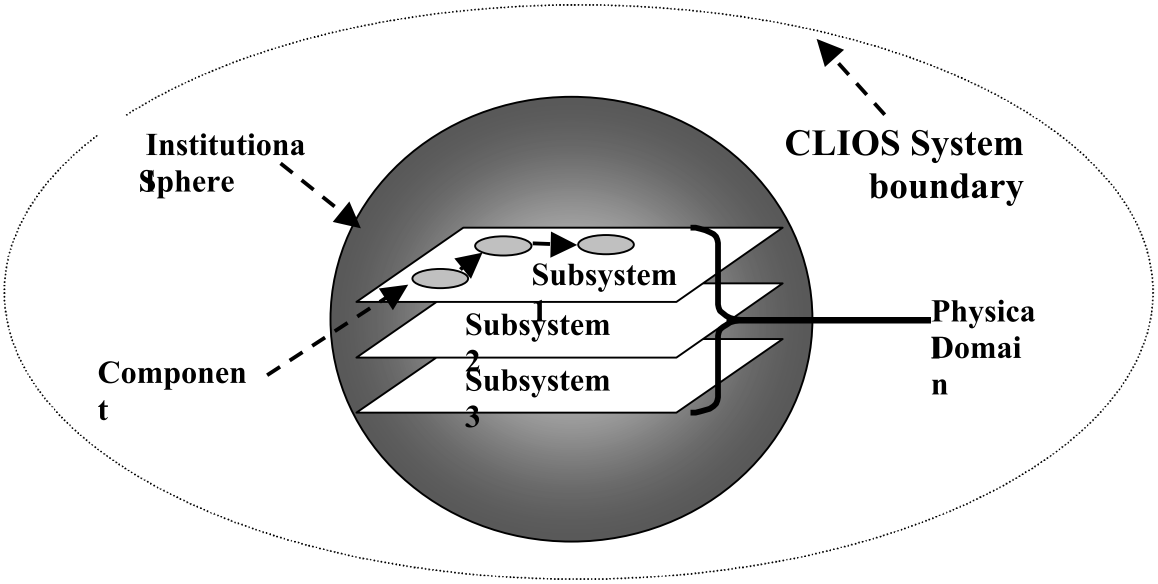
Open: CLIOS Systems explicitly include social, political and economic aspects (Sussman, 2000) beyond the technical or "engineered" system; we are concerned about system performance on these dimensions.

Sociotechnical: To distinguish CLIOS Systems from systems in which we may consider only technical aspects (such as complex computer programs) or purely social systems in which technology is not a central consideration (such as the social security system), we emphasize their sociotechnical nature. Technology plays a central role in CLIOS Systems, as does the social context within which the system is operating.

We think of a CLIOS System as consisting of a physical domain – with interconnected physical subsystems – embedded in an institutional sphere (i.e. nested complexity). This is illustrated in Figure 1. 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.

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 (or "layers"). As we will see, the choice of how to divide the physical domain into logical subsystems is up to the analyst and will depend on the issues and problems that motivate the analysis. Components (the small circles on the subsystem layers) are the basic units that make up a subsystem; links among them represent their interconnections. The institutional sphere includes actors and organizations (i.e. the institutional stakeholders) that influence and affect (and are affected by) one or all of the subsystems.

Figure 1: A CLIOS System consists of a physical domain (made up of subsystems), embedded in an institutional sphere.



As an example, a CLIOS representation of sustainable mobility may include the following *subsystems* in the physical domain: transportation, environment, energy, economy, and land-use. The transportation subsystem could incorporate *components* such as: private auto fleet, congestion, freight transportation demand, etc. Finally, the *institutional sphere* (in the U.S. context) would include agencies like the U.S. Department of Transportation (DOT), Environmental Protection Agency (EPA), and Department of Energy (DOE), along with advocacy groups, auto manufacturing companies, etc. Finally, the programs and regulations specified in the Clean Air Act would be an example of policy linkages from an organization on the institutional sphere (EPA) to components within the transportation and environment subsystems.

1.2. The Need for a 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 (see Figure 4). 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.

Because of the many subsystems involved, the uncertainty in the behavior of the subsystems and their interactions, and the degree of human agency involved, the behavior of CLIOS Systems is difficult to predict and often counterintuitive (i.e., exhibiting behavioral complexity). 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 (or "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.[2] For CLIOS Systems, similar "tools of visualization" are needed to build intuition and systems thinking for students and analysts. Figure 1 above is a basic example of how one can begin to visualize and conceptualize the system.[3] Section 4 describes more fully the steps in the "representation" stage of the CLIOS analysis, which is used to gain important insights into the system via visualization.

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 what we call "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.

1.3. Who Will Find Value in 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 A) at specific steps in the process.

[2] 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).

[3] Some students, see C. Osorio-Urzua (2007) have built upon Figure 1 to deepen their understanding of their own system of interest. Osorio-Urzua expanded the institutional sphere to an internal and external sphere, in order to better describe the roles of different organizations and groups on the institutional sphere in relation to the physical systems.

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.[4] 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.[5] 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.

Decisionmakers: In addition to its research and pedagogical role, the CLIOS Process can also be employed by public or private sector decisionmakers, 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 decisionmakers and stakeholders "populate" the institutional sphere.

Experts/Analysts: Individuals or groups that provide analysis and recommendations to decisionmakers 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 decisionmakers or stakeholders that do "populate" the institutional sphere).

Part of the value is that all of these individuals/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 decisionmakers using the CLIOS Process as a collaborative group process will (or should) occur (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 decisionmakers 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 decisionmakers to better see their function as "part of a complex system of linked factors in the physical environmental

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

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

and the governmental context" (Innes, 1997). We suggest that the CLIOS Process supports this effort.

2. KEY CONCEPTS

2.1. CLIOS System Representation

The CLIOS Process begins with a "representation" of the CLIOS System both diagrammatically as well as with supporting text. The motivation for the representation is to convey the structural relationships and direction of influence between the components within a CLIOS system and subsystems. In this sense, the CLIOS system representation is an organizing mechanism for mapping out the system's underlying structure and behavior – a precursor to identifying strategic alternatives for improving the system's performance. We will look at representation in more detail when we go through the steps of the CLIOS Process.

As noted earlier, the CLIOS Process can be applied by individuals or groups. When carried out by a group, it can generate a shared and more complete understanding of the system among various decisionmakers, analysts and stakeholders, each bringing to bear their own perspectives, knowledge, preferences and values. Because the representation is primarily qualitative in nature, the CLIOS Process allows for the participation of a range of actors with different levels of expertise.

2.2. Nested Complexity

As previously noted, a key motivation for a CLIOS Process is the characteristic of "nested complexity" present in all CLIOS systems. According to this concept, a CLIOS System is comprised of a complex physical domain, which follows quantitative principles that can be approximated by engineering and economic models, surrounded by a "messier" institutional sphere (see Figure 1). On the sphere is the organizational and institutional network of policymakers, firms, non-governmental organizations, and stakeholders that together comprise the institutions that interact with the physical domain.[6] Analyzing this sphere of organizations and institutions requires various methodologies – usually 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. However, while we make a distinction between the physical domain and institutional sphere – we also need to understand the *connections* between the physical domain and institutional spheres. Indeed, an important step in the CLIOS System representation is to identify and characterize these links. Understanding nested complexity is a necessary step in moving towards better integrating institutional design with technical design.

[6] We realize that representing the physical and institutional spheres in this manner – more structured and quantifiable *physical domain*s, compared to messier, more chaotic, and more complex, human-based *institutional sphere*s – runs the risk of overstating the dichotomy between systems composed of "things" and systems composed of "people." This discussion has been taken up by researchers from many disciplines; we would refer the reader to Almond and Genco, 1977 and Flood and Carson, 1993 (in particular, pp. 251-2).

2.3. Critical Contemporary Issues (CCIs)

As mentioned earlier, the boundaries of CLIOS Systems are often defined by the issues and problems that emerge within these complex sociotechnical systems and by the means available to the decision-makers to affect the system. Examples of critical contemporary issues 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.

Critical contemporary issues share the characteristic of requiring *interdisciplinary* approaches – approaches that do not come neatly boxed in traditional disciplines (engineering or non-engineering) but rather are integrative in nature. They also require systems thinking. Various kinds of *complexity* – structural, behavioral, nested and evaluative – as described in Section 1.1, are also invariably present. The CLIOS Process is designed with exactly these kinds of CCIs in mind.

2.4. Strategic Alternatives

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. Strategic alternatives are essentially 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."

Strategic alternatives may be developed for both the physical domain and the institutional sphere. Usually, strategic alternatives that influence the physical domain need to be complemented by changes in the institutional sphere that would make the implementation of the alternative possible.

3. OVERVIEW OF THE CLIOS PROCESS

We will now walk through the CLIOS Process step-by-step, presenting the basic or "barebones" structure of the CLIOS Process. At several points in our discussion, we will also describe ways in which the CLIOS Process can be "tailored" by utilizing additional methods, both quantitative and qualitative, at various steps in the process. In order to maintain clarity, we will differentiate between what the authors consider to be (a) the *core* of the CLIOS Process, (b) *examples* of how to carry out specific steps in the CLIOS Process, and (c) specific *models* and *frameworks* that can be used to "tailor" the CLIOS Process.

3.1. *The Basic Structure: 3 Stages and 12 Steps*

The CLIOS Process is composed of twelve steps, divided into three stages (see Figure 2). The three stages are: Representation; Design, Evaluation and Selection; and Implementation. In Stage One – **Representation** – the CLIOS System representation is created and considered in terms of both its structure and behavior. In this stage, we also establish preliminary goals for the CLIOS System – i.e. in what ways do we want to improve its performance. In Stage Two – **Design, Evaluation and Selection –**strategic alternatives for performance improvements to the physical domain and institutional sphere are designed, evaluated and finally some are selected. In Stage Three – **Implementation –** implementation plans for the physical domain and the institutional sphere are designed and refined. An overview of the three stages is shown in Table 1.

Table 1: Summary of Three Stages

Stage	Key Ideas	Outputs
Representation	▪ Understanding and visualizing the structure and behavior ▪ Establishing preliminary goals	System description, issue identification, goal identification, and structural representation
Design, Evaluation, and 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	▪ 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

In **Stage One**, regarding the representation of the CLIOS System structure, 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?

Also in Stage One, 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.

Turning to the design, evaluation, and selection in **Stage Two**, 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 the physical subsystems?
- How do key stakeholders and decisionmakers 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?

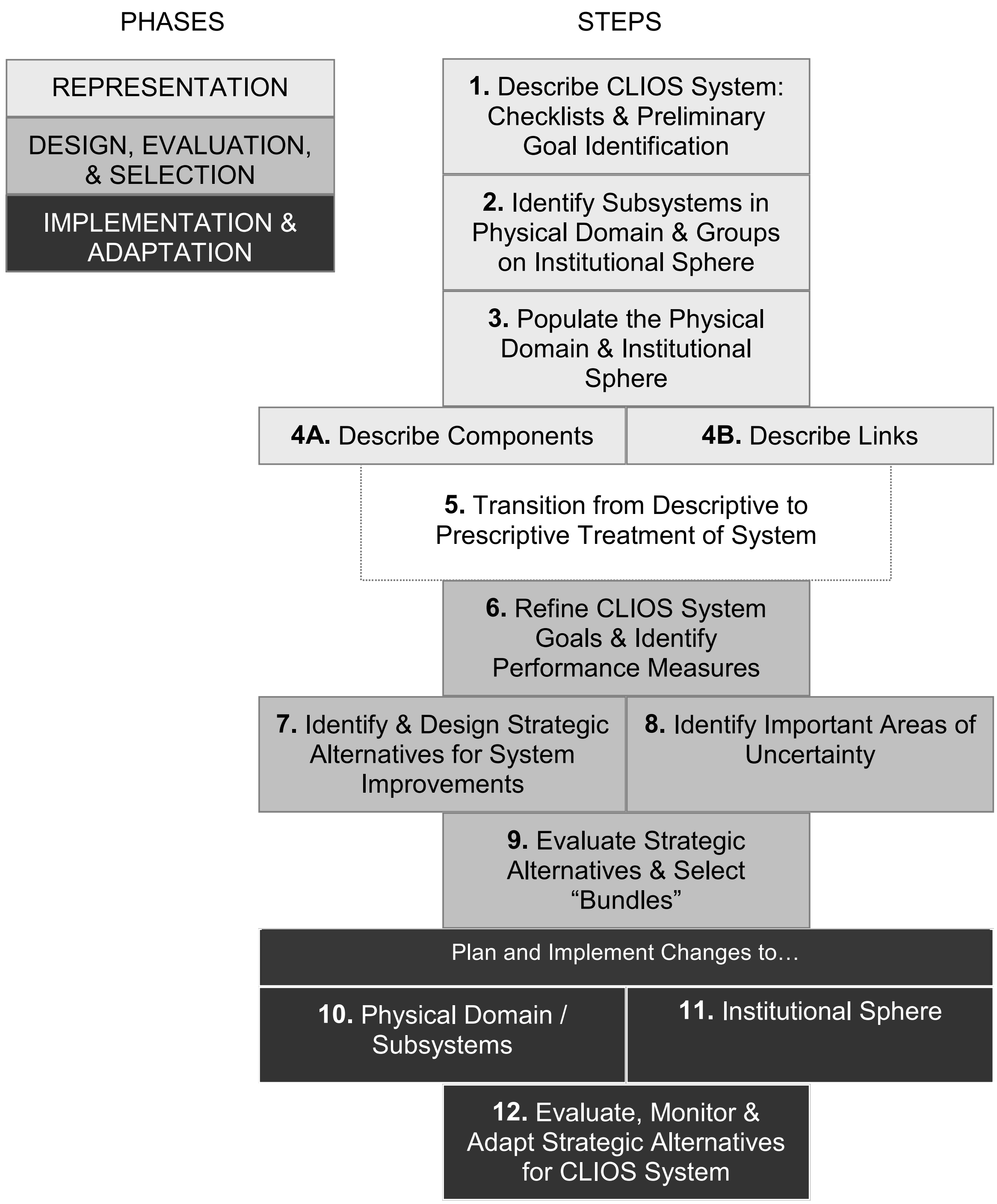
Finally, reaching **Stage Three**, implementation of the CLIOS Process, we can ask the following:

- 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. 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 and institutional systems.

We now present the full CLIOS Process in Figure 2. The twelve steps are coded by the shading of the boxes to indicate whether they are part of the representation; design, evaluation and selection; or implementation stage. Step 5 indicates more of a transition, than a "step" per se in the analysis. This marks the key transition from a descriptive treatment (trying to understand) to a prescriptive treatment (trying to intervene, change, improve) of the system.

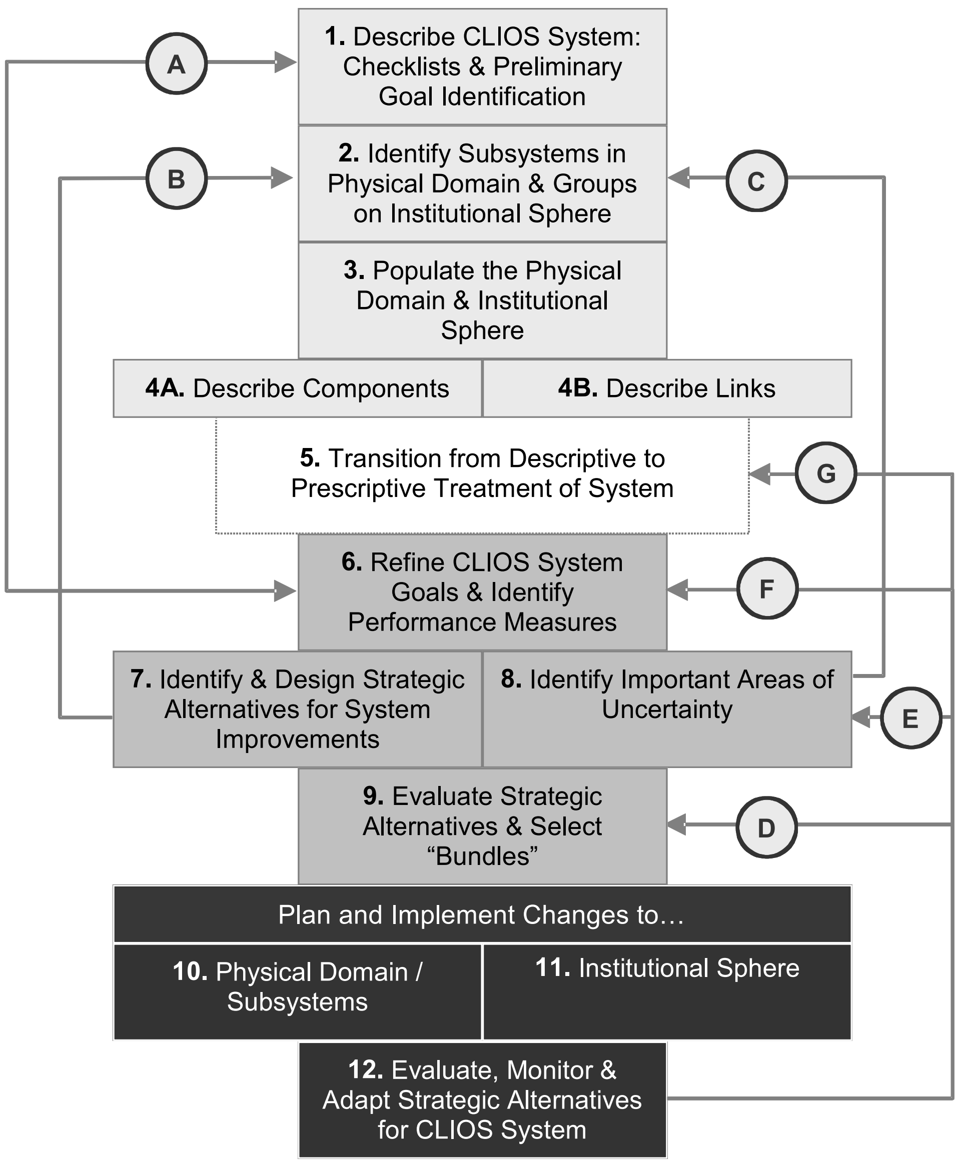
Figure 2: The Twelve Steps of the CLIOS Process



Many of the steps in the 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). Steps 7 and 8 will also occur more or less simultaneously. As one identifies and analyzes strategic alternatives to change the CLIOS system, additional uncertainties may begin to surface. 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.

The reader should bear in mind that while we show the CLIOS Process as a set of ordered steps, we emphasize that this is an iterative process, and not a rigid, once-through process. Indeed, as shown in Figure 3, there are several important points where iteration can occur. As we go through the steps of the CLIOS Process, we will highlight where and how iteration back to earlier steps can be done (having labeled some of these iterations as A, B, and so on, for reference).

Figure 3: Iteration in the CLIOS Process



3.2. Tailoring the CLIOS Process

The above discussion sketches out the basic structure for the CLIOS Process. However, we have noted earlier that this is a *flexible* and *modular* process. Additional tools and methods of analysis can be used to support the twelve steps introduced in Figure 2. 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 and qualitative analytical tools (we call these "models" and "frameworks"), which are suitable for each stage/step to be "attached" to the CLIOS Process like ornaments on a tree.

When conducting the CLIOS Process, one therefore has the opportunity to tailor the process according to the needs and abilities of the users – whether students, decisionmakers, experts/analysts or stakeholders. Presented later in this paper (Appendix A) is an overview of various tools (or "ornaments") and how these tools can be selected to "hang on to the CLIOS Process Christmas 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.

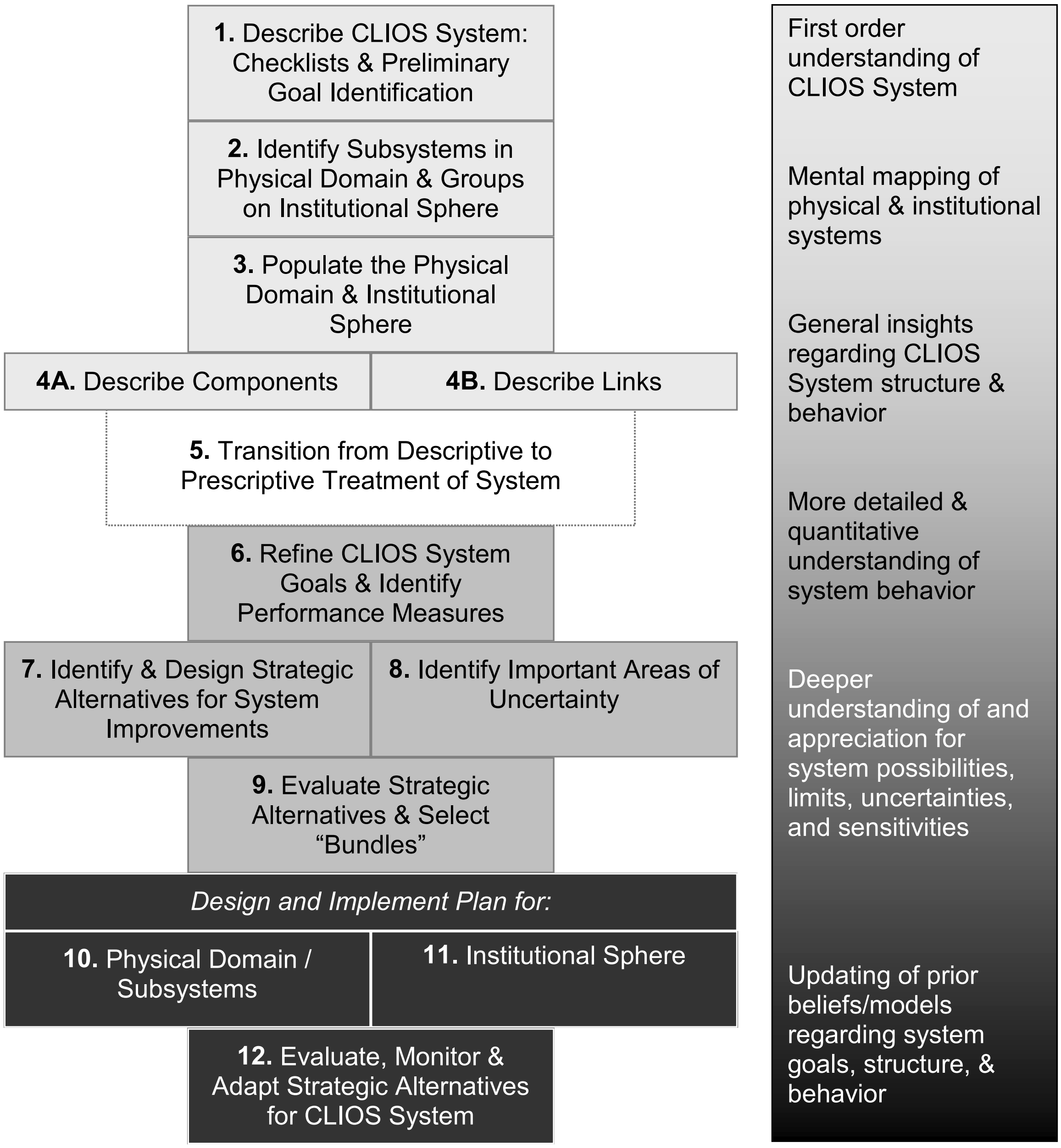
MODELS AND FRAMEWORKS As a note on how to read this user's guide, as we describe the steps in the CLIOS Process, we use separate boxes such as this box in order to highlight where specific models or frameworks – the "ornaments" on the CLIOS Process "Christmas tree" – can be applied to help the analysts through one or more steps in the process.

Although additional models and frameworks can be applied to support the analysis of most of the steps in the CLIOS Process, they will be most useful beginning after Step 5, when we transition from a descriptive to prescriptive treatment of the CLIOS System.

3.3. Learning about CLIOS Systems

In essence, the CLIOS Process is set up as an approach to learn about CLIOS systems and structure analyses in a way that enables continuous learning for students, decisionmakers, and stakeholders. The learning process occurs regardless of whether the CLIOS Process is carried out by individuals or a group. Figure 4 illustrates how the understanding of the CLIOS System should evolve as one progresses through the 12 steps of the CLIOS Process.

Figure 4: Learning Continuum in the CLIOS Process



Again, it is important to highlight Step 5 as a transition point in the CLIOS Process as one shifts from a mode of describing and understanding the system, to a more "prescriptive" mode in which one analyzes how to change (and hopefully improve!) the system. However, because this is an iterative process, even during the "prescriptive" mode, one's descriptive understanding 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.

4. STAGE 1: REPRESENTATION

The representation stage aids in the understanding of the complete CLIOS System by examining the structures and behaviors of the physical subsystems and institutional sphere and the interactions between them. The CLIOS Process usually uses a combination of diagrams and text to capture the critical aspects of the CLIOS System and present them in an easy-to-comprehend format. This allows the users of the CLIOS Process to understand the CLIOS System and establishes the basis for completing the second and third stages of the CLIOS Process.

When the CLIOS Process is carried out by a group of analysts, decisionmakers, and stakeholders, the representation stage is used to create a common understanding of the system among these actors. In this manner, the issues and goals associated with the CLIOS System can be reasonably discussed based on a good understanding of its basic characteristics. Some agreement on the issues and goals will be necessary to be able to successfully create and, ultimately, implement strategic alternatives for system performance improvements in later stages. While all the stakeholders may not agree about goals at this early representation stage, it is not too early to start building a common understanding that can lead, we hope, to consensus in the later stages.

In the steps below, we present *one approach* to complex system representation. It is, by no means, the only way. It may not even be the best way for all CLIOS Systems. However, this approach has proven useful in the CLIOS System representations that have been conducted to date. Because this approach to the CLIOS Process is flexible, it allows for creativity on the part of the users of the CLIOS Process, as to how to develop their system representations.

4.1. Step 1: Describe CLIOS System: Checklists and Preliminary Goal Identification

In developing the CLIOS System representation, we first create several **checklists** to serve as a high-level examination of the CLIOS System, as shown in Figure 5. The lists should address the question: "what is it about the system that makes it interesting?" (Puccia and Levins, 1985). 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 CLIOS Process user has previous experience with the CLIOS System under study, or with other related systems, and can bring that experience to bear on the checklists and preliminary goal identification.

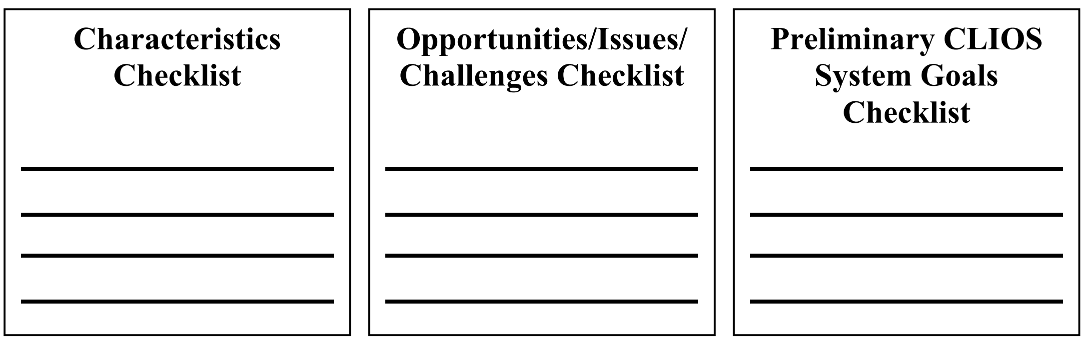
The first of the checklists is the **characteristics checklist** that may relate to: (a) the temporal and geographic scale of the system, (b) the core technologies and systems, (c) the natural physical conditions that affect or are affected by the system, (d) the key economic and market factors, (e) important social or political factors or controversies related to the system and (f) the historical development and context of the CLIOS System.

The second checklist captures **opportunities, issues and challenges** – those aspects of the CLIOS System for which we may seek constructive improvements through strategic alternatives in Stage 2.

Finally, in the third checklist, we identify **preliminary system goals**, which often relate to the opportunities, issues and challenges found in the second checklist.

The initial checklists for the CLIOS System serve as a valuable basis for the rest of the analysis. In particular, as we continue to develop the CLIOS System representation, we can return to these checklists to identify any major issues that have been omitted. The checklists should capture the concerns and needs of a broad set of stakeholders, including policy makers, system managers and operators, customers and so forth. As the CLIOS Process is intended to facilitate better performance of the system, one has to ask "What are the management and policy questions that need to be addressed?" and "What are the goals for the CLIOS System?"

Figure 5: CLIOS System Checklists



This first step also implicitly bounds the CLIOS System, at least preliminarily. Given that CLIOS is an iterative process, boundaries are expected to expand and/or contract as the CLIOS Process advances and focuses more clearly. Redefining the system boundaries in later iterations may actually signal a shift in the analysts' mental models of the system, as suggested by Figure 4.

A Our first example where *iteration* may occur, identified as "A" in Figure 3, is the iteration that occurs between Step 1 and Step 6. 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 (Refine CLIOS System Goals and Identify Performance Measures). 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.

4.2. Step 2: Identify Subsystems in the Physical Domain and Groups on the Institutional Sphere

To outline the general structure of the CLIOS System, we determine (a) which major subsystems make up the physical domain of the CLIOS System, (b) who the main actor groups are on the institutional sphere and (c) how they relate to one another on a macro-level. This is essentially establishing the structure as illustrated in Figure 1. One useful way to identify these subsystems and actor groups is by grouping the issues identified in the first step 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.

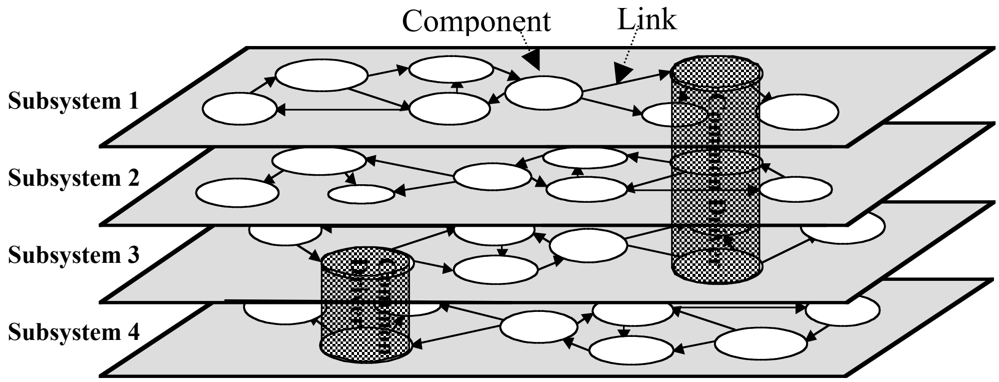
For the Physical Domain: Our approach to learning about the CLIOS System and organizing one's ideas about how the system works, is to parse the physical system into subsystems, map out the structure of those subsystems (which can be envisioned as layers), and finally identify the key linkages between 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 the Institutional Sphere: We then identify major actor groups on the institutional sphere. The general categories may include 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.

4.3. Step 3: Populate the Physical Domain and the Institutional Sphere

Populating the Physical Domain: In this step, we employ the type of basic subsystem diagram common in systems sciences, "defined as having components and relations that may be represented (at least in principle) as a network-type diagram with nodes representing components and lines the relationships" (Flood and Carson, 1993). Initial CLIOS subsystem diagrams are created by detailing each subsystem – for example, passenger transportation, land use, the environment, etc. – and identifying the major components in each subsystem and the links indicating influence of components on each other. Sometimes a component can be common to more than one subsystem. In these cases the component is called a common driver. We will discuss the different types of components later in this paper. Figure 6 shows the populated subsystems and the concept of the *common driver* linking those subsystems.

Figure 6: Populating the Subsystem Diagrams[7]



While the subsystem diagrams help to represent the CLIOS System, the use of this type of diagram can quickly reach its limit. There is a cognitive upper bound to the number of "components" that can be represented within such a diagram, while still providing an opportunity for insight for the creator or user of the diagram.[8] However, 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. Expanding focuses on critical components and magnifies their functions into separate diagrams for more detailed study. This is shown in Figure 7.

> **MODELS AND FRAMEWORKS** Different representation techniques can be used and depends on the analysts' preferences. For example, the *Design Structure Matrix (DSM)* is one alternative to the diagrammatic approach shown here.

It is left to the discretion of the CLIOS Process users to decide which approach is more appropriate for their objectives. In this paper, we suggest the construction of system diagrams as one way to usefully represent the system, but by no means do we consider this as the sole or the optimal method for all CLIOS Process applications. The nomenclature that is introduced here, however, can be useful for communication purposes as a common language irrespective of which representation method is used.

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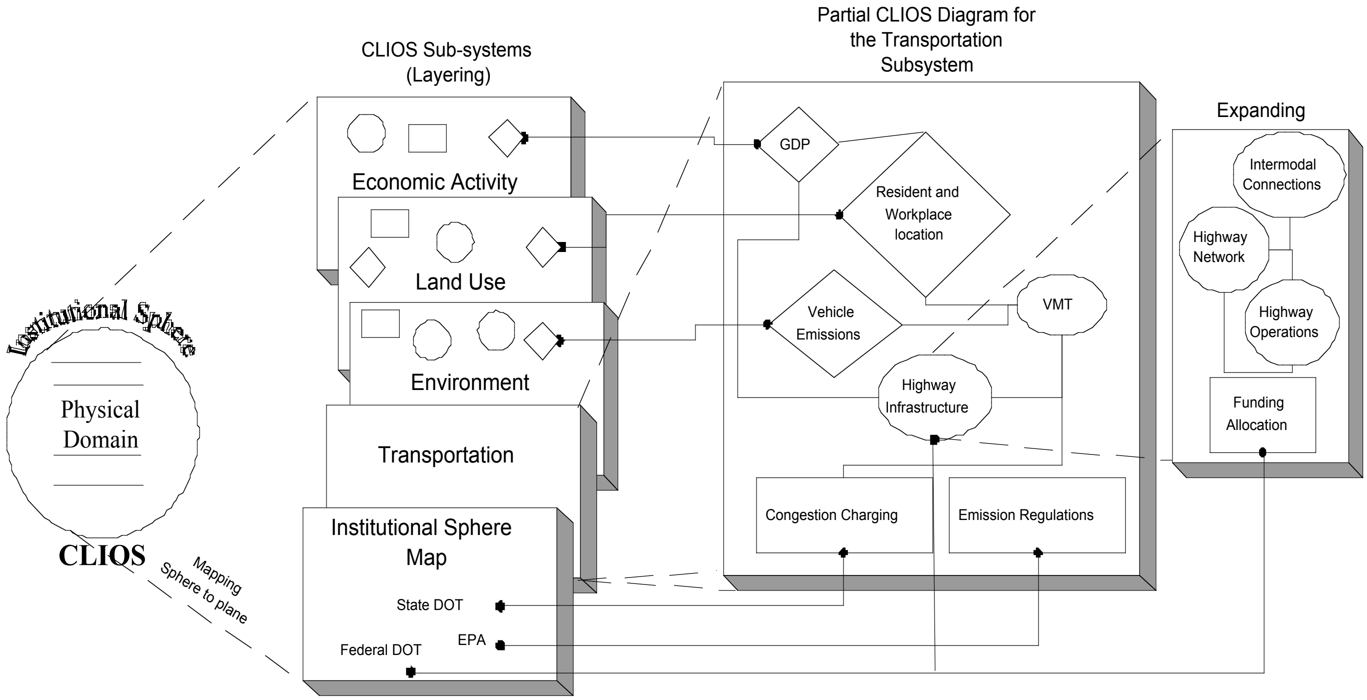
[7] The reader may notice similarities of the system representation as described in Step 3 of the CLIOS Process and other methods such as system dynamics and object-process methodology (OPM).

[8] From the authors' experiences, a single subsystem diagram should contain approximately 20 components—because of cognitive limits--although that number may be substantially more or less depending upon the preferences of the analyst.

Figure 7: Illustration of Step 3 for a transportation system example



Populating the Institutional Sphere: Parallel to populating the subsystems of the physical domain with components, we populate the institutional sphere with individual actors within each of the major actor groups and show the links between them. In order to show the institutional sphere conveniently, we flatten the sphere onto a two-dimensional plane. Figure 7 above illustrates the tasks described in Step 3 for a transportation example. It shows the various subsystems selected, the institutional sphere mapped onto a plane for convenience, with the subsystems and sphere populated with components and actors respectively. Further, we then expand those components or actors if the user feels they need greater detail.

4.4. Step 4A: Describe Components in the Physical Domain and Actors on the Institutional Sphere

Components of the physical domain: Up to this point, the components have been considered as generic. In this step we more carefully characterize the nature of the individual components. Within the physical domain, we consider three basic types of components. *Regular components* (or from now on, simply "components" and indicated by circles) are usually the most common in the subsystem diagrams within the physical domain. They can refer to concepts such as "congestion" or can contain complex internal structures such as "economic growth."[9]

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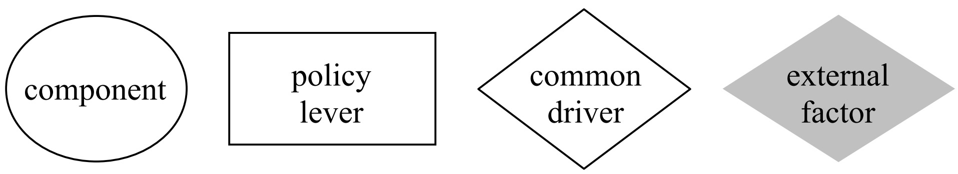
[9] Whether these components are broken out in more detail within the main subsystem diagram depends on the focus of the CLIOS System representation. Analytic insights may be better gained by "expanding" a particular component, as described earlier.

Policy Levers (indicated by rectangles) are components within the physical domain that are most directly controlled or influenced by decisions taken by the actors — often institutions and organizations – on the institutional sphere.

Common Drivers (indicated by diamonds) are components that are shared across multiple and possibly all subsystems of the physical domain.

In Figure 8, we show three shapes used for different CLIOS System components. External factors are indicated by shading, rather than by shape, and can still be either a component or a common driver. Deciding on the type of component, whether it is an external factor, and whether the component should actually be further expanded into greater detail, is not trivial. Box 1 provides some heuristics to help the analysts in making these decisions.

Figure 8: Suggested CLIOS System diagram component shapes



Returning to the idea of nested complexity, the policy levers are those components that directly link the actors on the institutional sphere to the subsystems in the physical domain. The common drivers, on the other hand, emerge from the process of dividing the system into separate subsystems. They are important components that "drive" the behavior of more than one of the subsystems. The common drivers are important both for understanding the behavior of the CLIOS System as well for implementing changes to the system (during later stages in the CLIOS Process). Many common drivers are also external factors that are exogenous to the physical domain. They may constitute major sources of uncertainty, since they impact the physical domain at several different subsystems. The uncertainty of common drivers, for example, population and economic growth, will have to be taken into account in any evaluation of strategic alternatives for system improvements.

Actors on the institutional sphere: In parallel to describing the components in the physical domain, we also describe the actors on the institutional sphere. In describing the actors, 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.

As we introduce the basic concepts of the CLIOS Process' representation stage in general terms, there are many specific questions the reader 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?

In Step 3 of the CLIOS Process we need to begin to explicitly address these questions. These are all difficult questions. Indeed, *there is no 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. As mentioned previously, these changes are indicative of shifting mental models and possibly precursors to important insights (as shown in Figure 4). That being said, there are heuristics that the analyst can use to support these decisions. We describe some of these below. 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, economical, 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 analysts consider 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.

Box 1: A note on heuristics for scaling and bounding the CLIOS System

4.5. Step 4B: Describe Links

As the components are characterized and divided into different types, we also in parallel need to characterize the nature of the several kinds of links. Link notation needs to be consistent; if they represent different things, one should use different diagrammatic components (Flood and Carson, 1993). In the diagrams used in the CLIOS System representation, these links will be largely qualitative. Generally, the links should indicate directionality of influence and feedback loops,[10] as well as the magnitude of influence (big/important or small/marginal impacts on the adjoining components). Other possible characteristics to include in the notation for the links could be the timeframe of influence (short-, medium-, or long-term lags), the 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), and uncertainty of the effect of one component upon another (including uncertainty in all of the above characteristics).

In thinking about the linkages, a key aspect of the CLIOS System representation is to develop a framework for thinking about and describing the links in the system. We identify here three classes of links:

(a) **Class 1:** links between components in a subsystem,
(b) **Class 2:** links between components in a subsystem and actors on the institutional sphere (also called "projections") and
(c) **Class 3:** links between actors on the institutional sphere.

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

In Figure 9 we show some suggested link notation. Components can have weak, average, or strong links to other components. Links can be one way or bi-directional. One can also have links that are positive or negative in their influence on the other component.

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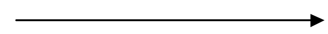
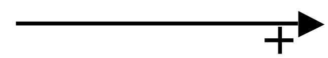
[10] We suggest that feedback loops in which one component has a feedback loop directly back onto itself would not be used in a CLIOS System representation. Instead, the intervening components need to be identified, to provide insight into the chain of causality that creates this feedback.

Figure 9: Some suggested link shapes for CLIOS subsystem diagrams

LINK	SHAPE
Class 1 (link between *components* of physical subsystems) Class 3 (link between *actors* on the institutional sphere)	
Class 2 (links "projecting" interactions 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)	

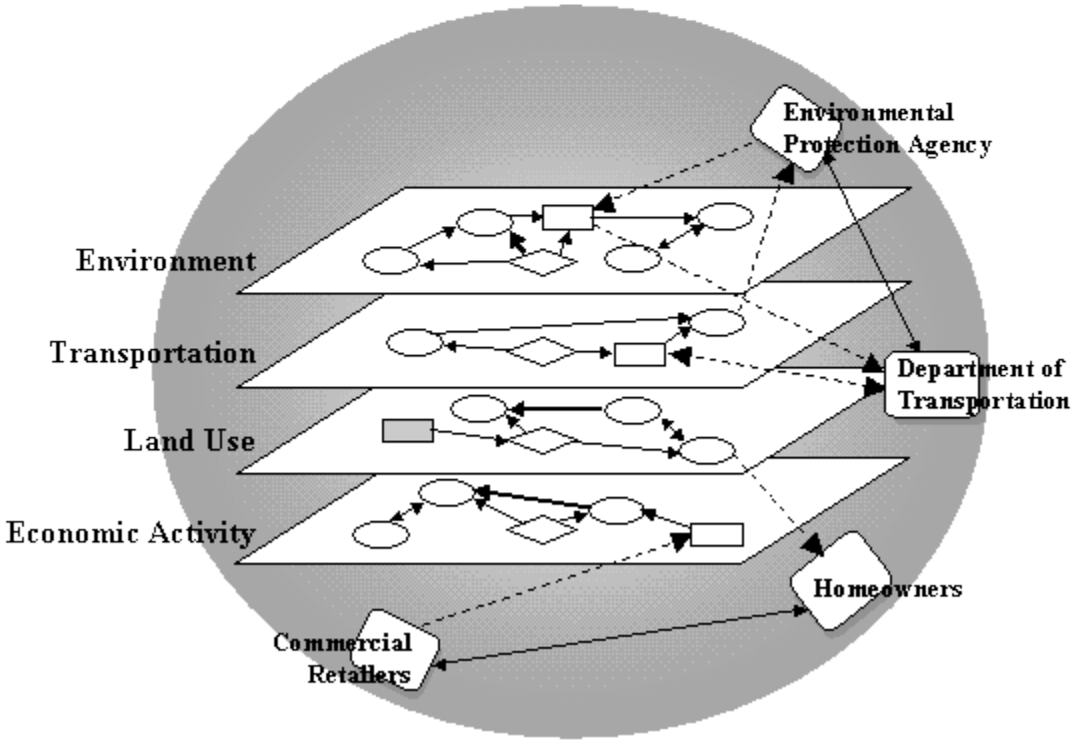
Different types of links can be identified based on what "goods" they carry from one component/actor to another. These include:

- *Causal*: Shows causation between two components, two actors, or a component and an actor.
- *Informational:* Shows information/decision flow between two actors or two components
- *Financial:* Shows 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:* Shows flow of materials between two components
- *Energy Transfer*: Shows flow of energy between two components

The exact shape or notation for the components and the links, or the level of detail in describing the types of links, is solely the decision of the analysts or decisionmaker following the CLIOS Process. What is most important is that the analyst *does* follow a systematic process of thinking through and attempting to classify the links in their systems. In that manner, the analysts will learn more about the CLIOS system, and gain intuition regarding its structure and behavior (refer again to Figure 4). *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"

Now, having described our suggested notation for the CLIOS System representation, we show a CLIOS System representation in Figure 10.

Figure 10: Example of a CLIOS System diagram at the end of Step 4



4.6. Step 5: Transition from Descriptive to Prescriptive Treatment of System

As noted earlier, this step marks a transition from a descriptive to prescriptive treatment of the system. We move from the initial representation stage to the later stages of design, evaluation, and selection, and implementation of strategic alternatives. We hope that some important insights will resulted about the nature of the CLIOS System under study and have emphasized that many of the most important insights about the system behavior will come during the process of creating the diagrams, and the discipline of bringing a systems mindset to a large complex system. However, before making the transition to Stages 2 and 3, we offer some questions and mental exercises that can hopefully draw out some additional insights regarding the CLIOS System.

Once the general structure of the CLIOS System has been established, and the behavior of individual components, actors, and links has been relatively well characterized, we can use this information to gain a better understanding of the overall system behavior, and where possible, counterintuitive or emergent system behavior. This entails essentially tracing through the system at its different levels – the physical subsystems and institutional spheres. By tracing through the pathways in the CLIOS System, there are several sources of important systems behavior that can be identified by asking the following types of leading questions.

First, with respect to the physical layers (Class 1 links), are there strong interactions within or between subsystems? Are there chains of links with fast-moving, high-influence interactions?

Are some of the paths of links strongly non-linear and/or irreversible in their impact? Finally, can strong positive or negative feedback loops be identified?

Second, looking at the links between the institutional sphere and the physical subsystems (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?

Finally, within the institutional sphere itself (Class 3 links), are the relationships between organizations characterized by conflict or cooperation? Are there any high-influence interactions or particularly strong organizations that have direct impacts on many other organizations within the 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 this stage, rather than attempting to quantify the relationships, the focus should be more on simply "getting the sign right" (Marks, 2002) or understanding the direction of change through a series of complex and uncertain chains of links. Furthermore, here we may also begin to develop a catalogue of issues and possible strategic alternatives for the CLIOS System. The idea is that in a CLIOS System representation, 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. These loops can be purely within the physical domain, but are also likely to arise when different actors on the institutional sphere have an influence on the same components within the physical domain.

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. We now move to Stage 2.

5. STAGE 2: DESIGN, EVALUATION AND SELECTION

Having considered the CLIOS System from the standpoint of its structure and behavior during the Representation stage, the next stage focuses on the design, evaluation, and selection aspects of the CLIOS Process. We therefore begin to consider in greater depth the *evaluative complexity* of the CLIOS System, in order to identify opportunities for improving both the physical domain and the institutional sphere. This culminates in the development of a robust bundle of strategic alternatives. Among these strategic alternatives may be organizational and institutional changes that may be necessary to meet the CLIOS System goals (defined in Step 1, and to be reconsidered in Step 6).

As part of Stage 2, we can also proceed with using the appropriate (quantitative) **models** using the refined system goals and the identified performance measures as guidance for model scope and scale. These models should be validated to evaluate the current state of the system; they 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; in our transportation example a traffic simulation would be such a model) and **system-wide** (i.e., models that aim to describe interactions at the CLIOS system level, such as a system dynamics simulation that combines economic, environmental and transportation interactions). 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.

5.1. Step 6: Refine CLIOS System Goals and Identify Performance Measures

Entering the second stage of the CLIOS Process, it is necessary to refine the preliminary goals developed in Step 1 to reflect the knowledge and insight gained at this point in the process. The Representation Stage should have revealed the needs and perspectives of the stakeholders more clearly and captured the opportunities and issues of the CLIOS system under study. This additional information can be used to refocus the preliminary goals into a concise, normative view of what the desired future state of the system should be, and give the analyst an idea of which goals are attainable and realistic and which goals may need to be modified in the face of reality. The concrete vision of the desired *future state* of the system, as prescribed by the *refined goals*, 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. In this sense, we are confronted with the *evaluative complexity* inherent in CLIOS Systems. "Performance" will depend heavily upon the viewpoint of the various stakeholders.

MODELS AND FRAMEWORKS: A useful way of tying together the needs/goals of the stakeholders with the identified performance measures is by the *Needs-Metrics Matrix* as described by Ulrich and Eppinger.

A

One may even 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. This is another example of the need to iterate throughout the CLIOS Process.

Box 2: Examples of performance measures in CLIOS System components for the case of urban transportation

In the case of urban transportation, certain *common drivers* such as economic development are important performance measures for many stakeholders. First, these measures reflect the economic health of the city. Also, economic growth depends in part upon the efficacy of the transportation system to bring goods to customers, customers to stores and employees to work. Therefore, 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). Of course, regular *components* such as congestion or human health, which may not be common drivers or policy levers, can be performance measures as well.

5.2. Step 7: Identify and Design Strategic Alternatives for CLIOS System Improvement

The establishment of better-refined goals and performance measures naturally leads to questions about *how* CLIOS System performance can be improved through strategic alternatives. 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. Detailed evaluation, selection and, of course, elimination of strategic alternatives will come later in Step 9.

Performance improvements through strategic alternatives can take three forms. Thinking about nested complexity, we can characterize strategic alternatives as:

- **physical** changes involving direct modification of components in the physical domain (e.g. expansion of a highway or the construction of a new rail line in our urban transportation example),
- **policy-driven** changes involving the policy lever projections from the institutional sphere on the physical domain (e.g., a vehicle trade-in policy or congestion pricing in the urban transportation example) and
- **actor-based** – architectural changes of the institutional sphere either within actors or between actors (e.g. a structural change in the EPA or a change in the way the EPA interacts with DOT on the institutional sphere of a U.S. transportation CLIOS System).

Thinking through system performance from the inner physical layers to the outer institutional sphere is a more bottom-up systems engineering approach, in which we look first at the physical domain and ask how the subsystems in the physical domain – through changes to the components or perhaps, in some cases, changes to the links between components – can lead to better performance. This approach often leads to more technology-driven strategic alternatives relating directly to the physical domain (physical strategic alternatives).

In many cases, in order to achieve changes in the physical domain, policy-driven strategic alternatives need to be considered. These strategic alternatives may rely on incentives or disincentives such as taxes, subsidies, voluntary agreements, and restrictions on certain behaviors. 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.

Finally, an important part of Step 7 should be to evaluate the institutional arrangements (sometimes referred to as the institutional "architecture"[11]) that govern the management of the CLIOS System and then devise strategic alternatives that change these arrangements, in order to support the CLIOS System goals. 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 (actor-based strategic alternative).

B

This is also a step for revisiting 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.

5.3. Step 8: Flag Important Areas of Uncertainty

A parallel activity to the identification of strategic alternatives for CLIOS System performance improvements is to look for uncertainties in the anticipated performance of the CLIOS System, both at the subsystem and the CLIOS System level. 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. For example, we should look carefully at individual links or loops that had large magnitude, fast-moving, non-linear or irreversible influences on other components within the system.

[11] We often use the term "architecture" to denote organizational interactions among the actors on the institutional sphere of the CLIOS System. This definition is adapted from Sussman and Conklin (2001), where a *regional architecture* is defined "as a methodology for designing organizational interactions among the various agencies and private-sector firms that would participate in providing transportation services of any type at a regional scale." Indeed, one can consider a regional architecture as a special case of an architecture, where the CLIOS System is a regional transportation system.

The common drivers, given their importance to the performance of a CLIOS System, are another key area that can affect CLIOS System uncertainty. Common drivers in our urban transportation example would include GDP and population, both of which can be highly uncertain, especially in the long-term. 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 when one considers the longer-run evolution of the CLIOS System. For example, whether an economy (a) grows only gradually, with occasional sharp downturns, or (b) suddenly takes off, can radically influence the entire CLIOS System 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 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.

MODELS AND FRAMEWORKS A promising qualitative methodology for identifying key uncertainties and understanding their impact on the CLIOS System is *scenario planning* as developed by Royal Dutch/Shell in the years leading up to the oil shocks of the 1970s. Ged Davis, head of Shell's Scenarios Team, defines scenarios as "coherent, credible stories about alternative futures" (Davis, 2002). Scenarios are used in the corporate context to make decisions in a complex and uncertain environment by fostering a new way of thinking about the future and its impact on strategy. Scenario planning has continued to evolve finding applications in a wide range of contexts besides corporate strategy.

Quantitative approaches are of value as well in this step of the CLIOS Process. They include estimation of probabilities for events in the CLIOS System and the use of *risk assessment* to identify and quantify their expected impacts. Another way of approaching uncertainty is exemplified by *real options* used to value flexibility and flexible strategic alternatives. One could create more flexible strategic alternatives, which could be modified as an uncertain future played out. McConnell (2005) describes ways that life-cycle flexibility can be integrated into the CLIOS Process.

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This may be another important point for iteration back to Step 2. As uncertainties are identified, 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. 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.

5.4. Step 9: Evaluate Strategic Alternatives and "Bundles"

In this step, 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 area(s) that it was designed for. The case-specific models are usually adequate for this evaluation. If the strategic alternative is causing the intended performance measure(s) 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.

> **MODELS AND FRAMEWORKS:** *Cost-benefit analysis* is a well-established tool for comparing, as one would expect, the costs and benefits of different alternatives. This is a well-established and common tool, when applied rigorously and with an understanding of its inherent limitations (specifically, having to reduce a number of disparate costs and benefits to a monetary equivalent).
>
> The use of *trade-off analysis* is an alternative approach which allows comparison of strategic alternatives across difference performance measures. A large number of alternatives can be compared in this manner, and there is no need to reduce performance measures to a single measure. As the name suggests, it allows decisionmakers to clearly see the tradeoffs between alternatives across various dimensions of performance.

Given system complexity, it would be unusual if a single strategic alternative could be deployed and meet CLIOS System goals. In other words, there is no silver bullet for CLIOS Systems. However, by combining strategic alternatives into **bundles**, the analyst may accomplish two objectives. First, 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.

Second, 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**.** For example, combinations of alternatives can provide insurance against extreme changes or shocks to the system, such as major shifts in the common drivers. The system-wide models from Step 6 and the uncertainty considerations from Step 8 are critical in the evaluation of bundles of strategic alternatives. 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, where the columns represent different futures and the rows represent bundles of strategic alternatives; then we can see how the bundles perform compared across a range of futures.

Table 3: Performance of Bundles across Different Futures

	Future1	***Future2***	***Future3***
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.

6. STAGE 3: IMPLEMENTATION

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

Steps 10 and 11 (shown as parallel steps) 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. 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. 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.

6.1. Step 10: Design and Implement Plan for Physical Domain/Subsystems

As mentioned above, this part of the plan for implementation concentrates on the physical and policy-driven types of strategic alternatives in the physical domain. In developing the plan, it is important to consider 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 we create a plan is focusing on all of 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. These considerations will inform the parallel Step 11.

6.2. Step 11: Design and Implement Plan for Institutional Sphere

Strategic alternatives developed earlier in Step 9 include needed changes to the structure of individual actors (e.g. organizations) and the relationships among them. In Step 11, we design a plan for implementation of these actor-based changes. Designing a plan for implementation requires a comprehensive understanding of the characteristics of the institutional sphere. We consider Step 11 to be a parallel activity to Step 10, with a plan for implementing actor-based changes explicitly being a central part of the overarching implementation plan.

When creating a plan for how the institutional architecture can be modified along the lines drawn from the actor-based strategic alternatives of the chosen bundle, 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. This consideration is central to Step 11 by returning to the issue of mitigation or compensation; one can consider the building of coalitions that will overcome resistance created from the opponents (See Appendix A on the political science concepts of Olsonian and Stiglerian system characteristics).

A well-crafted implementation plan for the institutional sphere notwithstanding, institutional changes 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.

6.3. Step 12: Evaluate, Monitor and Adapt Strategic Alternatives

Finally, once bundles of strategic alternatives have been implemented, the next 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. Because Step 12 is our final step in the CLIOS Process, it is also a critical point for additional iteration to earlier steps. We highlight four points of iteration here, starting with the iteration back to Step 9.

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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 transportation options worked relatively well, but did not meet their expected performance measures, one can consider adding additional strategic alternatives, perhaps in the area of land use changes, 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 (for example, switching from cost-benefit analysis to multi-criteria trade-off analysis).

E 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 At this point, 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 decisionmakers 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 Finally, an important point for iteration is from Step 12 back to Step 5. Again, Step 5 is where the user makes the critical transition from a descriptive treatment to a prescriptive treatment of the CLIOS System. In other words, the question shifts from "what do we know about the system," to "what do we do with the system?" It is also the point at which one can consolidate knowledge and emerging insights regarding the structure and behavior of the system. Iteration "G" 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 (as shown 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.

So, while we discuss these four "feedback loops" for iteration in the CLIOS Process, there are other possible points of iteration. A noted above, 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.

7. 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 doubtless have the need to iterate back through the process multiple times as understanding grows and conditions change.

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THESES

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Appendix A

Under development