

Engaging Stakeholders in Engineering Systems Representation and Modeling

Ali Mostashari¹ and Joseph Sussman²

Abstract

Engineering systems policy analysis, design and implementation is complicated by the fact that such systems often involve a complex technical and scientific analysis process that often does not take into consideration the social and institutional system, within which the technological system is embedded. Even in analyzing the physical layers of the system, expert models are affected by the cognitive limitations of experts. Given that most large-scale engineering systems involve high stakes for its stakeholders and involves high amounts of scientific and technical uncertainty, an expert model may provide recommendations that do not take into account stakeholder and decision-maker concerns and knowledge, and may thus be unsuccessful in meeting its goal of improving system performance. To address these issues, we propose to engage stakeholders from early on in the representation and modeling of engineering systems using a Stakeholder-Assisted Modeling and Policy Design (SAM-PD) process, which uses concepts from systems thinking and collaborative decision-making to facilitate the collaborative representation and modeling of complex, large-scale engineering systems. This paper argues that the involvement of decision-makers and stakeholders in the representation and modeling of the system can improve the modeling process and help take into account decision-maker and stakeholder concerns, and ultimately lead to decisions that are viewed as more legitimate by decision-makers and stakeholders.

¹ Ph.D. Candidate, Engineering Systems Division, Massachusetts Institute of Technology, amostash@mit.edu (*author to whom correspondence should be addressed)

² Professor of Civil and Environmental Engineering and Engineering Systems, Massachusetts Institute of Technology, sussman@mit.edu

Introduction

In making decisions on complex, large-scale engineering systems, decision-makers have often relied on expert models as a basis for their decisions. However, most expert models focus on the physical aspects of the engineering system, and often do not take into consideration the social and institutional system, within which the technological system is embedded. Even in analyzing the physical layers of the system, models developed by experts are affected by the cognitive limitations of the model-builders. Given that most large-scale engineering systems involve high stakes for its stakeholders and involves large amounts of scientific and technical uncertainty, an expert model may provide recommendations that do not take into account stakeholder and decision-maker concerns and knowledge, and may thus encounter resistance among stakeholders who have little or no understanding of the underlying logic of the recommendations. According to Venix (1996), “Even in the modern age of science and industrialization social policy decisions are based on incompletely-communicated mental models. The assumptions and reasoning behind a decision are not really examinable, even to the decider. The logic, if there is any, leading to a social policy is unclear to most people affected by the policy.”

Cognitive Biases in System Representation and Modeling

According to Sussman (2000), the approach we take to modeling a system depends on how the results are going to be used. Therefore, models that serve as decision-making tools have the aim of providing a basis for successful decisions, that is decisions that have a high probability of addressing the problems that have been identified in a system. Therefore, a “good” decision-making model for an engineering system with diverse stakeholders is one that takes into account the needs and concerns of the key stakeholders and decision-makers, and is able to produce results that can be used to address those concerns.

It can be argued that even given the same set of information and level of knowledge, system representation is heavily impacted by the mental map (how people see a system) of the group present at the modeling stage, making the inclusion of stakeholders imperative if a more accurate representation is sought in the model. Mental maps of engineering systems differ among individuals along the following dimensions:

System Boundaries and Boundary Elements: Individuals have different ideas of where to draw the boundaries of a system, and what elements constitute the final boundary elements that can serve as external inputs and outputs of a given system. For instance, when thinking about air quality management strategies for a transportation system, some people may try to look at the broader impacts of transportation on the economy, air quality, mobility and accessibility as well as land-use, while others may only focus on system boundaries that only address air quality.

Causality and Polarity and Feedback Loops: Individuals have different perceptions of what behavior a system is currently exhibiting and how the different components are

interacting. In the case of a transportation system, the relationship between building infrastructure, fleet size, mode choice, transportation demand and congestion may be construed differently, even among transportation experts, often depending on whether the individual recognizes the importance of feedback loops in the system.

Subsystems and their Components: The subsystems necessary to describe the system, and the components within each may also be perceived in different ways by modelers. For instance, in analyzing demand in a transportation system, the question of whether or non-motorized trips should be analyzed as affecting motorized trip rates often depends on the value system of the individual(s) modeling the system.

Quantitative Relationship between System Elements: Components within each physical subsystem are connected to one another by quantitative relationships. Given the uncertainty involved in such relationships, the fewer experts that are involved in reviewing the quantitative assumptions in these relationships, the more biased will the model seem to stakeholders and experts with different mental maps of the system.

The above differences indicate that the representation of a system is far from objective, and that the mental map of the individuals involved in modeling the system can have dramatic influences on how a system is represented and modeled. This point was demonstrated in related assignment given to MIT students in the graduate-level “Introduction to Technology and Policy” course. Student teams with no prior knowledge of the Mexico City transportation and air pollution system were given technical and institutional background material, and asked to represent the transportation subsystem of the Mexico City with CLIOS causal loop diagrams which would serve as a blueprint for modeling the transportation-air pollution system. Figures 1-3 show the different representations developed by the student teams. Stakeholder groups would develop similar representations, agreeing on the different components of the system and the linkages between the different subsystems.

If each of the above transportation subsystem representations were used as a blueprint for the transportation-air pollution model, they would result in different recommendations. The focus of the representation of Group 1, shown in Figure 3 is the link between fleet size, fuel quality, Inspection and Maintenance (I&M), congestion and their effect on air quality. Group 2 has its focus on the link between Metro electricity consumption, fleet age and fleet usage, congestion and freight transit. Group 3 takes into account only the effect of congestion and Metro electricity consumption on the air quality. In fact, if all the above are integrated they provide a better picture of the drivers and components that affect air quality in Mexico City.

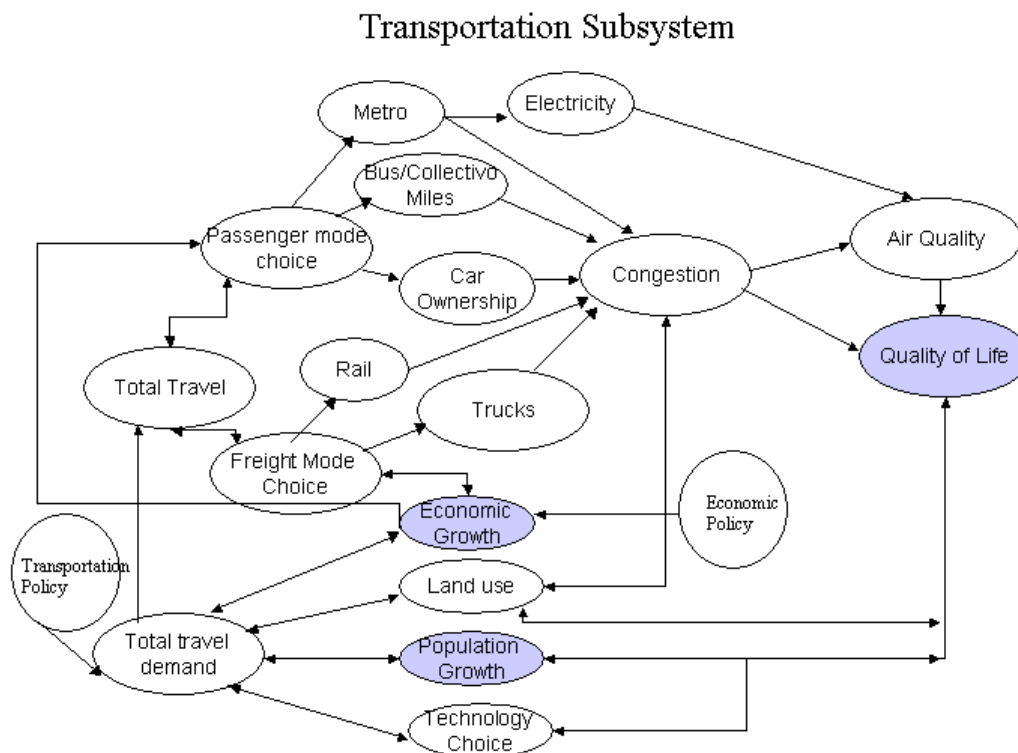


Figure 3- Student Group 3 Representation of the Mexico City transportation subsystem

Engaging Stakeholders in representation and modeling of systems

To address the above-mentioned issues, it is possible to engage stakeholders from early on in the policy analysis process. According to Cahn (2000), “the formal inclusion of stakeholder representatives, and by extension of the public at large, goes far toward resolving the primary tensions between science and policy. Formally linking policy staff and scientists with stakeholders creates an important linkage between technocrats and the public.” As the above analysis of mental maps shows, the engagement of a broader set of experts, decision-makers and key stakeholders can help shed light on different parts of the system and result in a more comprehensive analysis.

The basic rationale for involving stakeholders is as follows:

- Policy Implementation Considerations:** Complex large-scale integrated open systems (CLIOS) are characterized by high scientific uncertainty as well as high societal stake. When dealing with such systems, many decision-makers have drawn on scientists and experts for advice on policy issues. However, due to lack of direct interaction between experts and stakeholders, many of the recommendations that scientific and technical experts come up with do not take the needs of stakeholders into consideration. This can result in loss of

effectiveness of the recommendations at best, but most often leads to an increase in societal conflict on the issue.

- **System Representation and Cognitive Biases:** Research on cognitive or mental maps show that the representation of a system, and the framing of the problem is heavily dependent on the modelers' personal mental maps. The isolated scientific and technical analysis of a CLIOS can result in a biased representation of the system, resulting in lower-quality recommendations, which do not fully address the important aspects of a problem. Therefore, having multiple perspectives on the system shape the collective mental map of the system can improve the representation of the system from a scientific point of view.
- **Cognitive change through interaction and dialogue:** It has been argued that interaction among stakeholders, experts and decision-makers while not changing values and interests, can result in a more holistic view of a given issue for all involved. This will ensure that decisions are robust in the longer term, given that their underlying rationale is transparent to most people involved.
- **Deliberative democracy:** Finally, it has been argued that stakeholders have the inherent right to participate in making decisions that affect their lives. While not everyone affected can be involved, deliberative democracy seeks to strike a balance between direct democracy and representative democracy.

One of the ways to enable early stakeholder participation in the decision-making process for complex large-scale integrated open systems is to initiate a stakeholder-assisted policy design and modeling process, where the experience and local understanding of issues embodied in the stakeholder can be used within the scientific analysis model, in such a manner that it does not undermine its scientific credibility. Also, any recommendations resulting from such a modeling process have the potential of being accepted more readily, since stakeholders feel more ownership in the policy analysis and modeling process. Therefore, at later stages of the policy making process, the model can then be used to facilitate negotiations among the different stakeholders. The challenge is to create a model that sufficiently represents the complexity of the system, while still being understood by all the participants who are involved in the modeling process, and produce reasonable and useful recommendations. In this research, an alternative process called the Stakeholder-Assisted Modeling and Policy Design (SAM-PD) process has been proposed as an alternative approach to traditional policy analysis, design and implementation processes.

Stakeholder-Assisted Modeling And Policy Design (SAM-PD)

An alternative approach to the traditional policymaking process is allowing stakeholder participation from the beginning of the process. Involving these stakeholders helps to generate relevant information regarding the issue and at the same time creates ownership of and consensus on the resulting group recommendations for dealing with the issue.

The idea of non-technical stakeholders helping in the modeling process might be considered unrealistic, if one imagines the thousands of lines of code, or the hundreds of pages of spreadsheets that come to mind when thinking about a model. However, there

has been considerable progress in developing tools and techniques to support a group model-building process. According to Richardson (1994), building models with a group of stakeholders has become an established approach to support strategic decision-making. Graphical facilitation techniques, such as causal loop diagrams, stocks-and-flows diagrams and graphical functions have been used in combination with guidelines for structuring and facilitating group sessions, group knowledge-elicitation techniques and appropriate consulting roles, mostly limited to corporate decision-making. Stakeholder-Assisted Modeling and Policy Design (SAM-PD) is a process facilitating such a participatory approach. It proposes to accomplish this task by synthesizing successful insights from different aspects of the policymaking process into one coherent process. Specifically, SAM-PD uses:

- A CLIOS Analysis Methodology as a conceptual framework (Sussman 2000)
- System Dynamics, as a visual modeling platform for the CLIOS analysis.
- A Group Model-building approach as an organizational structure for the policy modeling and analysis stage of the process (Vennix 1996).
- And a Model-Based Negotiation approach as an organizational structure for the policy design and implementation stage of the process.

The underlying logic connecting these four elements is their role in facilitating stakeholder participation in all stages of the policymaking process. Figure 1 shows the difference between SAM-PD and more traditional policy making processes in terms of stakeholder involvement in different stages.

SAM-PD Process Element: CLIOS Process

As defined by Sussman (2000), the term CLIOS (Complex, Large-scale, Integrated, Open Systems), refers to systems which are composed of a group of related component and subsystems, for which the degree and nature of the relationships is not clearly understood; have large, long-lived impacts that span over a wide geographical area; have integrated subsystems coupled through feedback loops, and are affected by social, political and economic issues.

CLIOS analysis is an approach to fostering understanding of complex sociotechnical systems by using causal loop diagrams to highlight the interconnections of the subsystems in a complex system and their potential feedback structures. The motivation for the causal loop representation is to convey the structural relationships and direction of influence between the components within a system. In this manner, the diagram is an organizing mechanism for exploring the system's underlying structure and behavior, and then identifying options and strategies for improving the system's performance. The CLIOS analysis proposes the idea of "nested complexity" when the complex physical system is being "managed" by a complex organizational and policymaking system. While engineering and economic models can approximate the physical system, the organizational and institutional system it is embedded in requires a more qualitative framework of analysis. Figure 4 outlines the twelve steps of a CLIOS analysis.

In the modeling stage, a system analyst (normally part of the research group working on the problem) gathers quantitative and qualitative information from stakeholder interviews and literature and constructs an initial simplified model to start the

modeling process. The model is then shaped into a refined model in a stakeholder-based modeling process. The stakeholders understand all the underlying assumptions of the model, and understand why it produces a certain behavior. Stave (2001) indicates that environmental decisions generally involve complex scientific and technical issues and a wide array of stakeholders, scientific uncertainty, value conflicts, ecosystem dynamics, and social dynamics, so that environmental decisions are especially prone to challenge. Therefore stakeholder involvement is essential in drafting better policies. Communicating the complexity of a resource system to a broad stakeholder audience can be difficult, however, because of the dynamics of the system, differences in technical expertise of the audience, and potentially conflicting perspectives among stakeholders. Resource supplies and demands may vary over time and in response to other variations in the system. Changes in one part of the system can feed back to cause unexpected changes in other parts of the system. Interventions often have non-linear, indirect, or synergistic effects. A given outcome can have multiple causes and delays between actions and effects can make it difficult to identify effective policy options. Understanding the way resource systems work also requires a certain amount of technical knowledge, which may not be shared by all members of the audience. Finally, stakeholders in a resource management system may hold conflicting mental models about the way a system works, the causes of resource problems and acceptable solutions.

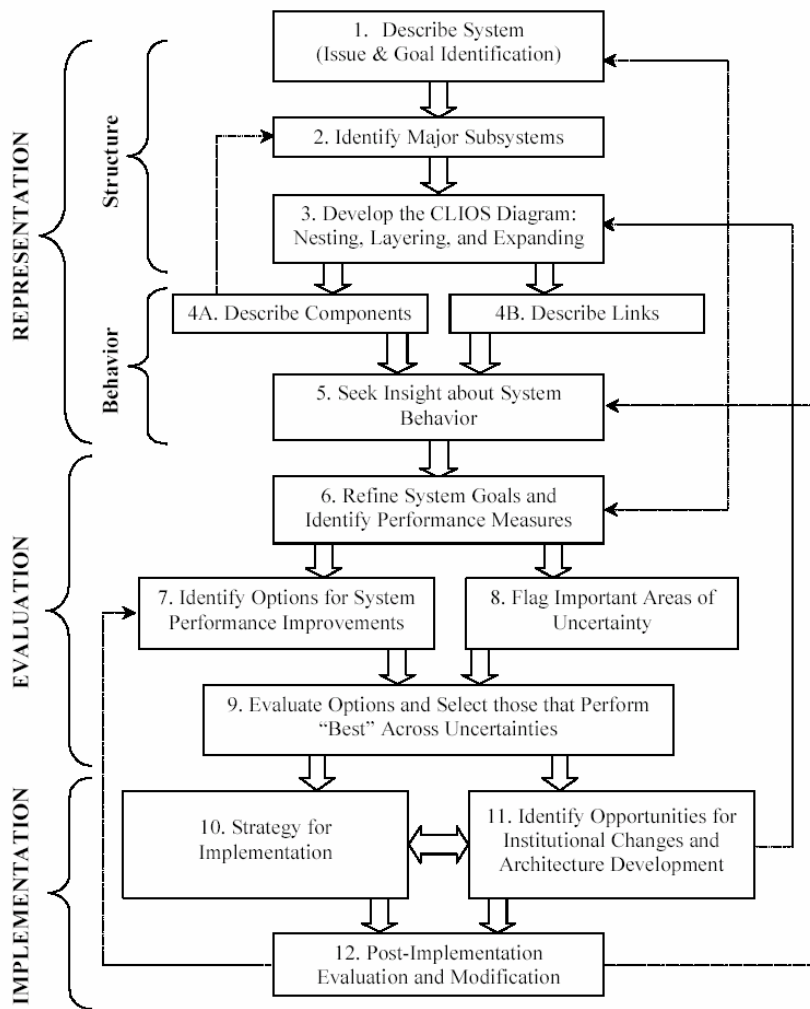


Figure 4. The 12-Step Approach of CLIOS Analysis (Dodder and Sussman 2002)

SAM-PD Process Element: System Dynamics

Once the qualitative links are established jointly with the stakeholder group, a System Dynamics diagram of the system and the corresponding subsystems can be developed. The SAM-PD process uses a visual model such as one created using System Dynamics that can act as an accessible interface between technical modeling and stakeholders. It consists of stocks and flows and causal loops, which can explain how the different elements of a complex system are linked together. Its qualitative representation combined with its quantitative output, make it a suitable tool for SAM-PD. System dynamics has the capability of performing extensive multi-variable sensitivity analysis. This means that if we are not certain of the inputs into the model or the relationship between the system components, we can provide a range for each, and the System Dynamics model will calculate all the possible combinations.

Figure 6, which also relates to the Mexico City transportation system, shows a sample interface that could help choose the different technological options for a bus fleet, such as the use of particulate matter filters. Using the jointly developed model stakeholders, decision-makers and the experts assisting them can explore the relationships between the different components and understand the underlying assumptions that produce the quantitative analysis.

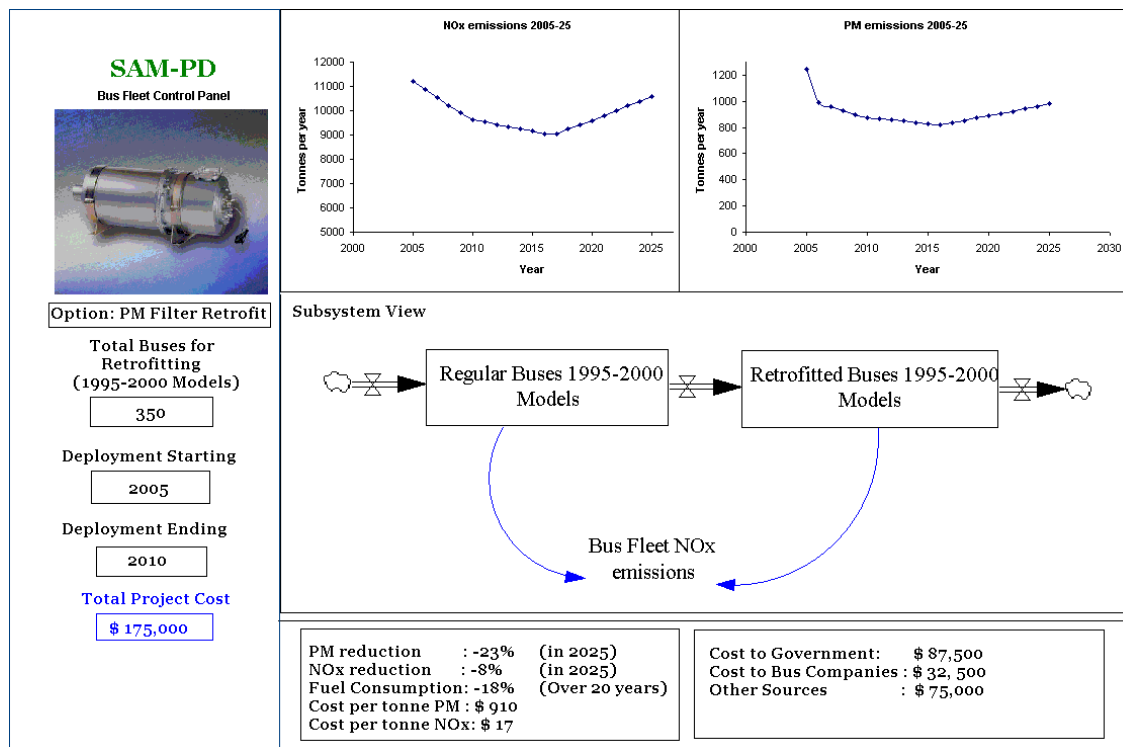


Figure 6. System Dynamics Interface for Bus Fleet Strategy Analysis for the Mexico City Transportation-Air Pollution System

SAM-PD Process Element: Model-Assisted Joint Fact Finding

An important part of the SAM-PD process is model-assisted joint fact-finding. The purpose of joint fact-finding is to develop shared knowledge and agreement about the system and its boundaries and important issues that ought to be considered in the scientific analysis. It is a step by which stakeholders initiate the process of gathering information, analyzing facts, and collectively making informed decisions (Ehrman 1999). Joint fact-finding rests on the following main principles:

- The process of generating and using knowledge is a collaborative effort on behalf of decision-makers, independent scientists and other stakeholders and their representative experts from all sides of the conflict.
- Information, expertise and resources will be shared among all participants.
- Participants are committed to finding a set of solutions to their conflict.

Basically, joint fact-finding may fail in situations when one or more of the above principles is violated in the process. Therefore, it is more advisable to engage in a

collaborative process before an issue is so polarized that it is impossible to convince people that a win-win situation is possible. Figure 7 shows how the larger collaborative process, within which stakeholder-assisted representation and model building is embedded.

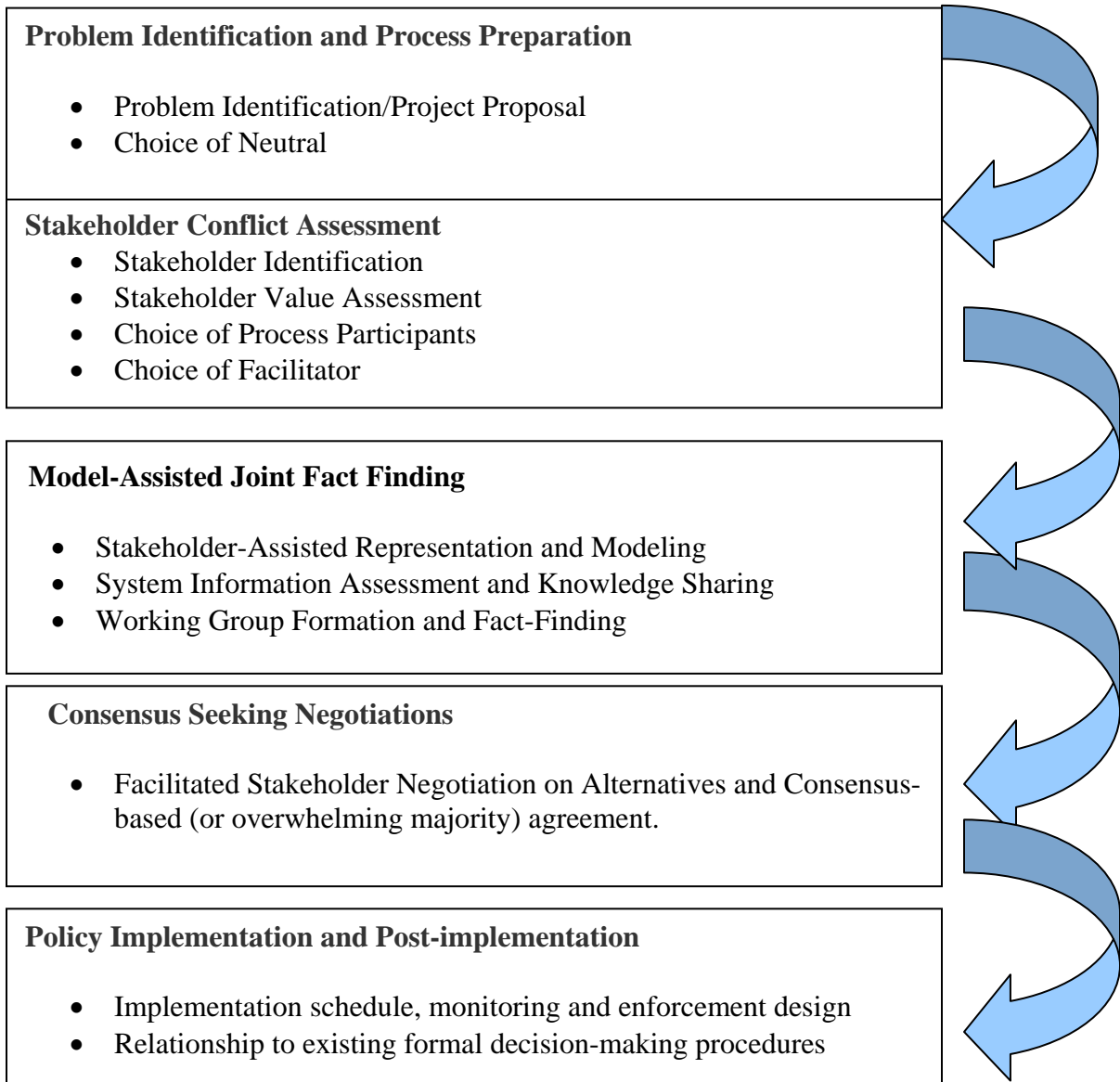


Figure 7. The SAM-PD stage within a consensus-based process (Based on a modified version of the Consensus Building Institute’s Consensus Building Diagram, Source: Consensus Building Institute 2002)

Advantages of SAMPD

SAMPD allows stakeholders (policymakers, other government agencies, private sector, citizen groups and NGOs) to better understand the logic behind the different air quality measures by allowing them to examine the underlying assumptions in the model and simulate the results of each strategy. The challenge at hand is to provide stakeholders with a model representation, which is accessible and understandable by stakeholders with different levels of technical expertise.

- Improved models that take into account stakeholders' local knowledge and experience.
- More inclusive policy process leading to higher legitimacy of recommendations in the eyes of stakeholders
- Better adherence to implementation due to process ownership.
- Better understanding of stakeholder concerns in direct modeling dialogue
- Better understanding of institutional issues at the modeling level

Challenges for SAMPD

The challenges that are created by such an approach are significant. They can be summarized as follows:

- Successfully bringing together stakeholders for the specified duration of the process.
- Successfully educating diverse stakeholder group on modeling fundamentals
- Successful design and management of an inclusive modeling process given hierarchies and stakeholders from different social standings.
- Validating a model created by stakeholders with differing technical backgrounds
- Demonstrating actual improvement over traditional policymaking processes
- Monitoring implementation success for environmental programs stretched over long periods of time.

SUMMARY

The SAM-PD process allows stakeholders (policymakers, other government agencies, private sector, citizen groups and NGOs) to better understand the logic behind the different air quality measures by allowing them to contribute to model-building effort and to examine the underlying assumptions in the model. Ideally it can lead to improved models that take into account stakeholders' local knowledge and experience, more inclusive policy process leading to higher acceptability of recommendations, better adherence to implementation due to process ownership, better understanding of stakeholder concerns in direct modeling dialogue and better understanding of institutional issues at the modeling. The challenge at hand is to provide stakeholders with a modeling interface, which is accessible and understandable by stakeholders with different levels of technical expertise. While SAM-PD is a promising approach, its applicability to real-life policy problems has to be explored through experimental research.

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