

Dynamic MCDM: The Case of Urban Infrastructure Decision Making

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Abstract

Many societal decisions involve complexity and conflicting objectives. Preferences in such environments can be expected to change as situations evolve. In this paper, we propose a procedure that incorporates MCDM into system dynamics modeling to handle dynamic multiple criteria situations, which we name dynamic MCDM. A case of urban infrastructure is presented to illustrate the procedure. Dynamic MCDM can handle different lags in economic, social, economic and technical effects of large scale systems; thus, it may help decision makers avoid selecting alternatives apparently effective in the short term, but detrimental in the long term.

1. Introduction

Humans have exploited the environment in order to meet their multiple individual and corporate needs. This activity has led to perceived imbalances in many areas (Forrester, 1973; Wildavsky, 1995). In response to this concern, the World Commission on Environment and Development (1987) has proposed the idea of sustainable development in which economic growth should be balanced with environmental protection to meet “the needs of the present without compromising the ability of future generations to meet their own needs.” Most decisions in large-scale systems at a macro level involve sustainability issues. Many recent researchers (Hersh, 1999; Kelly, 1998; Rauch, 1998) have addressed such issues in the study of various

large-scale systems such as energy, water resource, infrastructure, environment, and urban development.

Sustainable development in urban infrastructure requires decision makers to consider both intended and unintended effects, which tend to be long term, complex and interdisciplinary. While construction of infrastructure can push economic growth, it may have tremendous negative impacts on the environment as well as the social and political structures of the served communities (Choguill, 1996). Nielsen and Elle (2000) argue that because of environmental problems, urban infrastructure must be seen as socio-technical artifacts. To sustain an urban infrastructure system, there is a need to understand the complexity of the interactions that result from impacts of infrastructure on economic development and on the quality of life of citizens, which in turn have an impact on infrastructure development and degradation of the environment.

Sustainability, however, means different things to different people. Sustainability is a concept that involves a mixture of multiple long and short-term goals such as social, economic and environmental objectives. To operationalize the concept, we should define multiple, often conflicting goals in measurable terms or indicators (Kelly, 1998; Rijsberman and van de Ven, 2000). This task is difficult as it is hard to get consensus about indicators and their tradeoffs. When indicators interact in a complex manner, as they often do, sustainability is even harder to operationalize. Some techniques such as cross-impact analysis, causal mapping and system dynamics may be used to study the dynamics of the interaction.

There are important interactions among infrastructure, society and environment (Kelly, 1998; Rauch, 1998). As decision makers focus more on technical and economic issues, single criterion techniques such as cost - benefit analysis are less appropriate. Consideration of social interactions in infrastructure decisions exceeds the capability of conventional techniques of

evaluation. Without considering social interactions, the impacts of decisions on system sustainability are not identifiable. Urban infrastructure planning needs to be a dynamic process that is governed not only by economic but also by social and environmental conditions. It is important to understand the relationships between these conditions so that long-term impacts of decisions can be understood and decisions in infrastructure can be made. This consideration obviously will complicate the decision making process in urban infrastructure enormously.

In this paper, we propose the use of system dynamics to model complex systems incorporating the concepts of traditional MCDM to reflect the multiple goal nature of actors' decision making. The paper starts with a discussion of urban infrastructure as a complex system, followed by a discussion of the MCDM nature of actors' decisions within the system, leading to a procedure that incorporates MCDM into SD model. The paper concludes with presentation of an example that applies the procedure to an urban infrastructure problem.

2. Urban infrastructure as a complex system

An urban infrastructure system may be considered as complex as it consists of many different subsystems, involves human interactions, and interacts with the environment (Choguill, 1996). Relationships in urban systems are often nonlinear in behavior, reflecting social interactions. Such systems obtain a momentum that often becomes irreversible. Another complex feature is the presence of multiple stakeholders with multiple criteria. Kay et al. (1999) outlined categories of general complex systems.

The impact of infrastructure on economic development is non-linear as an increase in infrastructure will not lead to a proportional increase in economic growth. In social systems,

nonlinearity may be caused by human behaviors. An urban infrastructure system is hierarchical, as it is comprised of sub-systems such as roads and bridge, sewage and drainage, water supply, and solid wastes. Internal causality refers to “self organizing” which is characterized by goals, feedback loops, and emergent properties. Infrastructure interacting with society is self-organizing. The interactions among infrastructure, society and environment are dynamically stable. That means that the system practically never reaches equilibrium but may do so in some specific conditions. The behavior of the interactions can be predicted under some conditions with the help of simulation, but forecasting and predictability are always limited in practice due to uncertainty in human behaviors.

Urban infrastructure may also be viewed as a social system. Kelly (1998) reviewed Forrester's (1961) and Richardson's (1991) works, and summarized six characteristics of social systems: 1) complex systems are insensitive to changes in many system parameters, 2) complex systems counteract and compensate for externally applied corrective efforts, 3) complex systems resist most policy changes, 4) complex systems may contain influential pressure points from which forces may radiate to alter system balance, 5) complex systems often react to a policy change in the long run in the opposite to the way that they react in the short run, finally 6) complex social systems tend toward poor performance. Forrester (1971) called these counter-intuitive behaviors of complex social systems. According to Forrester, only simulation models are capable of revealing these characteristics through simulation experiments. An urban infrastructure system is expected to have similar properties. Society, including all aspects of human behaviors associated with the use of infrastructure, should be viewed as an adaptive system to the condition of infrastructure and environment (Bauer and Wegener, 1977).

The building of urban infrastructures takes time and an infrastructure does not grow *de novo*; it wrestles with the “inertia of the *installed base* and inherits strengths and limitations from that base (Star and Ruhleder, 1996). After prolonged growth and consolidation, they acquire “momentum” and become autonomous (Hughes, 1987). At this stage, they are to a large extent “irreversible” (Law, 1991) and appear as “social institutions” (Powell and DiMaggio, 1991). Once an infrastructure is designed, it is very difficult to go back and change. This irreversibility of urban infrastructure has some implications for the design of urban infrastructure; it is crucial, whenever the opportunity arises, to design urban infrastructures correctly the first time with consideration of not only short-term intended but also long-term unintended consequences.

An urban infrastructure system involves different groups of stakeholders who share the benefits of decisions and participate directly or indirectly in the decision process (Bauer and Wegener, 1977). Many actors may have influence on the system but no one actor is in control of its development. According to several authors and theories in social sciences, each group or community of practice (Brown and Duguid, 1991; Lave and Wenger, 1991; Wenger, 1998; Brown and Duguid, 2000) possesses “thought worlds” (Douglas, 1987; Dougherty, 1992), mental models (Argyris and Schon, 1978), frames (Orlikowski and Gash, 1994; Schon and Rein, 1994), or its own worldview (Churchman, 1971). Thus, different people may perceive the issue of urban infrastructure planning very differently and often their views are conflicting.

In particular, cultural theory (Douglas, 1970; Thompson et al., 1990) suggests that different groups of people have their own preferences and different set of goals or criteria which are deeply embedded in their social worlds (e.g., values, beliefs, interests). Thus, this theory maintains that different social actors’ policy choices for urban infrastructure are supportive and/or rationalized on the basis of their different belief systems or value orientations and such

worldviews are socially constructed rather than agency determined. People belong to a certain organization(s) or grouping(s). Which organization or grouping he or she belongs to actually determines his or her preferences and interests in urban infrastructure policy making.

Following this theory, we develop a set of groupings. Table 1 gives an example of three groups of social actors or stakeholders in urban infrastructure decision making: citizens (including residents and immigrants), businesses (including those who will move in), and governmental agencies. (In a real case, researchers may use Douglas’ cultural typology to characterize organizations or social groupings.) We assume that groups are homogenous and that they act rationally according to groups’ preference and goals (an assumption that is acceptable for purposes of demonstration). Citizens will consider whether to stay or to move depending on the quality of life criterion. Outside people may consider moving in if attractiveness to individuals is sufficiently high. Governmental agencies are assumed to make decisions based on the quality of life criterion. A model of urban infrastructure decision-making should include these groups’ goals and preferences.

Table 1: Stakeholders goals

	Citizens	Businesses	Governmental agencies
Customers	Businesses Governmental agencies	Citizens Governmental agencies	Citizens and Businesses
Goals and decision criteria	Max quality of life/attractiveness to individuals	Profit Attractiveness to businesses Long-run value of stock	Votes Providing service to the public

A result of minimum communication among planners, decision makers, and groups affected by planning is that there is no sharing of mental models about issues and consequences. Without a shared mental model, people are unable to participate in the planning process. We refer this to the P-O perspective gap (Vo, et al., 2001) as people (P) affected by planning may view the issues differently from the planners (who take the organizational (O) perspective). In

order to close this gap, information about intended and unintended effects about planning decisions should be conveyed to the public. The mental model that the planners use to make decisions needs to build on the mental models of people affected by planning or decisions.

Some decision makers may want to formulate an urban infrastructure planning problem to identify and adopt an optimal course of action. While the objective of infrastructure planning is to find a decision that gives the best performance for the environment and socio-economic system, optimization is much more practical when applied to static systems. For a dynamic and complex system, an “optimal” condition is nearly impossible to maintain. As a decision or a policy is implemented, the status of the system will change continuously. So our purpose in this research is not to seek an optimal solution but rather sustainable decisions or strategies for infrastructure systems based on understandings of a system’s behavior.

3. The MCDM Nature of Urban Infrastructure Decisions

Infrastructure systems involve a large number of objectives. A comprehensive system of goals may include technical, economical, environmental, societal and political attributes. The choice of a specific solution is a matter of giving priorities to these attributes (Nielsen and Elle, 2000). Some attributes (e.g. environmental, societal and political) may not be directly measurable. Kelly (1998) instead proposed the use of indicators, which can allow decision makers to assess the effectiveness of any course of action in the system. Some researchers in urban planning proposed the use of quality of life as the ultimate goal for urban decision-making. We believe that the use of quality of life as an indicator would create the same effect in terms of sustainability.

In traditional urban decision-making, it is assumed that the planning authority's interest and preference represent the interests of other groups of actors in the system. This assumption may not be true as the planning authority may have goals different from those of other interest groups. For example, the planning authority may want to emphasize technical and economic goals while other groups may be more interested in the impacts of infrastructure on economic development and improvement of quality of life. We propose to separate the goals of other interest groups from those of the planning authority. Including other groups' preferences helps the planning authority see patterns in the responses from the affected groups to urban decisions. We see this as a potential benefit to planners in better understanding how unintended effects occur so that a strategy to manage these effects can be proposed.

The classical solution to a multicriteria decision is identification of weights for a set of criteria important to the decision maker(s) as well as scores of alternative performance over each criterion (Olson, 1996). The most common form of preference function is

$$Value = \sum_{i=1}^k w_i \times s_{ij}$$

where k is the number of criteria or indicators, and j represents the alternative under study. The weight w_i represents the relative importance of criterion i and the variable s_{ij} is the value of alternative j on criterion i . Every individual may have his or her own set of weights reflecting tradeoffs. A group preference function might be developed on individual group members via group discussion and negotiation if that group is homogeneous.

In MCDM literature, most often weights are assumed fixed and people's preferences are unchanged over time. Based on this assumption, alternatives are evaluated, ranked, and chosen. For short periods, preferences can be assumed unchanged as often found in MCDM literature.

Preferences are, however, dynamic and subject to changes (Nielsen and Elle, 2000; Rijsberman and van de Ven, 2000). When environmental conditions are good, for example, people tend to overlook environmental indicators. But when the environment is seriously damaged, preferences will change towards increasing weight on environmental indicators. Although some theories of decision making (DM) actually consider the changes in preference under risk and uncertainty, this consideration is still “static” as it does not take the time-dependent component into account. When preferences and weights are changeable, ranks of alternatives will change, and decisions are dynamic. So there is a need to consider changes in peoples’ preference over time in a complex and dynamic system like urban infrastructure. We refer to the inclusion of the time dimension in MCDM as dynamic MCDM. The basic idea of dynamic MCDM is to incorporate MCDM into a modeling environment such as system dynamics which is able to capture and represent the dynamics of elements (including weights and preferences).

4. System Dynamics (SD) Approach to Simulating Complex Systems

Current practices in urban infrastructure decisions are based on the concept of one-way causality, partly because the complexity of the interactions between infrastructure, society and environment is poorly understood (Rauch, 1998). For example, decisions for building more infrastructure are justified if total benefits are greater than total costs. Benefits are measured in terms of utilities for human and business activities and costs including possible damage to environment are calculated. The assumption behind these practices is that both benefits and costs are calculated separately and that the interaction between the two is ignorable (Rauch, 1998). This may not be true in most large scale systems such as urban infrastructure systems.

Some authors have used system dynamics to model sustainability of complex systems based on the understanding of the systems’ behavioral dynamics. Radzicki and Trees (1995)

combined the system dynamics modeling approach with principles of sustainable development. Choucri and Berry (1995) developed a generic model of the sustainability and diversity of development. Parayno (1996) emphasized the importance of the systems approach to properly consider dynamic factors such as population growth, the marginal productivity of land, and income distribution between farming sectors of the rural economy.

SD simulation was not designed to generate optimal solutions although some attempts to identify optimal solutions in system dynamics have been seen (Coyle, 1996). Simulation is able to describe the consequences of decisions or decision policies, based on which better decisions or policies can be made. In a way, simulation is similar to the iterative process of planning: decision, feedback, and revision (Bauer and Wegener, 1977). The next section explains how multi-criteria analysis can be combined with system dynamics modeling to develop a procedure for the dynamic MCDM approach.

5. Dynamic MCDM (DMCDM)

In a multiple actor decision environment, MCDM techniques, system dynamics (SD) simulation (Hersh, 1999; Kelly, 1998; Rauch, 1998), and conflict resolution (Timmermans and Beroggi, 2000) can effectively be employed to assist decision makers in reaching satisfactory solutions within the sustainable development concept. Factors in DMCDM include people (stakeholders and decision makers), their goals (criteria), their preferences among goals/criteria, and variables measuring indicators of interest to stakeholders. Tools used to implement DMCDM include soft system modeling (supported by cross-impact analysis, to identify stakeholder mental models), systems dynamics simulation, and tools to elicit individual preference. There are many tools available to elicit individual preference functions. The most commonly used of these tools are demonstrated in Olson (1996).

The process of DMCDM first systematically identifies the stakeholders, their goals or needs, and preference patterns. System complexity will be captured via people's mental models using cross-impact analysis (Schlange, 1995), which is supported by causal and cognitive mapping (Markoczy and Goldberg, 1995). Important causal loops (Forrester, 1961; Richardson, 1991) among variables of interest from the causal maps of the stakeholders will be identified and assessed. The result of cross-impact analysis and causal loop analysis will be translated into a SD model (Forrester, 1961; Sterman, 2000) for simulation that also incorporates peoples' preferences. It is not the purpose to build a model that exactly represents the real system. The purpose is to build a system that is seen from stakeholders' perspectives. When the SD model is available, it can be used for experiments to assess long-term impacts of different alternatives.

The Dynamic MCDM process consists of 5 steps:

Step 1: identify a problem, the stakeholders and decision makers and their perspectives about the problem.

Step 2: identify the criteria or indicators that are important to decision makers and stakeholders and develop their preference weights. This can be accomplished through a number of commonly used techniques, to include multiattribute utility analysis, analytic hierarchy process, or other approaches given in Olson (1996).

Step 3: identify relevant variables or constructs; establish relationships among variables using cross-impact analysis and causal mapping; identify significant feedback loops that drive the system's dynamic behaviors. The process of doing this is discussed in Schlange (1995) and Markoczy and Goldberg (1995).

Step 4: build a SD model that incorporates peoples' dynamic preferences. The process to do this has been developed by Forrester (1961; 1969; 1973).

Step 5: run simulations; generate and evaluate policy options or decisions.

During model development, different opinions about relationships among variables or constructs can be expected. The way we recommend resolution of these differences is to use the SD model simulations to identify expected consequences of each of the different assumptions. This may (although there is no guarantee) lead to agreement on relationships. If not, the model will have at least identified the focal point of disagreement. No model can resolve fundamental disagreements.

The dynamic nature of human preferences can be dealt with similarly. The SD models would include initial preferences, which may well change as stakeholders see relationships between their emphasized criteria and results on variables of interest. Preference functions can be modified and the impact inferred from the complex system modeled through the SD simulation.

In **Step 1**, Soft systems methodology (SSM) (Checkland, 1981) may be used to identify critical issues to the systems and stakeholder groups who may be involved with these issues. Various techniques of brainstorming and visualization can be applied (Schlange, 1995) to identify critical issues. The use of advanced information technologies such as Conklin and Begeman's (1989) gIBIS (graphic Issue Based Information Systems) to facilitate arguments and dialogues among stakeholders can improve the effectiveness of this step. Stakeholder analysis (Pouloudi, 1999; Benjamin and Levinson, 1993) may be used with SSM's root definitions to create a table that compare stakeholders' goals, worldviews, and behaviors. Banville et al (1998) distinguished standard stakeholders from silent stakeholders. The former is both affected by and

affecting the decision and also participating in the process of formulating and solving it while the latter has no control over decision or problem solving. To identify stakeholders, it is important to define the problem. However, the relationship between stakeholders and the problem is circular; the identification of stakeholders may help to identify the problem from the stakeholders' perspectives.

To identify the stakeholders' criteria and generate patterns of preference functions for **Step 2**, important criteria are identified initially. Interviews, surveys and/or group discussion combined can be used to develop a more complete set of criteria for each stakeholders group. To develop dynamic criteria or preference functions, we should consider the dynamics in the perspectives of stakeholders. To support this, a stakeholder analysis (Pouloudi, 1999; Benjamin and Levinson, 1993) is helpful. For example, Pouloudi proposes that stakeholders' views and wishes [or preferences] may change over time. We are unaware of existing literature that discusses the dynamic nature of viewpoints and preferences of stakeholders. There may be many patterns of perspective dynamics that future research may address. In this paper, we identify a pattern of preference function based on Pouloudi's (1999) proposition that states that the viewpoints and preferences of stakeholders should be dependent on the context and time (p.13). Our pattern of preference dynamics states that when a criterion is improved significantly, the weight for that criterion will decrease. For example, quality of life is a criterion of attractiveness to individuals. A dynamic preference for quality of life can be assumed as follow: when quality of life is improved significantly, the weight for quality of life in attractiveness to individuals may decrease respectively. Another example is the environmental component of quality of life. A dynamic preference for the environmental component is that when the environmental conditions [pollution] become worse significantly, the weight for this component may increase respectively.

In **Step 3**, cross-impact analysis (Schlange, 1995) is used to capture the causal relationships in the system from peoples' mental models through three tasks: (i) development of a list of factors/ constructs; (ii) selection of factors relevant to the problem of study; and (iii) assessment of the causal relationships between pairwise selected factors.

The first task - to identify a list of factors - can be accomplished using interviews supplemented by literature related to the problem under study. A factor in a causal/ cognitive map can be an abstract construct expressed as a belief by human subjects about a social phenomenon (Markoczy, 1994), e.g. attractiveness to individuals, attractiveness to businesses, quality of life, etc. A factor can also be a variable expressed as level or rate of something (Diffenbach, 1982), e.g. level of pollution, level of infrastructure, rate of immigration, etc. Schlange (1995) states that the definition of a set of system-relevant variables is an important starting point for the modeling task. In the second task, stakeholders will be asked to sort factors into two columns: relevant and irrelevant to the problem under consideration. This task is to select a final list of relevant factors. It is important to obtain a manageable sized number of clearly defined factors that best describes the system (Schlange, 1995; Markoczy and Goldberg, 1995).

The third task involves assessing causal relationships for each pair of two factors using a cross-impact analysis via a questionnaire or interview (Markoczy and Goldberg, 1995). Stakeholders will be asked three questions for each pair of factors: (i) whether there is a direct relationship between two factors; (ii) whether the influence is positive or negative; and (iii) whether the influence is weak, moderate or strong. Answers to the questionnaire can be used to draw stakeholders' causal maps. Important loops from the stakeholders' maps will be identified and assessed. Common important loops across the maps will be congregated into a composite

map (Bougon, 1992). This map can be used to see how the feedback loops may qualitatively drive the dynamic behaviors of the system. The advantage of cross-impact analysis is that it guarantees that none of the potential interrelationships between the factors is omitted (Schlange, 1995).

Typically the congregate or composite map includes many loops among factors. A loop is a series of factors connected by links of the same direction that form a closed loop in which no factor appears more than once. Two types of feedback loops are reinforcing loop (R) and balancing loop (B). An R feedback loop has an odd number of negative links while a B feedback loop has an even number of negative links (Sterman, 2000). A B loop is self-regulated in the sense that an increase in a factor in the loop after following the loop direction will lead to a decrease in that factor. Differently, an R loop behaves as a vicious cycle; an increase in a factor after following the loop direction will lead to a further increase in that factor.

The composite map in Step 3 will be translated into an SD model in **Step 4** using stock and flow concepts (Forrester, 1961; Sterman, 2000). Constructs are often converted into stocks if they accumulate. A factor as a variable can be converted into a stock if it accumulates or into a flow if it does not (Sterman, 2000). In most SD software stocks are represented by rectangles. Stocks are altered by flows. Flows are represented by valves that control pipes pointing into (adding to) or out of (subtracting from) a stock. As stocks are accumulations that characterize the state of the system and generate the information upon which decisions and actions are based (Sterman, 2000, p.192), each “main stock” can make a submodel. Note that some submodels of abstract constructs may not represent real or physical entities in real world; but they represent human perceptions of social phenomena.

In SD, decision-making of actors is modeled as decision rules based on available information cues (Sterman, 2000). Decision rules are protocols specifying how a decision maker processes the available information cues. These cues are also criteria. In an SD model, flows of information cues are continuously converted into decisions and actions (Forrester, 1961). Finally dynamic preferences of individual stakeholders identified in Step 2 will be incorporated into the SD model.

In **Step 5**, simulations can be conducted to generate policy options or decisions. The system model will automatically generate scores (or score patterns) of each alternative on each criterion. The results of the sum product of weights and scores for each alternative over all criteria will be a time-dependent curve function. The patterns of the curves can be assessed and compared according to the decision makers' policy or preferences.

6. An Example: Urban Infrastructure System for a City

In this section, we will present an application of the dynamic MCDM procedure to an urban infrastructure system for a city. Infrastructure has played an important role in economic development of the city in the past, but has started causing some negative side effects such as pollution and health problems. The city management wants to understand the impact of infrastructure on quality of life in the long term so that sustainable infrastructure decision making can be made in the future. In this example, the procedure for dynamic MCDM described in section 5 will be used. A limitation of this study is that our model was built based on 'mental data' (Forrester, 1992) provided by experts. We are confident in our model in the sense that it is able to generate sensible patterns of behaviors of the system. As the model is not empirically tested, we do not intend to use the model to generate numbers of figures for operational decision making. The model is helpful, however, in terms of a strategic intent.

Step 1: identify the actors and decision makers and their perspectives.

The issue chosen was “the impact of infrastructure on quality of life of citizens” of the city. There was a consensus among the experts participated in this study that the issue is important to the research in urban infrastructure decision making. We assume three groups of stakeholders: citizens (including residents and immigrants), businesses (including industrial businesses, service and trade businesses), and governmental agencies. In this example, governmental agencies are decision makers (or standard stakeholders) who plan and decide how infrastructure will be built. Citizens and businesses are silent stakeholders, who do not directly participate in infrastructure decision-making. They, however, passively participate in the process by responding to infrastructure decisions.

Table 2: Actors’ goals

Actors	Citizens	Businesses	Governmental agencies
Customers	Businesses and Governmental agencies	Citizens and Governmental agencies	Citizens and Businesses
Goals and decision criteria	Find the best place to live. Max quality of life (residents) or attractiveness to individuals (immigrants)	Find the best place to do business with. Max attractiveness to businesses	Build the best city infrastructure to attract business and individuals. Max quality of life and attractiveness to businesses
Behaviors	Immigrants will move in if attractiveness to individuals increases. Residents will move out if quality of life degrades.	Businesses will move in or expand if attractiveness to businesses increases.	Plans, build and maintain infrastructure
Activity	Work for businesses Receive service and utilities provided by governmental agencies Pay fees and taxes to	Look for labor and infrastructure and market. Receive service and utilities provided by governmental agencies	Collect fees and taxes to maintain infrastructure performance and environmental conditions.

	governmental agencies	Pay fees and taxes to governmental agencies	
Environmental Constraints	Housing, school, transportation (mobility) and other basic utilities such as sewage and water supply.	Transportation (mobility), pollution control, tax, labor	Fund available is not enough for continuous development. Land is limited.

As summarized in Table 2, each group of actors pursues a different goal that guides their behavior within the system. The goal of citizens is to find the best place to live and to work. The goal of business is to find the best place to locate. The goal of governmental agencies is to build the city with the best infrastructure to attract people and businesses. Based on these goals, behaviors of actors can be anticipated. As three groups of stakeholders were identified, three preference functions were expected. Criteria for these functions are discussed in the next step.

Step 2: Identify the criteria or indicators that are important to decision makers and stakeholders and develop their preference weights.

In this step, we develop main criteria and indicators for each group based on the analysis in the previous step. Attractiveness to individuals (for immigration) and quality of life (for residents) are important criteria for the citizen group. An increase in *attractiveness to individuals* will result in more *immigration* into the city. *Attractiveness to individuals* is defined on a number of socioeconomic factors such as *jobs*, *quality of life*, *congestion* or *mobility*, and *utilities*. A decrease in *quality of life* will lead to some residents moving out of the city. In our study, *quality of life* consists of economic component (*jobs* and *cost of living*), environmental component (*pollution*), and transportation and utilities component (*mobility* and *utilities*)¹. *Attractiveness to*

¹ It is difficult to adopt an existing definition for quality of life and its components from the related literature. Researchers agree that quality of life is a multidimensional concept that is based on a set of variables and a weighting scheme but no studies have the same attribute set Ulenin, B.; Ulenin, F. and Guvenc, U. (2001), "A

businesses is a composite index that determines business growth. An increase in *attractiveness to businesses* will result in an increase of business units, which in turn will create more *jobs* for residents. Attractiveness to businesses is determined by *labor* availability, transportation condition (*mobility*), *utilities* and *quality of life*. Governmental agencies are assumed to use a combination of *quality of life* and *attractiveness to businesses* as a criterion for decision making.

In our weighting scheme, the economic component is assumed most important. This is consistent with the related literature. For example, Long (1985) found that jobs-related reasons are most important for migration; and Ulengin et. al. (2001) found that opportunity of finding a satisfactory job is the most important attribute in quality of life. We assume that environmental criteria are least important. This assumption is made on the belief that when environment is in good shape, citizens give little attention to environmental conditions. However, we also believe that this preference may change when environmental conditions become serious problems, in which case, people may increase weight on the environment component. This is referred to dynamic preference. How dynamic preference can be modeled in SD is presented in step 4. In step 5, we want to see whether this assumption may have an impact on alternative ranking.

Table 3: preferences by groups

	Citizens	Businesses	Governmental agencies
Criteria	Immigrants: - Jobs - Cost of living - Quality of life Residents - Jobs - Pollution	- Mobility and utilities - Quality of life - Labor	- Quality of life - Attractiveness to businesses

multidimensional approach to urban quality of life: The case of Istanbul," *European Journal of Operational Research*, **130**(2001), 361-374..

	- Mobility - Utilities		
Preference	Economic is most important (Long, 1985; Ulengin et al., 2001) Environmental criterion is least important	Labor (economic) is most important. Mobility is important as quality of life. Utilities are least important.	Quality of life is more important than attractiveness to business
Dynamic preference	Initially economic is most important and environmental is least important. When environment becomes seriously polluted, environmental criteria become more important		

Step 3: Represent the complex relationships in urban infrastructure using cross-impact analysis and causal mapping.

We followed the procedure presented in section 5 to build a composite cognitive map of the system. We had five stakeholders, who were involved in developing a conceptual framework² for the city’s infrastructure decision making develop a composite map. Based on the interview transcripts³ and related literature (Forrester, 1969; Lee, 1995), we developed a list of 16 factors or constructs: *Attractiveness to Individuals, Business Climate or Attractiveness to Businesses, Business Growth, Cost of Living, Housing Price, Immigration, Infrastructure, Jobs, Labor, Pollution, Pollution Control, Population, Property Values, Quality of Life, Tax Income, and Transport Congestion*. The stakeholders were asked to select factors that are relevant to the problem of study and assess possible causal relationships between pairwise selected factors. The purpose was to gather information that would enable us to draw a causal diagram that shows how

² This framework and a prototype of sustainable decision support systems were developed to improve policy planning and decision making regarding urban infrastructure investments such as investments in roads and bridges, fresh water supply systems, waste water treatment, drainage and so forth.

³ These interviews were made by the stakeholders and other researchers with people who are involved with the city’s infrastructure management

stakeholders believed infrastructure resource allocation affects the city. This map is given in Figure 1, which includes loops among factors.

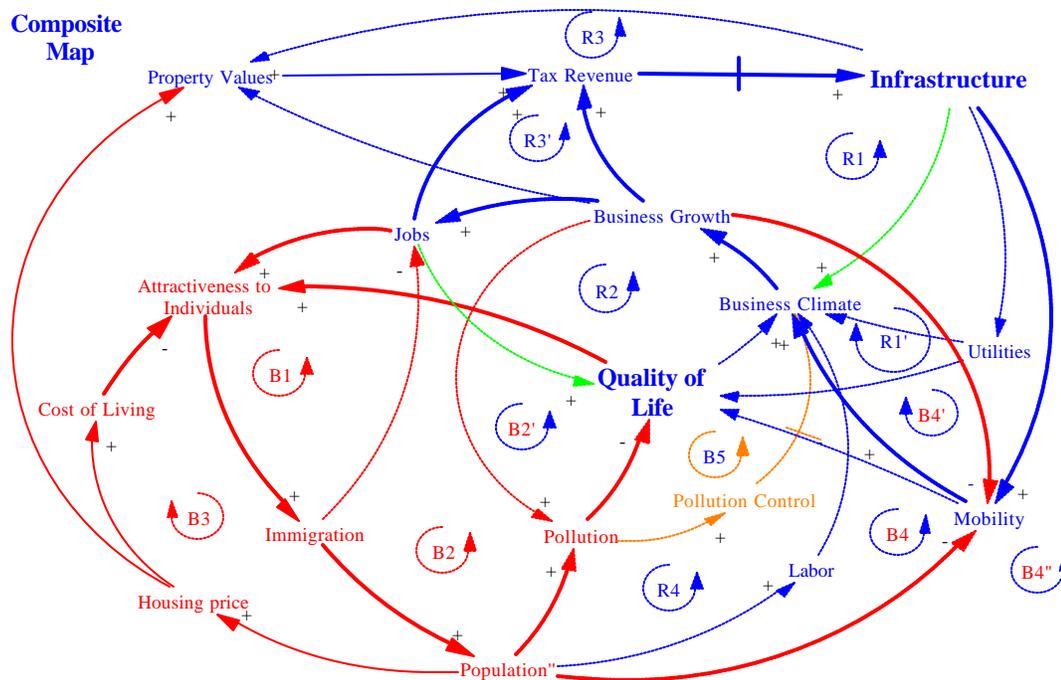


Figure 1. The Composite Map of the System

Notes on the use of colors and symbols: Blue indicates intended effects while others (red and orange) indicate unintended (side) effects. Green indicates indirect links. B indicates a balancing (negative) loop while R indicates a reinforcing (positive) loop.

Notes on feedback loops

R1: business growth, tax revenue, infrastructure, mobility, attractiveness to businesses.

R1': business growth, tax revenue, infrastructure, mobility, utilities, quality of life, attractiveness to businesses.

R2: attractiveness to businesses, business growth, jobs, quality of life.

R3: infrastructure, property values, tax revenue.

R3': infrastructure, mobility, attractiveness to businesses, business growth, property values, tax revenue.

R4: attractiveness to businesses, business growth, attractiveness to individuals, immigration, population, labor.

B1: attractiveness to individuals, immigration, jobs.

B2: attractiveness to individuals, immigration, population, pollution, quality of life.

B2': *attractiveness to businesses, business growth, pollution, and quality of life.*

B3: *attractiveness to individuals, immigration, population, housing price, cost of living.*

B4: *attractiveness to individuals, immigration, population, mobility, quality of life.*

B4': *attractiveness to businesses, business growth, mobility.*

B4'': *attractiveness to individuals, immigration, population, mobility, attractiveness to businesses, business growth, jobs, quality of life.*

The result is that every stakeholder came up with his own causal map. These maps were analyzed to find the common beliefs. Every map has some unique knowledge, but in this study, we were interested in the common knowledge across the stakeholders' mental models. In building the composite map, we used the congregate concept (Bougon, 1992), instead of the aggregate methods widely used in the literature (Lee et al., 1992; Eden, 1989; Kwahk and Kim, 1999). In the former, the composite map is built on common loops whereas in the latter the composite map is built on common labels (Bougon, 1992). We focused on feedback loops, because in system dynamics, feedback loops are critical drivers of the dynamic behaviors of the system (Forrester, 1961; 1971). As a result, the composite cognitive map of the system is shown in Figure 1.

A feedback loop can be interpreted just by following the causal links. R1, for example, can be interpreted as the following: An increase in *business growth* will increase *tax revenue*, which will increase the ability to build more *infrastructure*, which will increase *mobility*, which will increase *attractiveness to businesses*, which will increase business growth. In a complex composite map like this, there exist hundreds of possible feedback loops. Most system dynamics software can automatically identify these loops. The loops noted on the composite map are believed to have significant impacts on the system behaviors. Some of the loops may seem similar and overlapping; this is because loops are often "nested," with smaller loops included in larger ones.

The composite map can be interpreted as following: Infrastructure is built to accommodate businesses and citizens (**R1** and **R1'**) who will boost economic growth and development, which contributes to income and tax revenue that will feed back to infrastructure building. Business growth and quality of life reinforces one another (**R2**). This intended effect is strong at early stages of infrastructure development. Infrastructure growth, however, will be limited due to its unintended effects (overcrowding as shown in **R4**, **B1**, **B4** and **B4'**, high cost of living as shown in **B3**, pollution/ health as shown in **B2** and **B2'**) and natural resources constraints (such as land, not indicated on this map).

Step 4: build an SD model

When the composite map was converted into an SD model, most constructs were converted into stocks. Quality of life, attractiveness to individuals, and attractiveness to businesses, for example, were converted into three different stocks. Most factors (or variables) such as population, infrastructure, businesses, etc. were converted into stocks. Migration (immigration or emigration) was the only example factor that was converted into flows because it does not accumulate over time. Immigration is a flow adding to the population stock. As a result, we had fourteen 'main stocks' in our SD model.

In our SD model, decision-making of the citizen and business groups was modeled as decision rules based on their information cues (Sterman, 2000) or criteria. For example as identified in Table 3, the information cues for immigrants are jobs, cost of living and quality of life and their decision is whether to immigrate or not. A change in any of these cues will have an impact on *attractiveness to individuals* that lead to immigrants' decisions. So *attractiveness to individuals* represents the decision rule of immigrants. Similarly, *attractiveness to businesses* represents the decision rule for businesses. For the citizen and business groups, decisions are

made automatically in the SD model based on their decision rules. For governmental agencies, information cues for decision making are *quality of life* and *attractiveness to businesses*; and their criterion (or objective) is to maximize *quality of business-life*. For the governmental agency group, decisions are not made automatically based on a decision rule. This group makes decision by making a series of changes (or a pattern of decisions) on the flow into the infrastructure stock. The pattern of decisions can be represented in a graph (see Figure 4a, for samples), which can be plugged into the SD model for simulation. The interactions of decisions between three groups are represented in the composite map (Figure 1) above.

The overall model system consists of 14 submodels, which include: 1) population (and migration), 2) businesses, 3) quality of life, 4) pollution, 5) attractiveness to businesses, 6) attractiveness to individuals, 7) Jobs, 8) pollution, 9) cost of living, 10) mobility, 11) road capacity, 12) utilities, 13) utilities capacity, and 14) tax revenue. Figure 1 (the composite cognitive map) shows the structural interrelationships among submodels. A brief description of each submodel will be provided next. Submodels for population, attractiveness to individuals, and quality of life are given in Figure 2 for illustration.

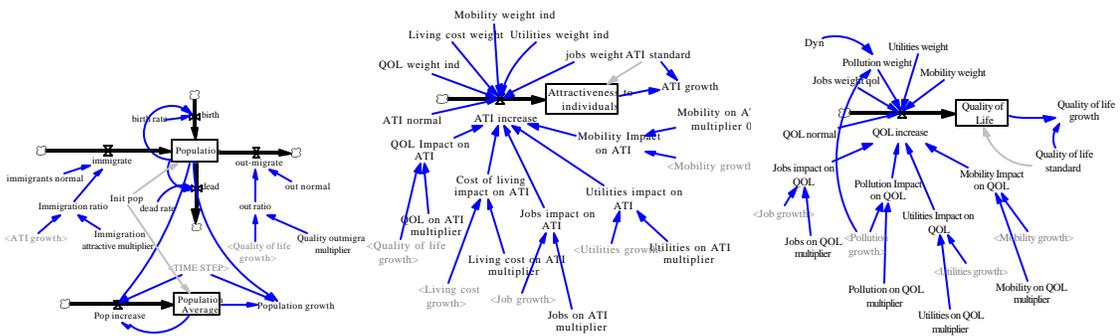


Figure 2. Population, attractiveness-to-individual and quality of life submodels

In the population submodel, *immigration* is an inflow that adds to the *population* stock. *Immigration* depends on *attractiveness to individuals (ATI)*, which is defined as a weighted

average of *jobs*, *quality of life*, *mobility*, and *utilities*. The weighting scheme for ATI is set such that jobs or economic factor is most important, *quality of life* is important, and *mobility* and *utilities* are equally less important. A similar definition of attractive factors to immigration is found in the literature (Lee, 1995). While *attractiveness to individuals* is applied to immigrants, *quality of life* is applied to current residents. In the quality of life submodel, quality of life is defined as a weighted average of jobs, mobility, pollution, and utilities. The weighting scheme for quality of life is set such that job is most important; pollution is least important; mobility and utilities are in between. In the businesses-jobs submodels, we divided businesses into three groups: industrial/manufacturing, service, and trade. Business growth is influenced by *attractiveness to businesses (ATB)*, which in turn depend on regional economic growth (constant), *quality of life*, *labor availability*, *mobility*, *utilities*, and *pollution control*. Service businesses and trade businesses depend mainly on *ATB* and *population*. Infrastructure is divided into two submodels: road capacity and *utilities* (including sewage, solid waste and water supply). *Mobility* is defined as a ratio of road capacity over population and businesses. In the pollution submodel, sources of pollution are population, industrial businesses, road and utilities. We adopted the absorption component for pollution from Forrester's world dynamics model (Forrester, 1973). In the cost of living and property values submodels, cost of living and property values are dependent on only population growth. In the tax revenue submodel, tax revenue depends on jobs, business growth and property values. These models are input into VENSIM software for simulation. (VENSIM is an interactive software environment that allows the development, exploration, analysis, optimization, and packaging of simulation models (Eberlein and Peterson, 1994); a free copy of VENSIM can be obtained from <http://www.vensim.com/>; for details how to model with VENSIM the reader is referred to Eberlein and Peterson, 1992).

Initially, the static weighting scheme as identified in Step 3 was input into the SD model for simulating the base case and some alternatives. When dynamics of preference function is considered, the dynamic weight of the environmental component is dependant on the pollution growth. In the SD model (see Figure 2 above, the quality of life submodel), this was done by setting a link from *pollution growth* to the environmental or *pollution weight* in such a way that an increase in pollution growth would lead to an increase in the environmental weight. As a result, the weight of the environmental component changed over time depending on the pollution growth. A sample of the weight curve is provided in Figure 5 below.

Step 5: do simulations and generate policy options or decisions.

We first run the model for the base case (as usual) for individuals and businesses and obtained the model outputs as in Figure 3. As shown, attractiveness to individuals and quality of life would decrease while attractiveness to businesses would increase over time. When we have confidence in the model, we use the model to do experimentation and to test policy alternatives.

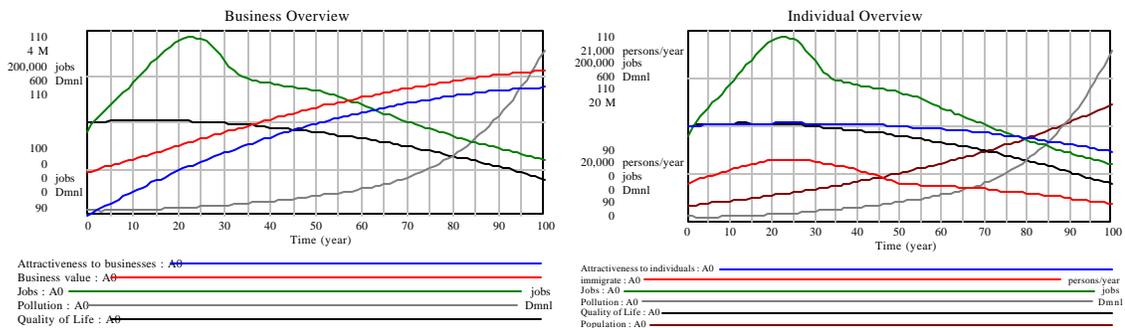


Figure 3. Business and Individual overview (base case).

The first experiment was to use the simulation model to assess the impact of dynamic MCDM on alternative ranking. We considered three alternatives: A0, A1, and A2 as shown on Figure 4a. A0 is a “doing nothing” or “as usual” alternative. A1 and A2 are alternatives that

invest in roads to improve mobility but follow different patterns. A1 is done in a short period (10 years) at a high rate while A2 is carried out over 50 years at a lower rate. A1 and A2 are supposed to have the same effect in terms of increasing road capacity and mobility. Also it is expected that A1 and A2 will improve attractiveness to businesses and quality of life over A0. For governmental agencies, the system performance is measured by a composite index called *quality of business-life*, which is a combination of weighted *quality of life* and *attractiveness to businesses*⁴.

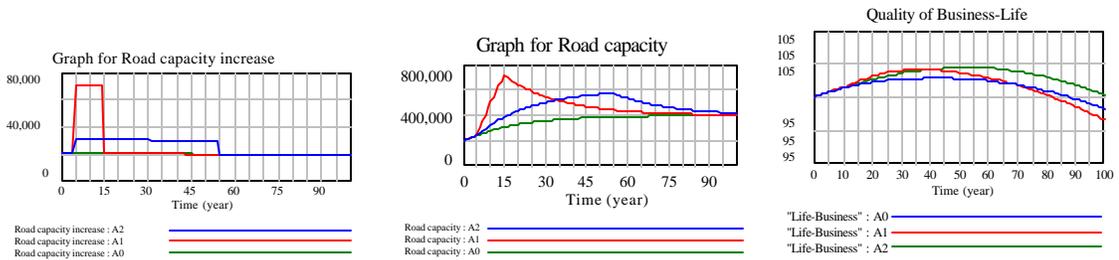


Figure 4. a) Three alternatives, b) their impacts on road capacity and c) their impacts on quality of business-life.

The simulation outputs (Figure 4c) indicate that investments in infrastructure (A1 and A2) would bring better quality of life and business climate. Fast growth in infrastructure (A1), however, may cause an adverse effect in the system performance in the long run. This is consistent to what Forrester (1971) described as counter-intuitive behaviors of social complex systems⁵: complex systems often react to a policy change in the long run in the opposite to the way that they react in the short run.

Table 4. Summary of ranking changes

⁴ Quality of life is assumed more important than attractiveness to businesses.

⁵ As reviewed in section 2, he further claims that complex social systems tend toward poor performance. We think that this statement may be true under an assumption that actors in complex systems follow short-term improvement strategies.

Term	Time horizon	Ranking
Short	Less than 40 years	A1 > A2 > A0
Medium	Less than 70 years	A2 > A1 > A0
Long	More than 70 years	A2 > A0 > A1

The simulation result (Figure 4c) also shows that dynamic MCDM would have an impact on alternative ranking over time. There are two points in time that ranking (measured by quality of business-life index) got changed: 40 and 70 years. Specifically, for a “short” term (40 years), ranking is: alternative 1 > alternative 2 > alternative 0; for a “medium” term (70 years) ranking is: alternative 2 > alternative 1 > alternative 0; and for a “long” term (beyond 70 years), ranking is: alternative 2 > alternative 0 > alternative 1. A summary is given in Table 4. For sustainability, alternative 2 is the best. However, as this alternative only becomes superior after quite a long time (40 years), practical decision makers may not be “patient” enough to be interested in this alternative. In practice, alternatives with short term emphasis like A1 may be adopted, as they show immediate effects. From the sustainable perspective, alternative 1 is even worse than the “doing nothing” alternative. An implication is that too fast growth may show significant short-term improvement but will cause side (unintended) effects in the long run, which are not sustainable.

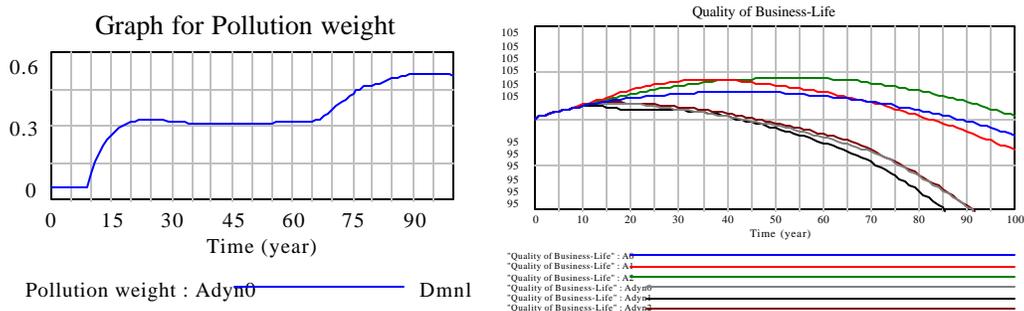


Figure 5. Impact of dynamic preference on alternative ranking

The second experiment was to investigate the impact of the dynamic preference assumption on alternative ranking. In this experiment, the pollution weight in quality of life submodel depends on the pollution level so that it will increase when pollution level grows. The simulation output (Figure 5) shows that the dynamic preference assumption dissolves the change in alternative ranking over time. So alternative ranking is consistent as it is in the long run.

7. Summary and conclusions

MCDM and SD have been used widely in many large scale systems. Traditional MCDM fails to handle different delays in economic, social, economic and technical effects of large scale systems, which can be handled appropriately using SD modeling. A procedure for incorporating MCDM into SD modeling, however, has not been fully developed in the literature although some authors have proposed that a combination of MCDM and SD would be a good tool for studying actors-involved complex systems. In this paper, we propose an incorporation of MCDM into system dynamics simulation to handle dynamic MCDM situations. The procedure consists of five steps: 1) identify a problem, the stakeholders and decision makers and their perspectives about the problem, 2) identify the criteria or indicators that are important to decision makers and stakeholders and develop their preference weights, 3) identify relevant variables or constructs; establish relationships among variables using cross-impact analysis and causal mapping; identify significant feedback loops that drive the system's dynamic behaviors, 4) build a SD model that incorporates peoples' dynamic preferences, and 5) run simulations; generate and evaluate policy options or decisions.

A case of urban infrastructure is presented for illustration of the procedure. First, three groups of actors were identified and their perspectives are discussed. Their goals and preference

were analyzed to anticipate their behaviors in the system. A composite cognitive map was built on the mental models of people who have good knowledge of the system. A system dynamics model was built on the composite cognitive map, incorporating preferences of three groups of actors. As soon as confidence in the model was gained, two experiments were conducted. The first experiment investigated the impact of different patterns of development on alternative ranking whereas the second experiment investigated the impact of dynamic preference on alternative ranking. In the first experiment, we found that the fast growth alternative shows best performance in the short run but worst in the long run whereas the steady growth alternative shows best performance in the long term. In the second experiment, we found that when dynamic preference is considered, dynamic ranking is eliminated. Alternatives under dynamic preferences are consistently ranked as in the long run.

Practical decision makers may be overly attracted to alternatives that improve the system performance in the short run. We recommend simulation modeling incorporating MCDM be a potential tool for sustainable decision making, particularly in infrastructure systems. With the help of dynamic MCDM modeling, decision makers may avoid selecting short term alternatives. The use of dynamic preference modeling may also have potential for decision making in dynamic systems, as it can show consistent ranking as in the long run. We believe that dynamic MCDM together with dynamic preference will be a powerful tool for decision making in dynamic environments.

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