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Dealing with Complexities and Uncertainties in a System-of-Systems: Case Studies on Urban Systems

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Abstract

Dealing with complexities and uncertainties in the design and planning of human-engineered systems such as urban systems is crucial. When the stakes are so high and consequences of alternative actions are so uncertain, a systematic consideration of complexities and uncertainties is warranted. This chapter describes a system-of-systems (SoS) framework to represent the interdependencies and dynamics among human and engineered systems. The framework comprises a set of tools including network theory, system dynamics, and exploratory modeling and analysis. Based on the framework, three case studies are presented. The first case analyzes urban systems' vulnerabilities to climate change using the context of the 2004 hurricane in South Florida, USA. The second case is a comparison of the performance of two design options for natural-gas powered electricity power plant. The third case is a system analysis for supporting an economic revival in the US Midwest City. The applications reveal information about (1) critical infrastructure nodes, (2) robustness of decisions under uncertainty, and (3) dynamics relevant to support decision-making.

Keywords: urban systems' vulnerabilities, urban economic revival, infrastructure investment decision, robust performance, failure modes

1. Introduction

Urban systems are increasingly under strain as about 54% of the world's populations currently are city inhabitants [1]. A growing trend of population growth and urbanization will increase this proportion to 66% by 2050. In urban systems, infrastructures constitute the physical framework within which our economy and society operate [2]. Disruptions in infrastructure, therefore, pose considerable threats to some of the very pillars of modern life. Infrastructures

including energy, food, water, transportation, manufacturing, and telecommunications are key components in enabling modern society to function.

From a conceptual point of view, urban infrastructure can be considered as a couple human-engineered system. An engineered system (ES) is *a combination of technological components that work in synergy to collectively perform a useful function* [3].

Recent structural changes, such as deregulation in the energy sector, have revealed infrastructure's vulnerabilities. Public dissatisfactions began to surface as the lack of capacity, reliability, and vulnerability of such provisions become increasingly prevalent causing politicians to take serious considerations. At the same time, many infrastructures have appeared to be inert to change because these infrastructures have long technical life time and are deeply interwoven in our social, economic, and political structure. Lack of systematic knowledge in addressing uncertainties may contribute to ad hoc political decisions, which may block timely adaptation and discourage further investment in the infrastructure system [4].

A system-of-systems (SoS) perspective is an attempt to structure the complexity of human-engineered systems by taking a broader view than just the physical design (i.e., traditional system engineering view) and operational aspect, to include commercial and financial, economic, social, and policy aspects couched within multiple levels. The goal is to improve analysis for decision-making.

A system-of-systems (SoS) consists of multiple, heterogeneous, distributed systems embedded in networks at multiple levels that evolve over time. Complexity in an SoS stems primarily from the heterogeneity of its constituent systems, the distributed nature of these systems. The complexity brought by the system heterogeneity exists both within a domain (e.g., power generation) and across domains (e.g., power generation, energy service economics, and governmental policy/regulation).

The chapter first describes a generic SoS conceptual model that characterizes the interdependencies among SoS constituents. Next, a model of uncertainty space evolution over time is presented. Three case studies are then presented to illustrate the framework. In the last section, the added values of SoS framework are discussed.

2. Conceptual model

2.1. Characterization of SoS interdependencies

An SoS consists of constituent systems that include individual engineered and actor system (**Figure 1**). An engineered system (ES) represents the performance and capabilities of relevant physical/technological systems. An actor system (AS) represents the development and operation of resources by an actor and, possibly, the management of other actor behavior residing either horizontally at the same SoS level or vertically across level.

The model is described using system model elements that are central to the policy analysis approach [5]. Policies (P) are the set of instruments within the control of the decision makers

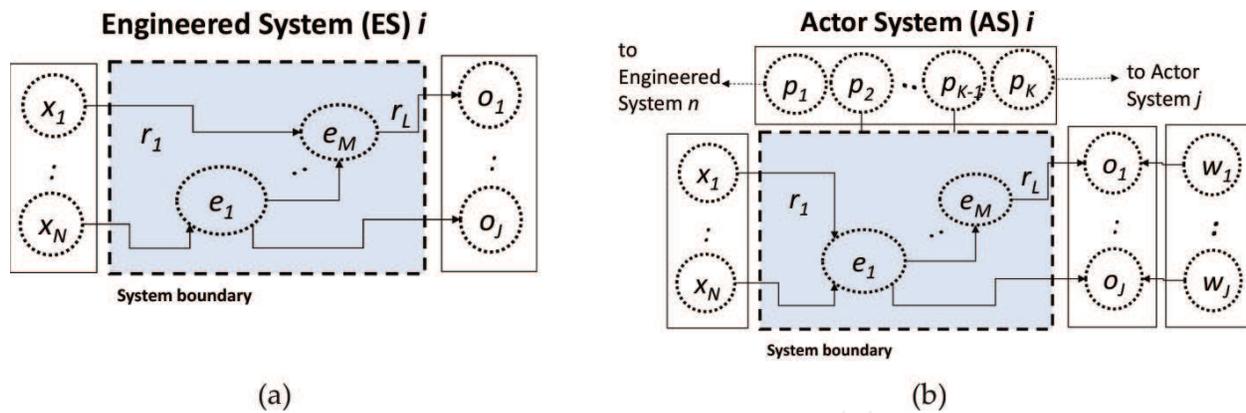


Figure 1. System-of-systems constituents: (a) engineered system and (b) actor system.

that can change the system. External forces (X) refer to factors that are not controllable by the decision maker but may influence the system significantly. The structure of an actor system can be specified as a set of endogenous factors (I) together with relationships (R), which may include functional, behavioral, or causal ones. The results of these interactions, the model outputs, are called outcomes of interest (O). The value systems (W) of decision makers and stakeholders reflect their goals and preferences. Notice that an engineered system is devoid of policy instruments and has no value systems.

An SoS of urban systems can then be constructed via assemblage of some ES and AS systems in a structure resembling the nested system in **Figure 2**. Each element represents an ES, which resides at the lowest level (α level) and an AS, which resides at the β level and above.

Based on the framework, several terms can be defined:

- A scenario is a single realization of one set of external forces (X).
- System structure is the configuration of E and R.
- Uncertainty space, S covers the entire scenarios, system structure, and value systems ($XERW$).

The different types of interdependencies within an SoS are given in **Table 1**. The system model variables in an SoS interact with one another, creating a network of interrelationships. These interdependencies are bidirectional. In one direction, the interdependency can manifest in a form of influence.

2.2. Dealing with uncertainties in a system-of-systems

To deal with uncertainties in a system-of-systems, a computational approach called exploratory modeling and analysis (EMA) has been proposed [6, 7]. EMA is founded on the idea of exploring multiple hypotheses about the SoS of interest by varying the assumptions underlying the system model. EMA is used to explore the implications of multiple hypotheses about the system by means of computational experiments. A computational experiment is a single computer run of the system model using one set of assumptions.

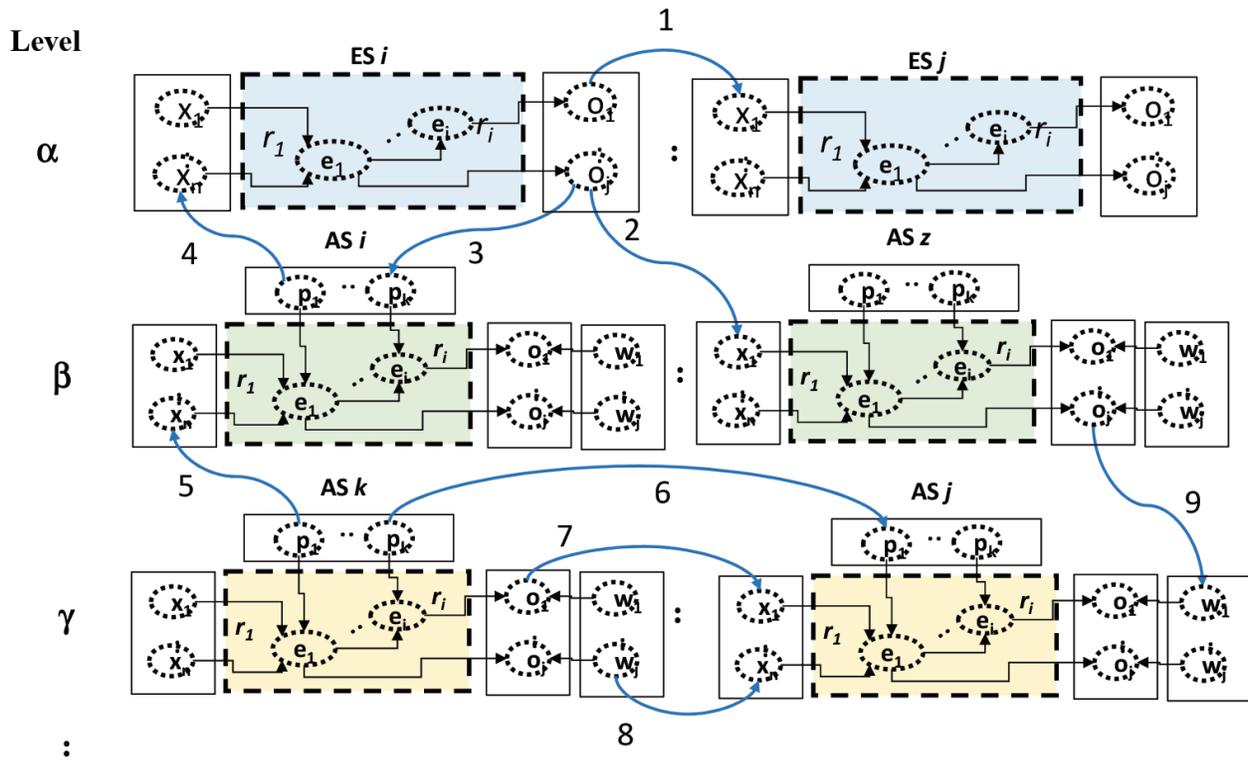


Figure 2. A system-of-systems consisting of engineered (ES) and actor systems (AS).

Linkage of interdependencies	Formalism
An outcome of an ES is an external factor for another ES	$\mathbf{o}_{ES i} = \mathbf{x}_{ES j(i \neq j)}$
An outcome of an ES is an external factor for an AS	$\mathbf{o}_{ES i} = \mathbf{x}_{AS i}$
An outcome of an ES influences actor decision	$\mathbf{p}_{AS i} = f(\mathbf{o}_{ES i})$
An actor's decision is an external factor for an ES	$\mathbf{p}_{AS i} = \mathbf{x}_{ES i}$
An actor's decision is an external factor for another actor	$\mathbf{p}_{AS i} = \mathbf{x}_{AS j(i \neq j)}$
An actor's decision influences another actor's decision	$\mathbf{p}_{AS i} = f(\mathbf{p}_{AS j(i \neq j)})$
The realization of an outcome of interest of an actor affects the decision of another actor	$\mathbf{p}_{AS i} = f(\mathbf{o}_{AS j(i \neq j)})$
A value system of one actor becomes an exogenous factor of another	$\mathbf{x}_{AS i} = \mathbf{w}_{AS j(i \neq j)}$
The outcomes of one actor system affect the value system of another actor	$\mathbf{w}_{AS i} = f(\mathbf{o}_{AS j(i \neq j)})$

Table 1. Interdependencies among SoS elements.

2.2.1. Characterization of the evolution of SoS uncertainty space over time

Figure 3 shows an ‘uncertainty space funnel’ that models how the future realizations of the model variables will unfold in a time horizon of n periods. In a future of multiple discrete time periods, one unique realization in the first period leads to multiple possible realizations

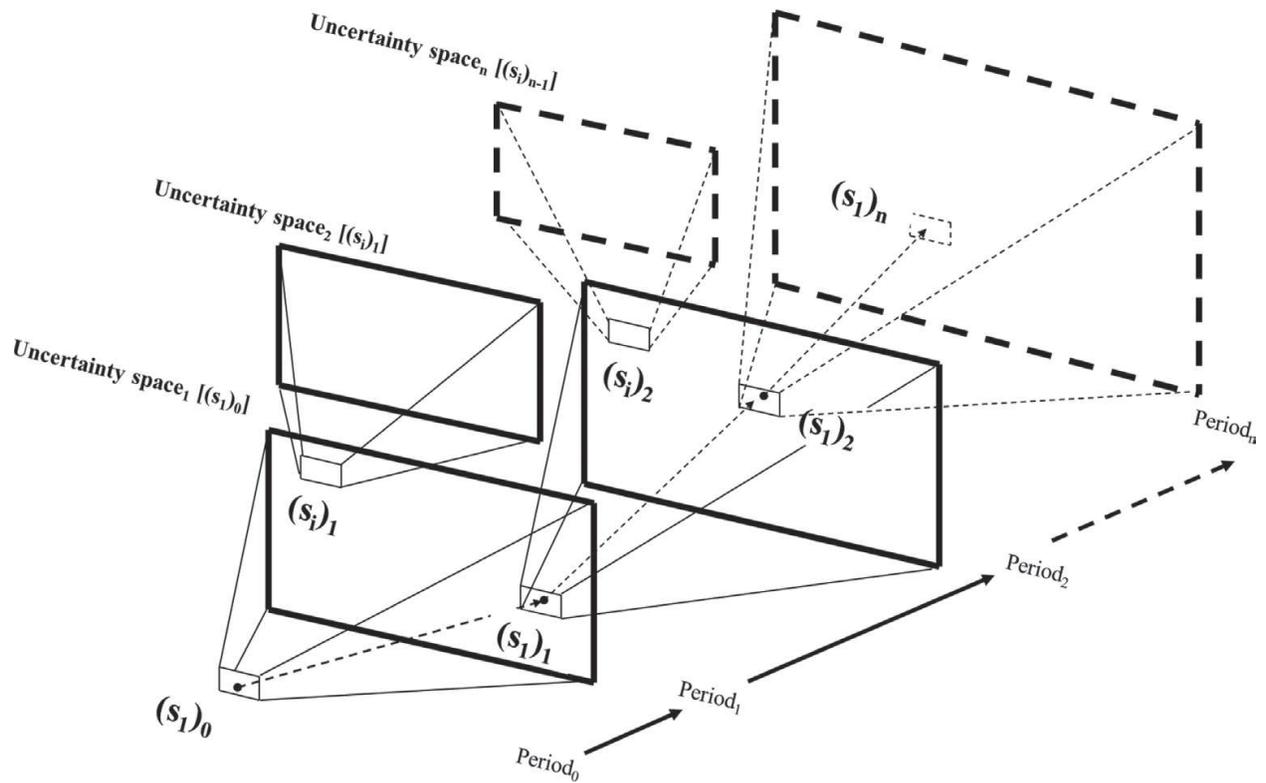


Figure 3. The evolution of SoS uncertainty space.

in the second period, each of which will then lead to multiple possible realizations in the third period, and so on until the last period is reached.

Uncertainty spaces at one particular period can be modeled in different ways. For example, the *uncertainty space₁ [(s₁)₁]* and the *uncertainty space₂ [(s₂)₁]* can have exactly the same nature (i.e., the *X*, *E*, *R*, and *W* elements) and the same size (i.e., the choice of range of the *X*, *E*, *R*, and *W* elements). When a structural change occurs, however, the nature and size of one uncertainty space may be totally different with the other.

Three main characteristics of SoS uncertainty space are described as follows:

1. The degree and scope of uncertainty increases as the time period progresses. This is a default characteristics since the longer the time span the greater the uncertainty.
2. The degree and scope of uncertainty actually decreases as time progresses. This occurs, for example, in case the threshold market share of a certain technology is reached, which reduces the range of the share of other technologies (i.e., *lock-in effect*).
3. The nature of the uncertainty space in one period is different from that in the subsequent period, which may also depend on the realization preceding it. For example, when a structural change (*I*, *R*) occurs, some of the variables become irrelevant and new ones need to be added. Also, the value system of decision makers and stakeholders may change over time. Future decision makers may have different decision criteria or put different weights on the criteria.

This way of characterizing SoS uncertainty space highlights its path dependency nature. Suppose that $(s_1)_0$ is the realization of the uncertainty space in period₀ (i.e., the initial condition). In period₁, the uncertainty space that is path dependent on the initial condition $(s_1)_0$ is the uncertainty space₁ $[(s_1)_0]$. The evolution of uncertainty space progresses over time until the end of analysis' time horizon, *Period_n*. In *Period_n*, there will be a set of uncertainty spaces, each originated from the realizations of all the preceding periods (i.e., uncertainty space₁ $[(s_1)_{n-1}]$, ..., $[(s_1)_2]$, $[(s_1)_1]$, $[(s_1)_0]$). One future path (illustrated by the dashed arrows), for example, can be represented by $(s_1)_0 \rightarrow (s_1)_1 \rightarrow (s_1)_2 \dots \rightarrow (s_1)_n$.

3. Case study 1: vulnerabilities of urban systems

An urban system is a complex system comprising an infrastructure-actor network, whose complexity is confounded by their close physical proximity and functional interdependencies. An understanding of its complexities can support policymakers to maintain quality of life amidst perturbations, growth and decay, discontinuities, and stress in the system. Building upon [8], we aim to establish the level of influence and vulnerability of a network of multiple infrastructure-actor networks in urban systems.

3.1. A typology of urban system complexities

An overall urban system comprises several individual systems such as energy, water, telecommunication, and transportation. We develop a typology for classifying different types of system interdependency (**Figure 4**), which is based on (1) whether the network accounts for the connectivity within an individual system (i.e., intrasystem) or across systems (i.e., inter-system) and (2) whether the context of such connectivity takes place in an emergency condition (i.e., with drastic service discontinuities) or in a non-emergency one.

To a certain extent, each of the resulting quadrants has a different focus of inquiry and hence policy implications in terms of actors' actions and coordination. For instance, the first quadrant (Q1) focuses on connectivity within a single sector (e.g., transportation) in a non-emergency condition. An example of inquiry in this sector may revolve around the issue of reducing traffic congestion. By contrast, in the third quadrant (Q3), the inquiry considers interdependencies among multiple sectors (e.g., a city as a whole) and addresses broader issues (e.g., impacts of extreme weather events). In this chapter, we focus on the fourth quadrant.

3.2. Network theory perspective and the network model

Network theory is employed to obtain measures that can illuminate the degree of infrastructure influence and vulnerability within an urban system. We consider a particular infrastructure as a node. A directional link between two nodes means that the failure in the source affects the end node. This formulation implies that fewer links among nodes are actually desirable. We use and interpret sample data from [9] to model the (inter)dependencies among infrastructure and the repair team for the urban systems in Florida during the 2004 hurricane season. The resulting network model of infrastructure-actor connectivity is depicted in **Figure 5**. To generate some network measures, we employ the UCINET software [10].

Inter-System Connectivity	[Q3]  e.g., how a city can adapt to climate change	[Q4]  e.g., how to maintain a minimal critical service when a disaster strikes a city
	[Q1]  e.g., how to reduce road traffic congestion	[Q2]  e.g., how to prevent a cascading failure in an electricity network
Intra-System Connectivity	Non-critical/emergency Condition	Critical/emergency Condition

Figure 4. A typology of urban system complexities.

3.3. Results and implications

A summary of the network measures is given in **Table 2**. Each of the measures and its implication is described later.

3.3.1. Centrality degree

It counts the number of outgoing (i.e., influence) and incoming (i.e., dependence) links. For the case study, road infrastructure exerts the most influence to others, whereas (waste) water plant and electricity transmission receive most influence from others and hence are most vulnerable. This insight can inform prioritizing infrastructures that need to be decoupled from other.

3.3.2. Betweenness centrality

This measures node importance in terms of its role as an ‘intermediary’ in a failure path. The electricity plan appears to play the most dominant role. Consequently, urban system needs to be disconnected with electricity plant by, for example, having own backup power.

3.3.3. Eigen-vector centrality

It measures the importance of an infrastructure not only by the number of nodes it affects but also the importance of the nodes to which it affects. It appears that the supervisory control

and data acquisition (SCADA) system is the infrastructure with the highest score because it affects three very important nodes such as electricity transmission, electricity plant, and phone/Internet infrastructure.

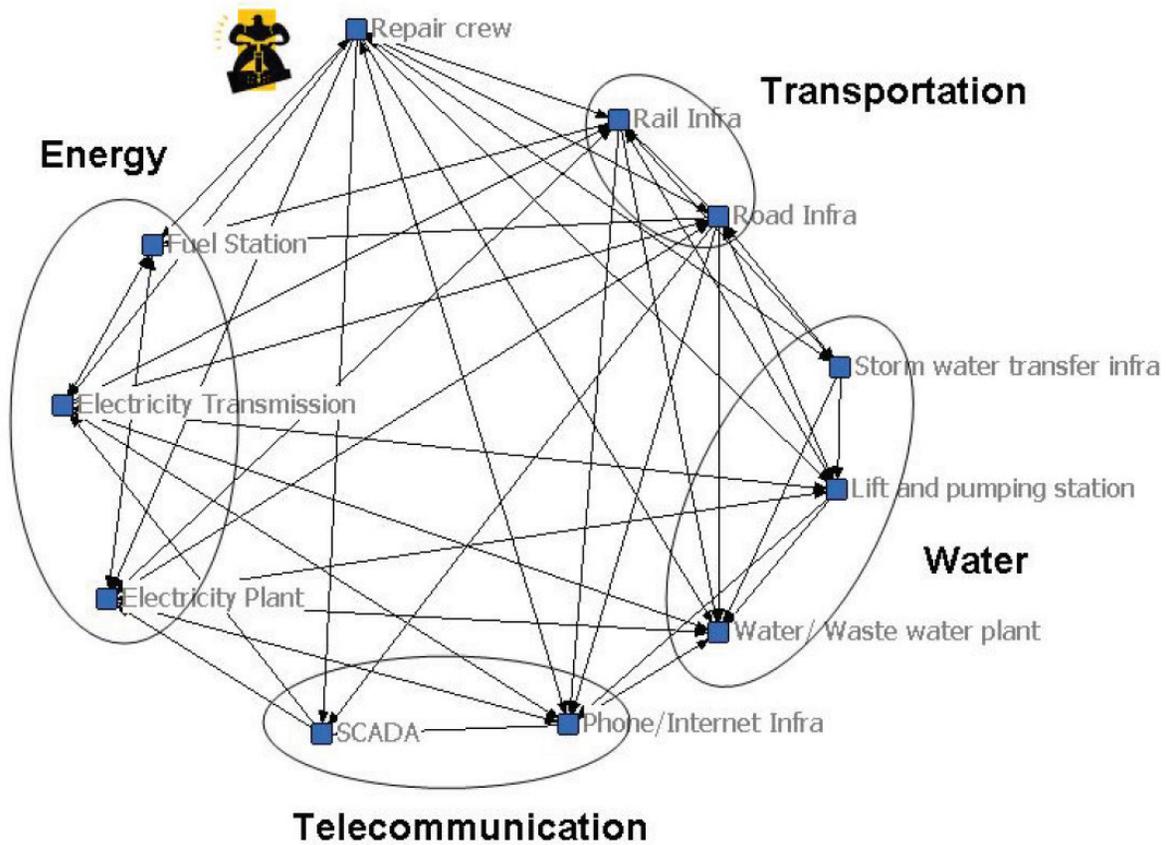


Figure 5. Infrastructure-actor network in the context of Florida urban systems.

Infrastructure-Actor Elements	Centrality degree (out)	Centrality degree (in)	Betweenness Centrality	Eigen vector centrality
Electricity Plant	6	7	12.167	0.179
Electricity Transmission	6	8	7.250	0.297
Fuel Station	3	5	1.700	0.319
Phone/Internet Infrastructure	5	7	7.367	0.275
SCADA	2	3	0.200	0.404
Water/Waste Water Plant	2	8	0.667	0.348
Water Lift and Pumping Station	6	6	2.533	0.270
Storm Water Transfer infrastructure	4	3	0.250	0.343
Road Infrastructure	9	5	7.167	0.279
Rail Infrastructure	7	5	3.833	0.322
Actor: Repair Crews	10	5	9.867	0.213

Table 2. Summary results of network analysis of urban infrastructure systems.

Our initial work employs network theory to establish the degree and influence and vulnerability of infrastructure-actor interdependency in urban systems. The insight obtained from the work can potentially be used to set priority of actions and to find a balance between vulnerability and performance.

4. Case study 2: investments in energy infrastructure

Uncertainties abound in making investment decisions in energy infrastructure such as electricity power plant. There are some major uncertainties they have to deal with in liberalized energy markets ([11]). It is difficult to predict the future electricity demand price as well as the price of input fuels. In addition, there are several structural uncertainties. These include regulation on price mechanisms (e.g., price cap) and environment (e.g., cooling water, emissions, and waste), the developments in the natural gas industry (e.g., the extraction of gas through fracking), and the unbundling of the energy industry into separate electricity generation, transmission, and distribution function.

4.1. SoS model of investment in energy infrastructure

An SoS model for electricity power plant investment is given in **Figure 6**. It consists of two engineered (power plant and house building technologies) and three actor systems (utility companies, household consumers, and public utilities commission).

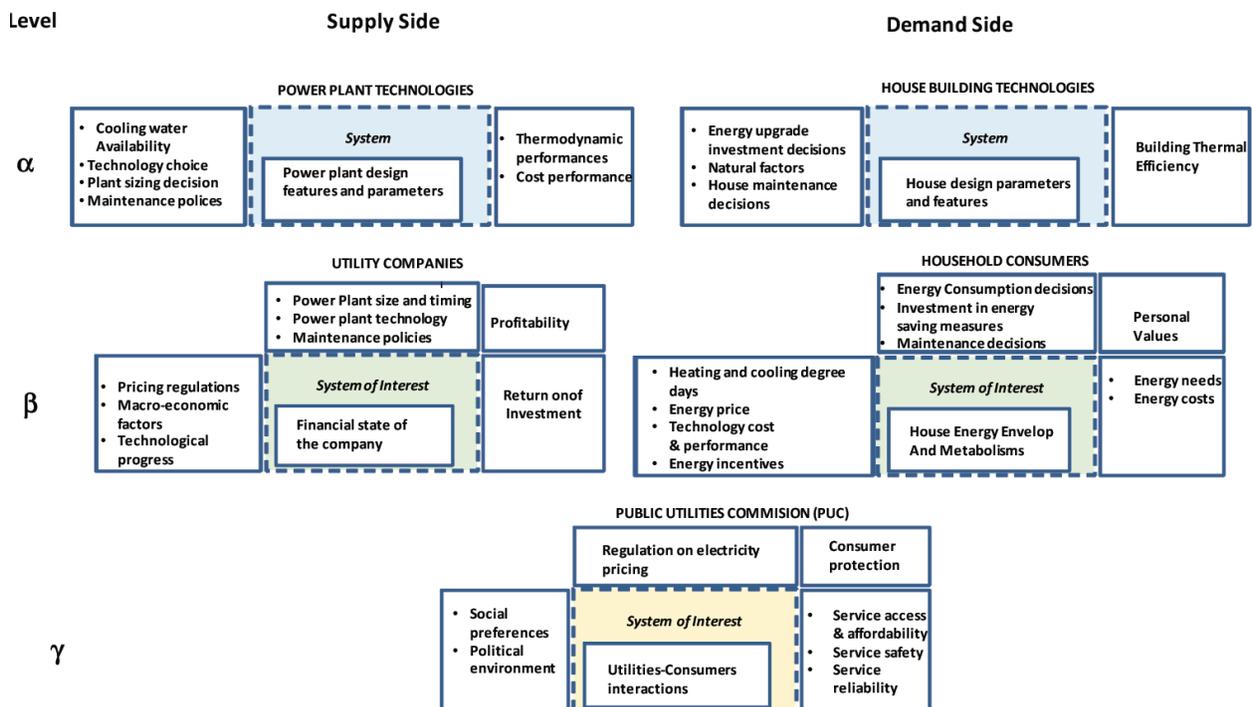


Figure 6. SoS model for electricity power plant investment.

Some of the main elements of system-of-systems model are described as follows:

- Policies (P): At the beta level, policy variables for utility companies involved: the size of the plant, the timing of plant construction, and maintenance policies. These are the actions that would become external forces to the power plant technologies at the alpha level. For the household consumers, their decisions are mainly associated with energy consumption and investments in energy saving measures, which in turn affect house building technologies (at alpha level).
- External forces (X): At the beta level, the utility companies would be concerned and uncertain factors such as electricity pricing regulations, macroeconomic variables, and technological options. The household consumers would be uncertain about natural gas price, electricity demand, and electricity price. At the gamma level, the public utilities seemingly would face uncertainties about political climate and dynamics in societal values.
- Endogenous factors I: For utility companies, they are the variables that determine the cash flow of the investment: (1) installed and used capacity, (2) costs: construction (sunk cost), fixed and variable operations costs, and fuel, and (3) revenues.
- Outcome of interest (O): Profitability is one key outcome for utility companies, which will be measured in net present value (NPV). For public utilities commissions, one outcome they want to monitor is the level of service reliability and affordability.
- The relationships (R): For utility companies, the relationships involved include: (1) revenue functions, (2) cost functions, and (3) functions that translate the costs, revenues, and discount factors (i.e., interest rate) into NPV.
- The value system of the decision makers (W): Utility companies are driven to maximize profitability. In contrast, the utilities commissions are mandated to promote and protect public interests.

4.2. Computational model of electricity power plant investment

Based on the abovementioned definition of SoS, a simple computational model of electricity infrastructure investment was developed. In response to these uncertainties, utility companies may choose not to invest in capital intensive, long lead-time generating technologies such as large nuclear- or hydropower plants or in technologies with relatively high pollution such as coal plant. Instead, they may opt for cheaper, smaller, and less polluting plants that have shorter lead times to build [12].

The model compares the performance of two alternative investment decisions. *Investment1* builds a power plant with a production capacity of 563 MW, whereas *Investment2* constructs a smaller plant of 264 MW. Both power plants use natural gas fueled combined cycle plant technology. The complete model is described in [6].

The uncertainty space for the investment decisions spans a period of 20 years and is discretized into an interval of 10 years. Major uncertainties of future conditions over the time span include several factors. First is electricity demand of which an annual growth rate range between -5 and 5% was taken. Second is the change in electricity price that was assumed to

grow between -20 and 20% per 10 year. Lastly, the volatility of natural gas price is modeled using a binomial method [13]. The gas price change follows a 'random walk' pattern with specific upward (up) and downward (down) movement factor.

To assess the success of investment decisions, three decision criteria are used: net present value (NPV), regret, and robustness criterion. A regret value represents the difference between the NPV of a decision compared to the NPV of the *best alternative* in a particular scenario. Based on the NPV and regret criteria, an investment is considered to be successful if it has a positive NPV and has 'no' (NPV difference: 0—\$0.09 million) or 'mild' (0.1—\$14.9 million) regret. On the other hand, an investment is considered to fail, if it has 'a lot' (15—\$99.9 million) and 'overwhelming' (greater than \$100 million) regret even though the NPV is positive. Failure also includes all regret outcomes with negative NPV.

A robustness score represents the ratio of the number of successful scenarios with the total number of scenarios. Four categories of robustness can be specified. The robustness falls into Category I if the score is between 1 and 0.75 and Category II for the score between 0.5 and 0.74. A decision is considered robust if it has Category I and II score. Decision makers should then compare the robustness of decision alternatives and choose a decision with maximum robustness.

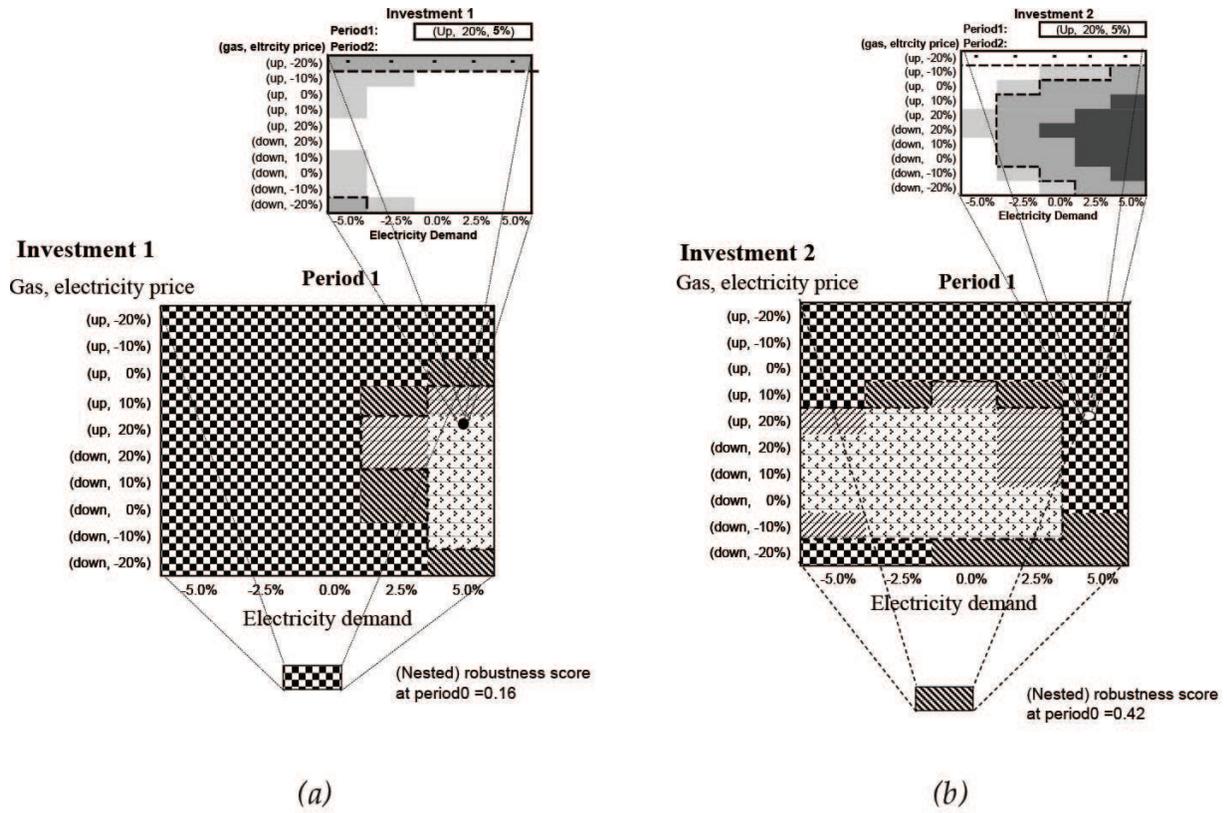
4.3. Results and analysis

Computational experiments were performed across the uncertainty space. The resulting regret category and robustness score of *Investment1* and *Investment2* is given and compared in **Figure 7**. For *Investment1*, a mapping of regret category is illustrated for a scenario at Period1 (i.e., year 1–10), in which electricity demand grows by 5%, the gas price moves upward, and electricity price increases by 20%. Compared to *Investment2*, at the end of Period2 (i.e., year 20), *Investment1* ends up largely successful. This is indicated by 44 scenarios (out of 50) with 'no' and 'mild' regret. This performance is aggregated into a single robustness score of 0.88 (i.e., 44 divided by 50), which falls into robustness Category I. The same calculation is repeated for all other scenarios (a total of 2500).

In a multiple period decision problem, the robustness score can be further aggregated by taking score average. In this way, the path dependency of decision performance can be traced back to the time when the decision is made (i.e., Period0). The nested robustness score for *Investment1* and *Investment2* is 0.16 and 0.42, respectively. Based on these results, *Investment2* should be chosen because it performs better in more scenarios than *Investment1*.

4.4. Seeking failure modes: future conditions that might turn a robust decision into a failure

Decision makers are also interested in knowing other conditions that will make their seemingly promising decision fail. To illustrate sensitivity, analysis was performed on the interest rate, which has been held constant at 5%. **Figure 8** shows that the ranges of interest rate that will make *Investment1* fail. For example, when the interest rate reaches 11%, the *Investment1* is no longer robust across some of the most favorable conditions in period1 because all the robustness scores fall into Categories III and IV.



Regret Category

No regret
Mild
A lot
Overwhelming

	Robustness category	Range of robustness score	Shading for output display
Robust investment	I	$0.75 \leq \text{score} \leq 1$	
	II	$0.5 \leq \text{score} < 0.75$	
Non-robust investment	III	$0.25 \leq \text{score} < 0.5$	
	IV	$0 \leq \text{score} < 0.25$	

Figure 7. Investment robustness outcomes (a) Investment1 (563 MW) and (b) Investment2 (264 MW).

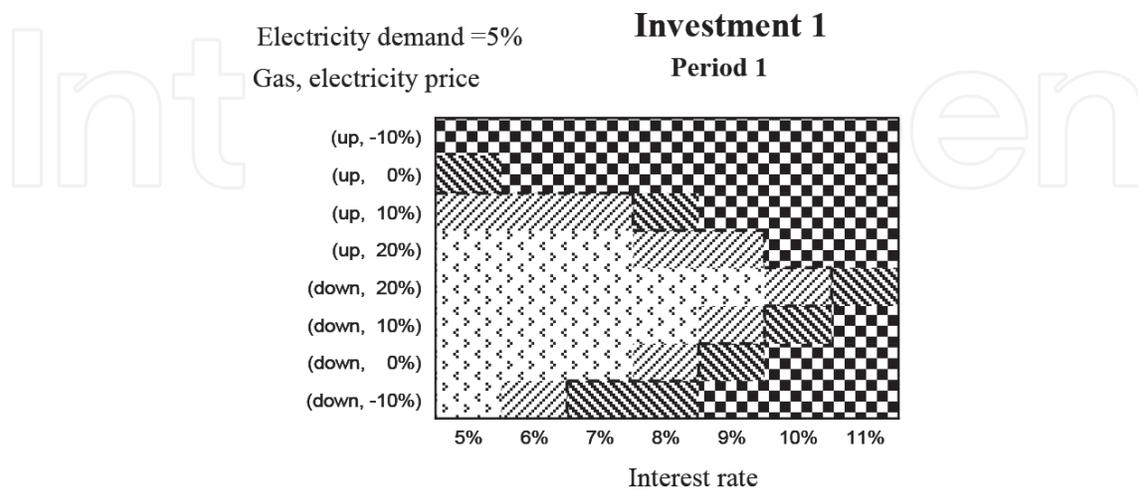


Figure 8. Sensitivity of favorable scenarios to interest rate.

5. Case study 3: informing economic revival initiatives in the northern Illinois region

5.1. Introduction

The economy of the Northern Illinois Region, USA with Rockford as its largest city has suffered since the late 1980s as a result of the decline of manufacturing industry. Currently, a diverse initiative has been launched by various agencies to try to reverse the trend.

The case study presents a development of a decision-support tool to inform policymakers and stakeholders to revive the region's economy. To this end, the proposal will implement a holistic system approach. The approach used will be a combined system dynamics and SOS perspective. The issues that will be addressed include the interactions between the city quality of life factors and investment decisions.

5.2. SoS conceptualization

The combined SOS perspective and system dynamics have a capability to model economic decisions at three different levels such as city, company, and individual. **Figure 9** shows the multi-level decision making occurring within a macroeconomic context.

5.3. System dynamics approach

System dynamics is an approach to understand the behavior of complex systems over time. It deals with internal feedback loops and time delays that affect the behavior of the entire

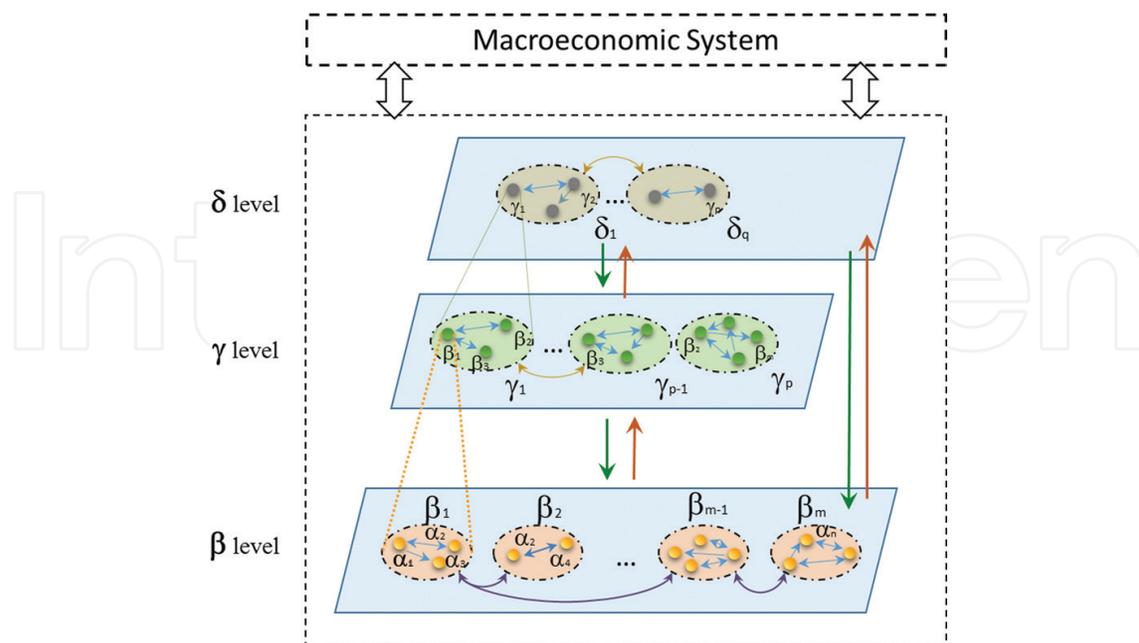


Figure 9. SoS for urban systems.

system. It employs a causal loop and a stock and flow model to represent the change and accumulation of system variables (**Figure 10a, b**, respectively).

5.4. Dynamics at macroeconomic level

At the macroeconomic level, the approach captures the relationships between key economic factors of production (labor, land, capital, and technology) and economic output (e.g., production and GDP) (**Figure 11**).

At this level, several causal and feedback loops can be identified. We can identify, for example, two loops associated with migration. An increase in net migration will add to work force, and availability of work force will in turn reduce the rate of net migration (Loop 1). In the same way, an increase in migration will increase the competition for housing (reduced house availability) and availability of housing will make the city more attractive (increased net migration) (Loop 2).

5.5. Dynamics at city level

For the greater Rockford area, for instance, much efforts have been put in to increase the attractiveness for companies to invest (Source). The efforts focus on industrial infrastructure but also on factors contributing to the quality of life (school quality, housing, safety, health care, recreation facilities and parks) (**Figure 12**). They clearly want exploit the positive feedback in which companies expect quality workers, who in turn is attracted by improved quality of life.

5.6. Dynamics at company level

At company level, an issue of interest is how investment decisions affect the production capacity and company's hiring (**Figure 13**).

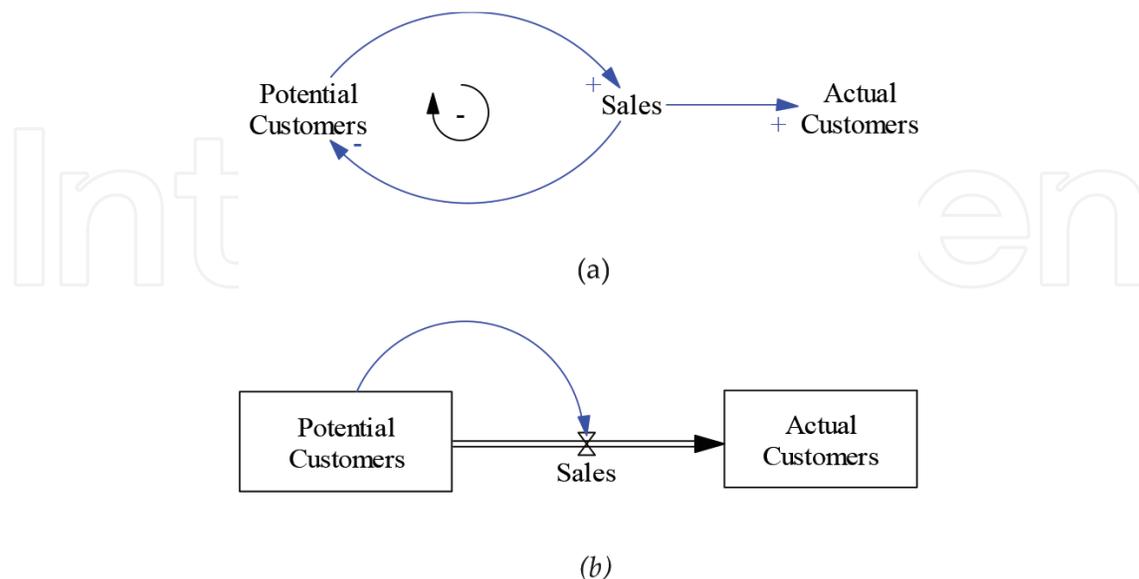


Figure 10. System dynamics main building blocks (a) causal loop and feedback diagram. (b) Stock and flow diagram.

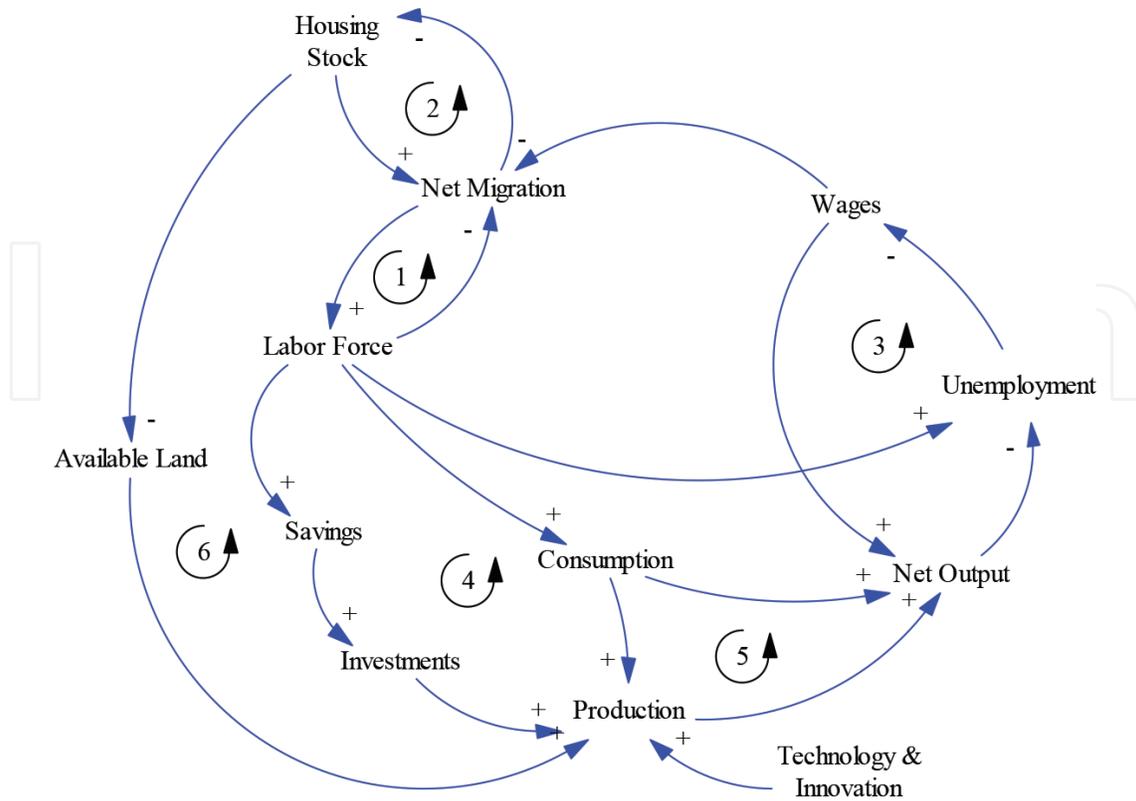


Figure 11. A macroeconomic view of urban system interdependencies.

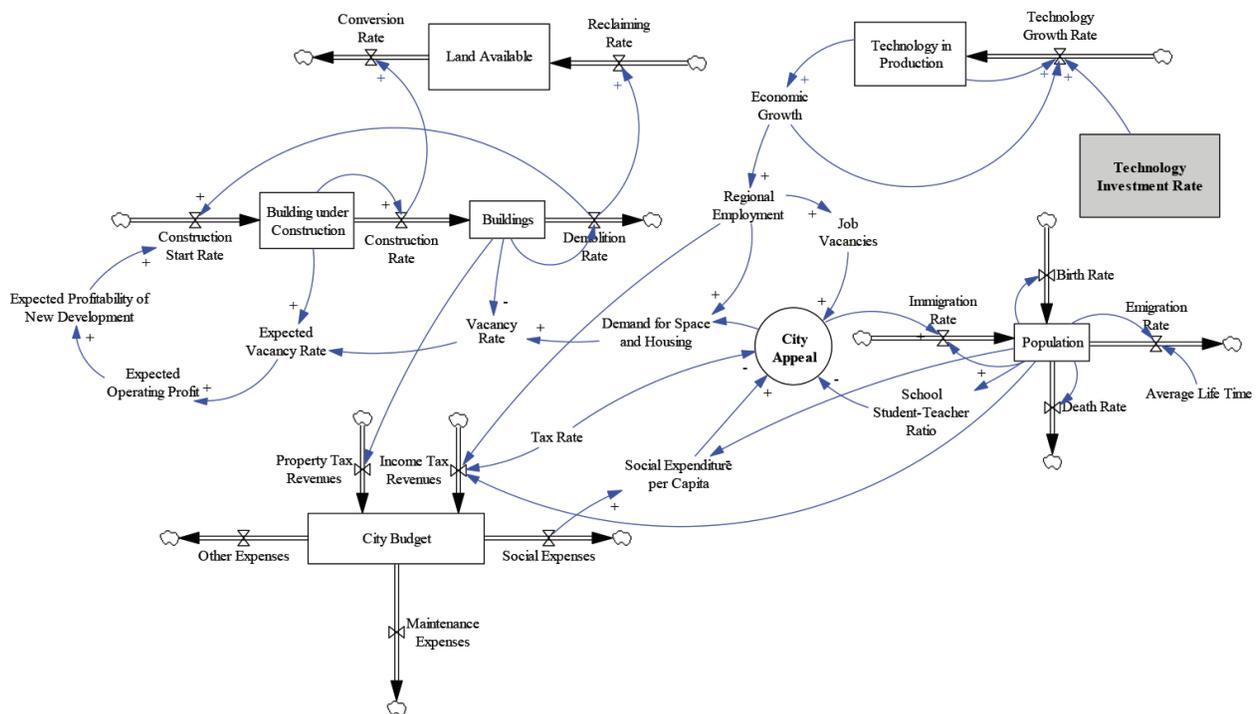


Figure 12. Interrelationships between investment decisions and city attractiveness.

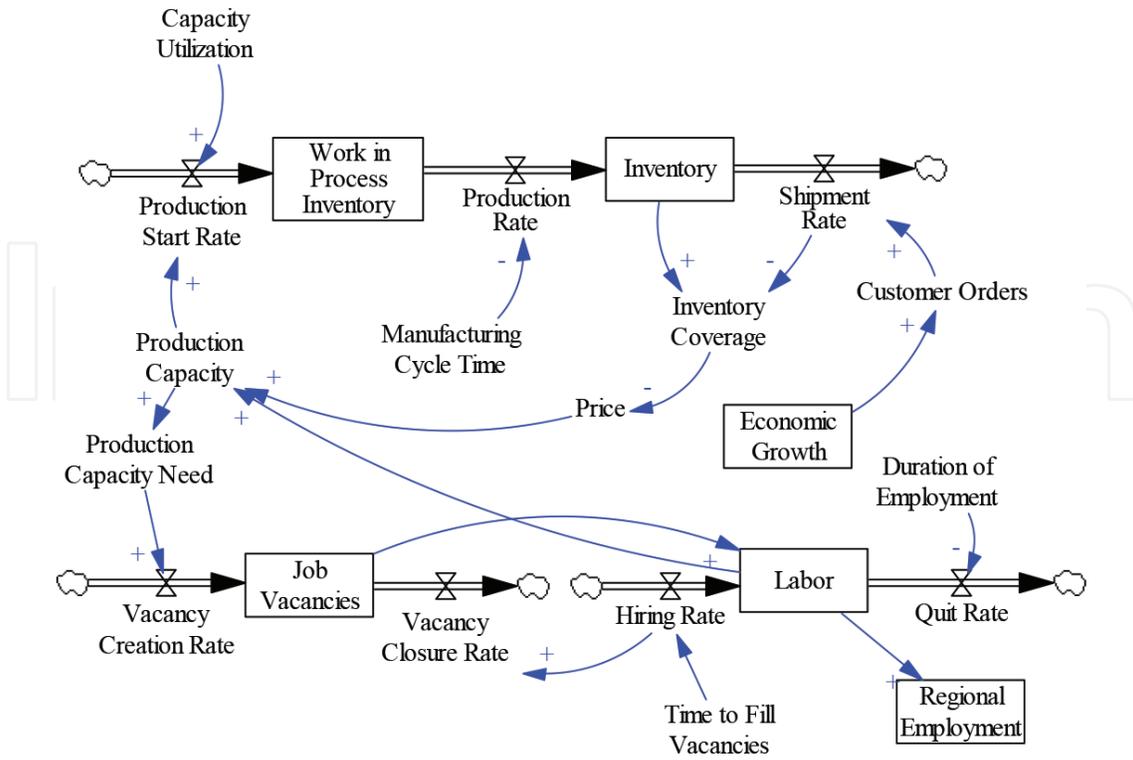


Figure 13. Company's hiring mechanism as a response to customer orders.

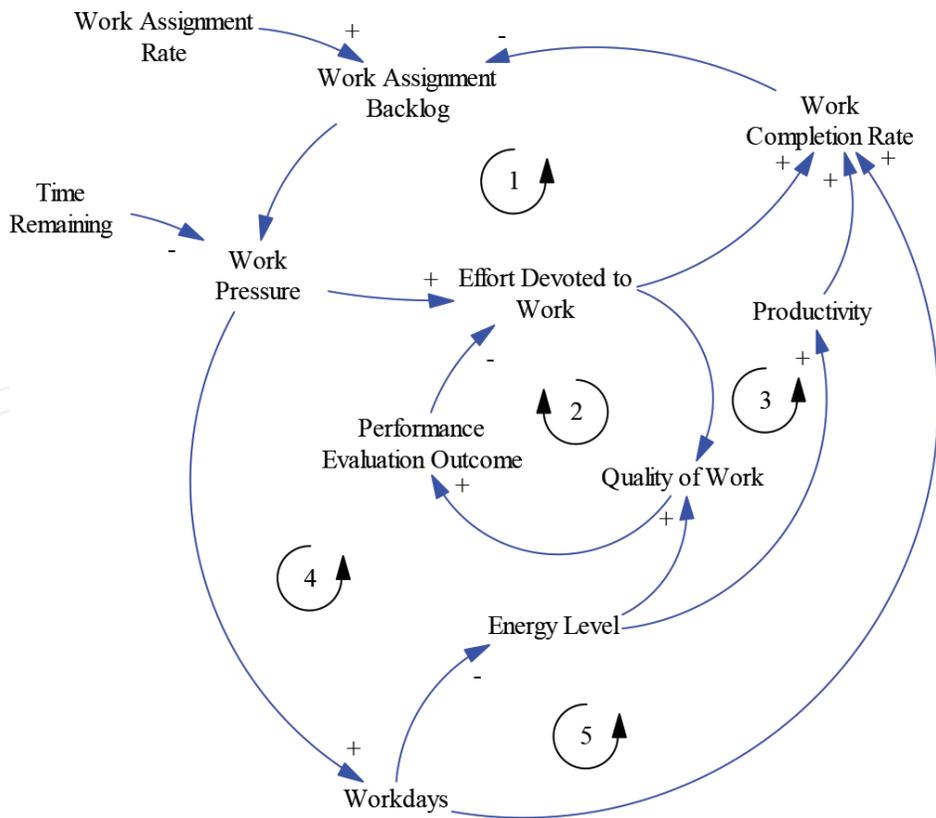


Figure 14. Worker's motivation and work accomplishment dynamics.

The level of regional employment (at macroeconomic level) depends on the number of job vacancies at companies. The demand for workers will be driven by the need to fill production capacity, which in turn depends on customers' orders as they are influenced by how well the economy is doing (i.e., economic growth at macroeconomic level).

5.7. Dynamics at individual level

At individual motivational level, research has suggested psychological behavior that can be best captured using system dynamics [14]. **Figure 14** illustrates factors that are affecting workers' motivation at work and their accomplishments. For instance, quality of work will depend on the effort devoted, which in turn depends on work pressure.

6. Concluding remarks

Urban systems are facing pressures from population growth, urbanization, and climate change. Keeping the status quo could lead to failures in the systems. Given these challenges, better understanding of various elements of urban systems and their interdependencies is needed to inform decisions to improve the systems.

The chapter presents a system-of-systems (SoS) framework to structure complexity of urban systems. A way to deal with future uncertainties within urban system SoS is described. As a whole, SoS forms a network of decision makers and engineered systems at various levels. Over time, the elements of SoS and their relationships will evolve. Their uncertainties can be handled using a computational approach called exploratory modeling and analysis (EMA).

The framework described in the chapter is applied to three case studies. Each case study highlights a unique aspect of urban systems. Different tools were employed to generate insights relevant for decision-making. The first case study looked at the vulnerabilities of urban system under perturbations and disruptions. It uses data related to urban infrastructure in Florida, USA that was devastated by hurricane. Network theory was applied to identify nodes of infrastructure that are influential in causing system failures and are critical for recovery.

The second case study assesses the performance of alternative investment decisions on electricity power plant. EMA is applied to define and explore uncertainty space in terms of measures of regret and robustness of each investment alternative. Once a preliminary robust decision has been identified, EMA can reveal a set of circumstances that may cause the decision to fail. The last case study conceptualizes the dynamics of urban economic revival within a larger macroeconomic environment. A system dynamics tool was employed to represent the context of an economic region in Midwest, USA. Detailed causal loop and stock-and-flow models were developed to specify factors and their relationships across individual, company, and city level.

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