# TOWARDS VALUE-BASED, CLOSED-LOOP DYNAMICAL SYSTEM APPROACH TO ASSET MANAGEMENT

by

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# Abstract of the Dissertation

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DYNAMICAL SYSTEM APPROACH TO ASSET MANAGEMENT

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**Dissertation Director: Professor Mohsen Jafari**

In this dissertation a methodology is proposed for value-based management of networks of assets where the underlying flow and system dynamics are greatly influenced by the way the decisions are made and executed. In this paradigm, users and owners of assets are characterized by their decisions and the impacts that their behaviors will have on the overall flow of the network. Short or intermediate term impacts in network flow occur as assets deteriorate and users start practicing alternative options. These impacts also occur as owners change the state of assets by investing on new assets or practicing different maintenance options. User demand elasticity to the quality of service received from an asset defines flow from or to that asset. Any reduction or disturbances in flow is an indication of inefficiencies in the management of assets. Longer-term impacts occur due to major investments or structural changes in the network, leading to major economical shifts and new flow patterns in the underlying society. These societal changes in turn create new flow dynamics in the asset network.

To tackle this problem we first explain cost-based and value-based approaches to the infrastructure maintenance for a standalone asset and show the differences in optimal maintenance policy of the asset under cost-based and value based regimes. We then add the physics of the underlying network to the decision-making framework and show the impact of maintenance decisions on an asset within a network. We show that the structure of the network and the boundaries for which the value is defined, are important factors in the selection of optimal policies.

To evaluate the impact of investment decisions on different value dimensions of the society we create a primal society of autonomous agents with the objective of maximizing their utility through leisure and consumption. We show the impact of availability of transportation infrastructure on the “spatial” shape of the society and on the key performance indicators of the society such as production, travel time and utility. We verify our model aggregate societal behaviors can be modeled through the simulation approach created by explaining the change in the intensity of US grain production and show how policies and regulations can impact infrastructure investment decisions.

## Dedication

*To my parents,*

*for their endless love and support*

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# 1. Chapter 1: Introduction

## 1.1. Objective

We intend to develop value-based optimization techniques for the management of networks of assets where the underlying flow and system dynamics are greatly influenced by the way the decisions are made and executed. In this paradigm, we look at the environment as complex closed loop system where users and owners of assets are characterized by their decisions and the impacts their behaviors will have on the overall flow of the network. Short or intermediate term impacts in network flow occur as assets deteriorate and users start practicing alternative options. These impacts also occur as owners change the state of assets by investing on new assets or practicing different maintenance options. User demand elasticity to the quality of service received from an asset defines flow from or to that asset. Any reduction or disturbances in flow is an indication of inefficiencies in the management of assets. Longer-term impacts occur due to major investments or structural changes in the network, leading to major economical shifts and new flow patterns in the underlying society. These societal changes in turn create new flow dynamics in the asset network. To the best of our knowledge, this work is the first attempt to close the loops between the asset management decisions and flow dynamics, and between these and the underlying societal changes. In particular, the combined macro and micro view that we employ here is unique in the field of asset management.

## 1.2. Problem Statement & Preliminaries

A fundamental and practical problem in the management of network of assets is to understand and model the closed loop interaction between operational and maintenance decisions made by owners or operators ("*owner agents*"), the behavior of network users ("*user agents*"), the flow dynamics, and the exogenous societal impacts. This problem becomes particularly more important and complex when there is more than one owner operator in the network and the management actions are regulated (by "*regulator* agents").

Figure 1 (left) illustrates the information and feedback flow in a three layer structure. The arrow from decision making layer to the physical layer indicates the impact of decisions at dynamical system level which includes users and asset owners who tend to optimize their own utility in the society. The arrow from the society level to network level indicates aggregation of individual behavioral feedback which are then transferred and observed by the system owners or regulators. Figure 1 (right) illustrates the modeling hierarchy that we are presenting in this work to capture the three layers and the feedback and information flow between these layers. The top level is again decision-making layer where we run owners or regulators run their own optimization routines. The second level is a network flow model which captures the flow dynamics and changes that may occur as a result of asset detritions and decisions made by the owners.  Finally at the lowest level we build a primal society and its economic model to capture the dynamics of individual behaviors and how they are impacts by the network and decisions at the higher levels.

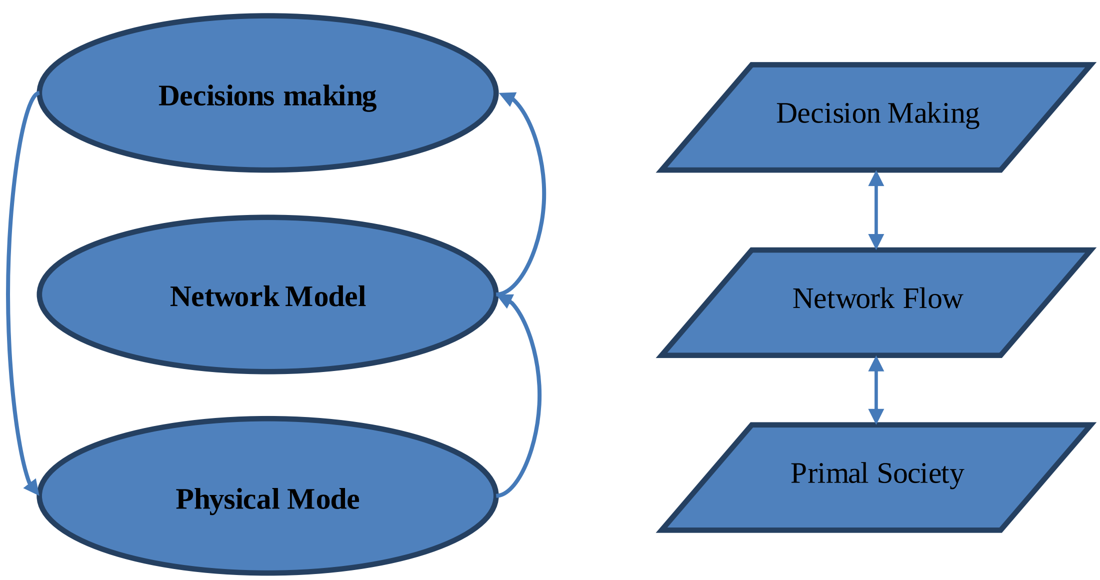


**Figure 1: Information feedback and modeling hierarchy**

The problem of closed loop asset management can be studied within the context of a control-theoretic framework by considering owners to be controllers with the objective of maximizing the reward of their actions while abiding to regulations and system constraints. The impact on the flow dynamics of the underlying network is illustrated through a combined agent-based simulation and optimization methodology. The impact of structural changes and investments are demonstrated by the virtue of a primal economy, which is simple, but possesses some of the fundamental characteristics of a real economy. The development of simulation-optimization environment, formulation of value-based optimization, and the development of primal economy are major problems of interest here. Generally speaking, the following assumptions are made:

1. The system environment or boundary is not controllable
2. There may be more than one *owner agents:*
    a. Principle-agent problem (the agent doesn't necessarily follows principle interest)
    b. Different value spaces (agent-agent, agent-policy maker)
    c. Different goals (agent-agent, agent-policy maker)
3. Exponential increase in the computational complexity of the problem due to increase in number of users and owners (Curse of dimensionality)
4. Stochastic response of the system and the environment to decisions made and implemented by agents (*owner* and *regulator*)
5. Regulators do not always know the response of agents to its regulations

We will start with a single asset network and will extend our results to more general networks where users' response and feedback are directly fed back to the decision making process. Such a closed loop control-theoretic platform for asset management is unique and novel. To demonstrate the generality of the methodology developed here, we also present the extension of our results to other applications, in particular, manufacturing/production systems.

Our technical approach will include the creation of a simulated primal "society" with self-interested "agents". In this society three different types of agents exist: (1) *User Agents* who are on the demand side and will use the infrastructure assets; (2) *Owner Agents* who are responsible for the operation and maintenance of their portfolios of assets in the network; and (3) *Regulator Agents* who are responsible for creating rules and regulations for the system.

These agents are self-interested agents with the following objectives:

> *Owner Agents* have the objective of maximizing their value by selecting an optimal set of maintenance options for their portfolio; *Regulator Agents* have the objective of maximizing the total network value; and *User Agents* have the objective of minimizing their usage cost with maximum QoS (Quality of Service).

The thesis will particularly address the following methods and models:

- Location selection and trip generation models for *user* agents;
- Route selection model for *user agents*;
- Basic *cost based* and *value based* maintenance models for *owner agents*;
- A scalable simulation model for a virtual primal society of *users*, *owners* and *regulator agents*;
- Implementing cost based and value based approaches for a single asset case and comparing them in the simulation environment;
- Expanding the single asset model to scenarios where:
    - Networks with single owner - The owner agent has the complete ownership of the network;
    - Networks with multiple owners – Only partial ownership by a single agent and collaboration or competition with other agents.

- Adding a regulator agent to ensure the optimal operation of the network by limiting User and Owner Agents actions

## 1.3. Major Contributions

This thesis tackles the optimal maintenance planning and investment for transportation infrastructures and treats them as complex systems in closed loop with artificial societies. This modeling approach considers interactions between members of the artificial society: *regulator*, *owners* and *user agents* and their responses to endogenous and exogenous changes in the transportation network. In this research *user*, *owner* and *regulator agents* have different value spaces and objectives for interaction. The notion of complex systems with inter-system dependencies and conflicting responses together with the stochasticity of the response from the surrounding artificial societies is a novel idea and is expected to lead to completely new decision-making paradigms. In this modeling approach we have closed the feedback loop from the network flow into the activity system of the society which can be used for better assessment of infrastructure investment decisions. By closing this link the net worth of an investment can be properly measured in three dimensions of social, economic and environmental.

In Chapter 2 we will illustrate the formulation and decision making process of *owner agents* and explain how different approaches for solving a problem can lead to different optimal policies. This chapter will also include the extension to network of multiple assets. Chapter 3 will explain the network flow environment and show the implementation of the model developed in Chapter 2 for a special single asset case. Chapter 4 will discuss the impact of transportation network investments on the welfare dynamics of society that it serves, as well as the demand modeling by creating an artificial society of self-interested agents. Chapter 5 will show the implementations of framework developed in previous chapter in explaining societal behaviors and identifying optimal investment strategies and policies. Chapter 5 will also include extensions and a game-theoretic illustration of how a regulator agent can impact the decisions made by multiple owners. Chapter 6 will illustrate shortfalls of the current framework and lay down the path for future work.

## 1.4. Motivation

We are motivated by a number of factors as described below.

### 1.4.1. Sustainable Development

Sustainable development is a way to “meet the needs of the present societies without compromising the ability of future generations to meet their own needs” (1) . United Nations World Summit 2005 (2) refers to economic development, social development and environmental protection as three interdependent and mutually reinforcing pillars of sustainable development. Sustainable development is important because uncontrollable growth cannot be sustained for a long time.

Economically speaking, sustainability requires the growth of system wealth over time. New investments and maintenance expenditures on transportation infrastructure of a society should be done in a way to increase the wealth (net of the impact on the environment) of that society. To adhere to this goal the organization in charge of regulating the infrastructure assets should set policies to ensure that interactions between different entities (*users* and *owners*) in the system lead to increase in the overall system wealth.

High capital costs of transportation infrastructure, the lack of public funds, and environmental and land use constraints necessitate the development of new and more advanced decision support techniques and solutions for rehabilitation and replacement of infrastructure assets. The new trends in infrastructure investment and the changes in the transportation asset ownership will drastically increase the complexity of the decision-making process so that the commonly applied minimum cost lifecycle models will no longer be useful. Common asset management practices are not designed to optimally handle these trends in infrastructure investment.

The research on optimal pricing and investment on highways goes all the way back to 1962 (3). Keeler and Small (4) studied optimal pricing and investment in relation to tolls, capacity, and the service level. In more recent studies De Borger and Van Dender (5), De Borger et al (6) and Verhoef (7) worked on congestion pricing and investment in relation to capacity or franchising. Peterson (8) uses a dynamic programming model, QROAD, to calculate an optimal sequence and timing of improvements for a highway corridor or a number of corridors subject to budget constraints. Most of these researches take a public view of the roadway pricing and maintenance with not much attention on the availability of funds. It is anticipated that with the recent trends on Public Private Partnership (PPP) in infrastructure investments, different decision making paradigms will be needed to support infrastructure investments.

### 1.4.2. Better Public Infrastructure Management

Public infrastructure is necessary for functioning of the economy and society. The quality and efficiency of infrastructure affects the quality of life. There is a relationship between infrastructure and economic development (9). In his work, Queiroz (9) showed a strong association between Gross National Product (GNP) and road infrastructure. In a lag analysis it was shown that a very high correlation exists between Per capita GNP of a given year and the Length of Paved Road (LPR). This result suggests that an investment made on paved road today will result an increase in PGNP in about four years.

In the infrastructure boom of 1950s, 1960 and 1970s, Figure 2 (10), many advances were made in planning, design and operation and management of public infrastructure. However at the time (until recently) maintenance, rehabilitation/renovation and replacement costs were not considered in the planning process of infrastructure investment. Condition of an infrastructure asset can be preserved if maintenance and rehabilitation actions are taken properly. At the same time, maintenance and rehabilitation costs are directly correlated to the type of decisions made in earlier stage of the asset lifecycle. A lifecycle look toward asset maintenance can help in minimizing the lifecycle cost of the asset. Asset performance also depends on network level conditions and external factors such as structure of the society, availability of funds and new investments. Such a holistic approach to asset management is expected to reveal better results compared to the traditional practices where optimizations are done on the basis of single assets.

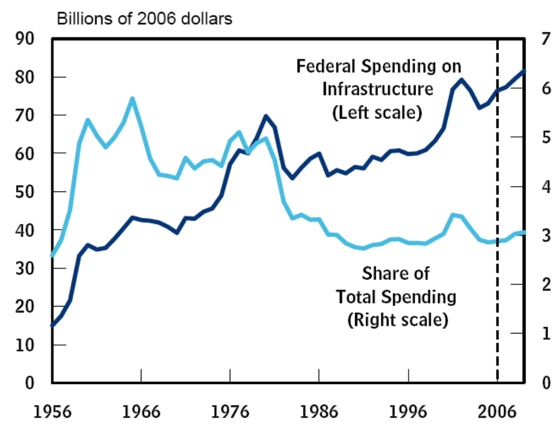


**Figure 2: Infrastructure Spending, Trends in Public Spending on Infrastructure, Congressional Budget Office, February 5, 2008**

### 1.4.3. Better Management of Public-Private Partnership (PPP) Projects

PPPs enable public sector to spread out the capital cost of the facility over its lifecycle. This cost can be directly charged to users rather than paying taxes or charged to public sector budget over the lifetime of the asset. This enables public sector to get away from short-term investment constraints and develop infrastructure assets, which would not be possible otherwise.

PPP projects also improve value of the investments. PPP projects transfer certain risks from the public sector to private sectors. The transferred risks of the projects are better managed by the private sectors compared to the public sector.

Another significant benefit of PPP is whole lifecycle costing. Because the investors are also responsible for the operation and service delivery of the facility, they are incentivized to design the infrastructure to fully pay back the investments over its lifecycle. In PPP maintenance and financing cost of the asset is transferred to project investors and lenders. A PPP contract makes sure that the maintenance standards are met by not letting the public sector cutting back on its routine maintenance. It also makes the private sector to keep the standard level service to be paid by the service fees.

PPP projects let private sector bring its expertise to the project. PPPs tend to work more efficient because private sector is profit oriented and inefficient management is usually not tolerated. Additionally PPP leaves more space for innovation of private sector by just specifying the output and leaving the detailed design of the projects to the private sector. A PPP project also benefits from third party due-diligences by lenders. In PPP projects, there is more incentive to make sure that the design is right and services meet necessary standards. With PPP, however, the public authorities (PAs) lose their direct control over maintenance and management of infrastructure. In the new movement public authorities will act as entities responsible for public infrastructure with the ability to affect the infrastructure network through setting regulations.

Using PPP to fill the gap for public funds requires the development of new decision support tools for infrastructure management. The following requirements must be met: At the *owner* level the focus must switch to value based optimization in a three-dimensional space. At the *regulator* level new models are required to help understand the effect of decisions made by *users* and *owners* on the overall network value.

### 1.4.4. Combined framework

In a network of infrastructure assets, different owners have their own values and priorities in managing their portfolios. While private owners are more focused on economic return of their assets, public owners put more emphasis on the social aspect of asset management. As the entity responsible for the operation of public infrastructure, PAs have to make sure that their policies support the sustainable development of the society. This assurance can’t be acquired without having a thorough understanding of sustainable development and mechanisms involved in infrastructure asset management leading to a sustainable development.

While there are many technical papers addressing problems with asset management, they are mainly focused on optimization problems for a single owner network with little to no attention on the impact of transportation infrastructure assets on the society. In the literature there is not enough research on models, which combine the idea of managing for sustainable development and looking beyond the growth with new methods for delivery of public infrastructure investment such as PPP.

## 1.5. Scientific and Technical Merits of this Research

In this research we create a general methodology that can be applied for management of different assets in network settings. We demonstrate applications of our methodology on transportation infrastructures and production systems. We use *multi-agent systems* to model the society of *users*, *owners* and the *regulator*. For the optimization of maintenance policies we use dynamic programming to generate a maintenance policy that maximizes the value generated by an asset. We use basic game theory framework to model the interactions among asset owners and between asset owners and the regulator.

## 1.6. Related Literature Review

### 1.6.1. Asset Management

Asset management is defined as "a systematic process of maintaining, upgrading, and operating physical assets cost-effectively. It combines engineering principles with sound business practices and economic theory, and provides tools to facilitate a more organized, logical approach to decision-making. Thus, asset management provides a framework for handling both short – and long-range planning." (11)

Infrastructure asset management is a special derivation of asset management, which considers special characteristics of infrastructure assets. Infrastructure assets are immobile; in fact transportation infrastructure investments are particularly cumbersome to transfer or reallocate elsewhere and, if reallocation were possible, it would imply prohibitive transfer cost (12).

Transportation asset management is policy driven and performance-based. It considers different alternatives or options and tradeoffs among programs (13). It works by establishing performance expectations, collecting and analyzing inventory and performance information and creating variable cost-effective strategies for allocating budgets to satisfy agency needs, and user requirement using performance expectations as critical inputs (14). High level of stochasticity and uncertainty is involved in the asset management process due to uncertainty in infrastructure deterioration models associated with high level of uncertainty caused by exogenous factors i.e. environment and level of utilization; endogenous factors i.e. facility design and materials and statistical factors i.e. limited size and the scope of data set used to generate models or differences between data generated in a laboratory setting versus in the field (15). At network level there are also Markov and Linear Programming approaches to model the problem of selecting the optimal maintenance strategy. Madanat suggested uses of robust optimization in modeling maintenance planning for networked assets (15). Ng 2011 (16) suggested an integer programming alternative to Markov models for dealing with uncertainties in the programming process. Abaza and Ashur (17) applied a Markov model to predict future pavement performance and used non-liner optimization for optimal planning of maintenance actions while de la Garza (18) suggested a liner programming approach to model network level maintenance optimization decisions.

### 1.6.2. Public Private Partnership

A PPP contract is a long-term contract for design, construction, financing, and operation of public infrastructure by the private-sector party with payment over the lifetime of the PPP contract to the private party for the use of the infrastructure facility. The facility remains in private-sector ownership, or reverting to public-sector ownership at the end of the PPP contract (19).

In recent years there has been an increase in cooperation between the public and private sectors for development and operation of environmental and transportation infrastructure (20). These contracts became fashionable 30 years ago (21). European investment bank (EIB) has supported the development of more than 100 PPP projects, for amount of about 15B Euros (22).

Using PPP as a method for delivery of public infrastructure projects has certain advantages because of its budgetary benefits, additionally (PPP is out of public budget), risk transfer and value for the money, economy of scale, whole lifecycle costing and maintenance, using private sector skills and helping in public sectors reform. This method has also have some drawbacks, Salamon (23) suggested that PPPs can pose government with problems of exercising management supervision, ensuring degree of accountability and encouraging coordination, when decision making is widely dispersed and vested in organizations with their own independent sources of authority!

Loffler 1999 (24), suggested that a major problem of partnership approach to public issues is that it brings fragmentation of structures and processes, which in turn leads to blurring or responsibilities and accountability. PPP projects are also criticized for following reasons:

- Staff lose the job
- Politicians fear losing control
- Service-user and citizens becoming subject of a profit making calculus
- Voluntary organizations and NGOs are reluctant to become principally service providers in partnership with public sector organization

Despite the drawbacks, it has been the general belief that PPP projects can lead to efficient resource allocation by virtue of a market driven mechanism. Resource allocation is most efficient when it is arranged through markets in which potential suppliers compete with one another to cut cost and to attract customers by improving the quality of the goods or services (Adam smith). Transport investment are very sensitive to risk allocation (20), (25), (26) and PPP can provide a great tool for sharing that risk between entities who can handle them best. However investment through PPP is not always the best method for delivery of a new project due to high transaction costs. Wherever the underlying contracts are complex, the high costs of designing, letting, monitoring and enforcing these contract means that organizations may well be better off undertaking many activities in-house unless relational contracts could be set up (27), (28).

### 1.6.3. Game Theory

Game theory studies interactions among self-interested agents (29). Depending on the context, a problem can be modeled using different types/variation of games: cooperative/non-cooperative, symmetric/asymmetric, zero-sum/non-zero-sum, simultaneous/sequential, perfect information/imperfect information and etc. Having more than one agent in the system gives birth to the concept of game theory. In PPP structure there are two types of games, the first game is among PPP contractors (*owner agents*) to maximize their gain and market share; and the second game is between PPP contractors (*owner agents*) and Public Authority (*regulator agents*) where the objective of *owner agent* is to maximize its own returns and the objective of the *regulator agent* is to maximize the value generated by the whole network.

The second game focuses mainly on risk allocation where risk is defined as any factor or event that threatens the successful completion of a project in terms of time, costs or quality (20), (30). This allocation of risk is examined as bargaining process between the two agents confronted with the decision about risk allocation offers (30) with following principles:

- The agent that bears the risk is best able to influence and control the risky outcome.
- The risk should be borne by the agent to bear the risk at the lowest cost;

Risk allocation in infrastructure projects between the private and public sector is an uncertain task. Risks and their correct allocation are complex to determine (31), (32) which makes games such as final offer arbitration game become popular in PPP negotiations (33), (34) and (35).

### 1.6.4. Sustainable Development

Sustainable development is a pattern of using resources to meet human needs and preserve the environment so that these needs can be met for future generations as well as today. To achieve a sustainable development we need to understand the difference between growth and development. To grow means ‘to increase naturally in size by the addition of material through assimilation or accretion’ and to develop means ‘to expand or realize the potentialities of; bring gradually to a fuller, greater, or better state’. Growth is quantitative increase in physical scale and development is qualitative improvement (36).

Human societies/economies are sub-systems within a global system and since this global system cannot grow, constant growth in human sub-systems is unsustainable. In a sustainable development setting:

- Harvest Rate should be equal to regeneration rate;
- Waste emission rate should be equal to natural assimilate capacities of ecosystems;

In a sustainable investment the emphasis is on technologies that increase resource productivity (development) and the amount of value extracted per unit of resource, rather than technologies for increasing the resource throughput itself (growth).In the problem of sustainable development, natural capital as well as man-made capital should be considered as part of the scope. However, it should be kept in mind that maximizing sustainable annual profit is not the same thing as maximizing present value by discounting future costs and benefits (37). Several research works have been performed on creating indexes for measuring the sustainability of communities (38), (39), (40). It is the regulators job to overlook the interactions between different agents in the society and maintain the weak criterion for sustainable development by preventing them from getting into games that lead to destruction of the society's wealth.

### 1.6.5. Agent Based Modeling

Wooldridge and Jennings (41) has the following definition for an agent:

> "An agent is a computer system that is situated in some environment, and that is capable of autonomous action in this environment in order to meet its design objective."

The various definitions discussed in the literature involve different properties of an agent. Agent characteristics can be categorized as:

- Reactive: Responds in a timely fashion to changes in the environment based on local information (42)
- Proactive: Has ability of taking the initiative; not driven solely by events, but capable of generating goals and acting rationally to achieve them (41)
- Goal Oriented: Does not simply act in response to the environment and plans to achieve goals  with domain knowledge (43)
- Autonomous: Senses the environment and acts on it, over time, in pursuit of its own agenda and so as to effect what it senses in the future (44)
- Learning: Changes its behavior based on its previous experience (44)
- Communicative: Communicates with other agents and solves problems by collaboration and synergy (41)
- Mobile: Has ability to transport itself from one machine to another (45)

- Intelligent: Attempts to make the best decisions based on a given performance measure (46)

For the purpose of this research, an agent is defined as an intelligent being that has one or more goals and is capable of communicating with other agents in its environment. Furthermore, agents are goal oriented and react to the changes in the environment.

### 1.6.6. Agent Based Simulation

Agent based modeling is a bottom-up approach which looks at a complex system as a large set of interacting components where the global system behavior emerges from the behavior of individual components (47).

An agent based model has roots in Complex Adaptive Systems. These systems are *aggregate*: allow groups to form, *nonlinear*: invalidate simple extrapolations, *flow*: allow the transfer and transformation of the resources and information and *divers*: allow agents to behave. Complex adaptive systems have following mechanisms: *Tagging*: agent can be named and recognized, *Internal models*: agents can reason about their worlds and *Building blocks*: components and whole system can be composed of many levels of simple components (48)

To create an agent based model one has to define Agents by identifying the agent types and other objects (classes) along with their attributes, Environment by defining the environment the agents will live in and interact with, Agent Methods by specifying the methods by which agent attributes are updated in response to either agent-to-agent interactions or agent interactions with the environment, Agent Interactions by adding the methods that control which agents interact, when they interact, and how they interact during the simulation and Implementations by implementing the agent model in computational software. (49)

Verification and Validation of agent based models are done through face validation, sensitivity analysis, calibration and statistical validation (50). Discrete event simulation models can also be used for validation of agent based model (51) . Additionally the data log by agents in an agent base model can checked for any violation by Simulation Specialists with the help of Subject Matter Experts.

### 1.6.7. Agent-based Computational Economics

Agent-based Computational Economics (ACE), is the computational study of the economics processes modeled as dynamic systems of interacting agents (52) current ACE research follows four different objectives *empirical understanding*: why have particular global regularities evolved and persisted, despite the absence of centralized planning and control? (53) and (54), *normative understanding*: how can agent-based models be used as laboratories for the discovery of good economic designs? (55) and (56), *qualitative insight and theory* generation: how can economic systems be more fully understood through a systematic examination of their potential dynamical behaviors under alternatively specified initial conditions? (57) and (58) and methodological advancements: how best to provide ACE researchers with the methods and tools they need to undertake the rigorous study of economic systems through controlled computational experiments? (57) (54).

# 2. Chapter 2: Value based Vs. Cost based Asset Management

## 2.1. Preliminaries

Asset management is a systematic and cost-effective process of maintaining, upgrading, and operating physical assets. The owner's ultimate goal is to generate a set of maintenance and investment actions to optimize its objective function over a planning horizon. To establish a set of optimized actions the owner has the option of using a cost-based or value-based approach. The *cost-based* approach minimizes the cost of ownership of the assets while *value-based* approach generates maintenance policies that maximize the value generated by the assets. In this chapter we formulate and compare *cost*- and *value-based* approaches in maintenance planning, and develop a general modeling framework for the asset management problem.

Both *cost-based* and *value-based* approaches follow similar fundamental steps in modeling and solving the problem of asset management. The *cost-based* modeling is commonly used with the objective of minimizing the ownership cost of an asset over a planning horizon. The ownership cost of an asset consists of the cost of maintenance actions and penalties paid by the owner for the poor performance of the asset. In some cases the user cost is also added as an element of the ownership cost. The *value- based* approach, on the other hand, is not a common practice; in this method the objective is to maximize the value that an asset generates for its owner(s) over a planning horizon.

While there is a clear and generally common definition of cost of ownership, the definition of "value" is not a clear one. To create a value based maintenance framework first we need to have a definition of "value". British Standard EN 12973:2000 defines "value" as the relationship between satisfaction of needs and the necessary resources; here actions are evaluated based on resources they use towards satisfying the goal.

Every investment or maintenance action has economic, social and environmental impacts and the value that an action creates should also be measured within these dimensions. Using "value" as a measuring stick requires a different modeling approach for complex systems in contrast to the *cost-based* modeling. The cost-based modeling techniques normally assume independency among assets and ignore inter-asset interactions; consequently they produce sub-optimal solutions. With increasing system complexity, the inter-asset interactions also increase and the cost-based optimality conditions for the individual assets come short of guaranteeing optimality for the whole system. To address this major problem, we propose an approach, which takes into account the inter-asset interactions by the virtue of the values that they jointly generate towards achieving the common goals and objectives of the system as a whole. We will first introduce our modeling approach with a single asset system in this chapter. In the forthcoming chapters, we will address the complexities of this new modeling approach and present extensions.

## 2.2. Problem Formulation

In the single asset problems the *value-based* and *cost-based* models are uniquely characterized by their objective and contribution functions. In *cost based* models, the contribution function is usually defined on user and maintenance costs. In *value-based* models, the contribution function is defined based on the goal of the system and resources used in maintenance actions to direct the system toward its goal. For *value-based* models the objective is to maximize the contribution function while the objective of *cost-based* models is to minimize it. In the constrained side the cost based model looks at available resources as an exogenous input to the optimization process while the value based model looks at it as an endogenous variable. Table 1 summarizes the two approaches. In the sequel we describe the details for each approach.

Table 1: Value Base vs. Cost Based Single Asset Optimizations

| Value based model | | Cost based model | |
|---|---|---|---|
| Objective function: | $z = \max_{(x_t)_{t=0}^{T}} \sum_{t=0}^{T} \gamma_t \mathrm{P}'(c_t, x_t)$ | Objective function: | $z = \min_{(x_t)_{t=0}^{T}} \sum_{t=0}^{T} (1+\mathrm{r})^{\mathrm{t}} \mathrm{P}(c_t, x_t)$ |
| Constraints: | Resource constraints<br>Performance constraints | Constraints: | Resource constraints<br>Performance constraints |

Here we will focus on a stand-alone single asset. Chapter 3 integrates the single asset model into network of assets, and studies the impact of value and cost based approaches on the flow dynamics of the network. In the remainder of this chapter we will describe our technical approach to building these optimization models and present an illustrative example. The analytics will focus on single asset problems, but extension path to multiple asset problems will also be presented. Finally we will touch upon the impact of cost based vs. value based asset management on larger economic scales.

## 2.3. Technical Approach

Here we formulate cost-based and value-based single asset optimization problems. The problem formulation includes the definition of state variables, decision variables, exogenous data, transition functions, contribution functions, and the objective functions as shown in Table 1 above.

### 2.3.1. State variables

State variables capture the information required for making decisions as well as information required for describing the evolution of the system over time. Here we need two pieces of information to plan the necessary maintenance actions, namely, condition of the asset ($c_t$) and available resource vector ($r_t$) at time *t*. Condition of the asset is a value between 0 and 1, which represents the health of that asset. This value is equal to 1 at the beginning of asset's lifetime and changes based on asset's specific deterioration pattern. $r_t$ shows the level of resources available to the asset owner for performing maintenance actions. The state variable is given by $S_t = (c_t, r_t)$

### 2.3.2. Decision variables

Decision variables are set of actions that an owner can take over time to control the process. Here, the decision variables define the type of maintenance actions applied to the asset at different times. These actions are selected from an array of $n$ possible maintenance options where 1 stands for "do nothing" and $n$ stands for "complete reconstruction or renovation".

The cost of maintenance actions depends on the state of the asset. Maintenance actions cost less when the asset is in good condition. At any given time period the cost of applying maintenance treatments to the asset can't be higher than the available maintenance resources. We define

$x_t$: maintenance action at time $t$,

$k_{t,c_t,x_t}$: cost of maintenance at time $t$ when the asset is in condition $c_t$ and action $x_t$ is taken, and

$I_{t,c_t,x_t}$: improvement made to the asset at time $t$ when the asset is in condition $c_t$ and action $x_t$ is taken.

To include the resource availability constraint we have:

$$k_{t,c_t,x_t} < r_t$$

where $r_t$ shows the available resource at time $t$.

### 2.3.3. Exogenous information:

Exogenous information defines data that becomes known at each time period. In an asset management problem the decision maker doesn't have complete information on exogenous variables and only has a stochastic knowledge of those variables before they are observed. Here, the demand on the asset and its condition deterioration are exogenous variables.

In a network setting the demand for an asset at time $t$ depends on the condition of the asset at time $t$, as well as the condition of other cooperating and competing assets. The deterioration in the condition of the asset is a function of the demand for the asset which is a stochastic variable itself, and of some other environmental factors which are unknown/uncontrollable and stochastic by nature.

The other exogenous factor on this problem is the change in the state of available resources. The available resource level in the cost based problem is stochastically known. The value for demand, available resource for maintenance and deterioration in the asset condition can be stochastically predicted through time series and regression models.

We define the demand for the asset as $\widehat{D}_t$, the change in the asset condition as $\hat{d}_t$ and the exogenous changing available resources as $\hat{R}_t$. The new information learned at time $t$ is then defined by $W_t = (\widehat{D}_t, \hat{d}_t, \hat{R}_t)$.

### 2.3.4. The transition function:

The transition function determines the future state of our system $(S_{t+1})$ given its current state $(S_t)$, the decision made at time $t$ and the new information that arrived between $t$ and $t+1$. Equation 1 and Equation 2 show the transition functions for available resources and condition of the asset.

Equation 1: Change in the available recourses

$$R_{t+1} = R_t - k_{t,c_t,x_t} + \hat{R}_{t+1}$$

Equation 2: Change in the condition of the asset

$$c_{t+1} = c_t - \hat{d}_t + I_{t,c_t,x_t}$$

### 2.3.5. The contribution function:

The contribution function determines the cost incurred or rewards received during a given time interval. The value of the contribution function depends on the asset management approach taken by the owner. The contribution function changes from the cost of holding the asset to the value that the asset generates over a pre-defined planning horizon. In addition to the asset management approach, the scope of the problem plays an important role in identifying the measurement dimensions for the contribution function. In a conventional cost based model the contribution function is the cost of applying a maintenance treatment. In more advanced models, the contribution function is defined as the cost of applying the maintenance treatment plus the usage cost of the asset and possible penalties for poor levels of service. The contribution function of the cost base method, in general, can then be defined in Equation 3.

Equation 3: Cost based contribution function

$$\mathrm{P}(c_t, x_t) = k_{t,c_t,x_t} + u_{t,c_t} + p_{t,c_t}$$

where $u_{t,c_t}$ is the usage cost and $p_{t,c_t}$ is the penalty for asset's poor performance.

Here we will introduce a value-based approach with an expanded scope. In the expanded scope, the value of a maintenance action will be measured in different dimensions of economic, social and environmental. There are no general and universally accepted metrics for measuring the value; each asset owner can have his/her own metric system for value measurement within these dimensions.

The definition of value results in different optimal maintenance policies compared to the cost based method. The economic, social and environmental impacts of owning an asset at time $t$ when the asset is in condition $c_t$ and the demand is $D_t$ can be defined as $(e^g_{t,c_t,D_t},\ s^g_{t,c_t,D_t}, v^g_{t,c_t,D_t})$. Similarly every maintenance action taken at time $t$ can be associated with economic, social and environmental costs. These costs are defined by $(e^c_{t,c_t,x_t},\ s^c_{t,c_t,x_t}, v^c_{t,c_t,x_t})$. For a given owner the value of its asset is defined by the wealth generated by the asset at time period $t$ minus resources used for maintenance actions during that time period. Hence the new contribution function can be shown as Equation 4.

Equation 4: Value based contribution function

$$\mathrm{P}'(c_t, x_t) = (e^g_{t,c_t,D_t},\ s^g_{t,c_t,D_t}, v^g_{t,c_t,D_t}) - (e^c_{t,c_t,x_t},\ s^c_{t,c_t,x_t}, v^c_{t,c_t,x_t}).$$

The proposed method for calculation of the contribution function increases the complexity of the problem. While in the *cost based* it is sufficient for the asset owner to focus on its asset, in the *value-based* method the owner has to have an understanding of the network that the asset belongs to as well as the impact its decisions has on both the asset and the whole network.

### 2.3.6. The objective function:

The definition of the objective function depends on the asset management approach taken by the owner. In the cost based approach the objective is to minimize the discounted sum of the contribution function. This objective function is shown in Equation 5.

Equation 5: Cost based contribution function

$z = \min_{(x_t)_{t=0}^{T}} \sum_{t=0}^{T} (1+\mathrm{r})^{\mathrm{t}} \mathrm{P}(c_t, x_t)$ where $r$ is the discount factor.

In the value based approach the objective of the optimization model is to maximize the value generated by the asset over the planning horizon. For the economic dimension of the contribution function there are known methods of discounting future expected economic value into current time, however similar methods are not fully developed for the other value dimensions.

The objective function for the value-based optimization is to maximize the value that asset creates over its planning horizon. Additionally the increase in dimensions of the value measurement results in a Pareto set of solutions. These complications should be addressed before solving the problem using a multidimensional contribution function. The value based contribution function is shown in Equation 6 where $\gamma_t$ is coefficient vector for discounting the future social and environmental effects of the asset and *w* is the weight vector defined on the three dimensions of economics, social and environmental.

Equation 6: Value based contribution function

$$z = \max_{(x_t)_{t=0}^{T}} \sum_{t=0}^{T} \gamma_t \mathrm{P}'(c_t, x_t).w$$

### 2.3.7. Implementation Issues

Using a *cost based* approach the owner has to go through the following two steps:

Step 1: The owner observes the state of the asset and predicts the future state of the asset. The asset condition changes over time.

Step 2: The owner has to select the best possible maintenance action to minimize the ownership cost of the asset.

Using a *value based* approach the owner goes through the following three steps:

Step 1: Predict the future state of the asset;

Step 2: Predict the effect of the future state of the asset on its value generation potential;

Step 3: Determine maintenance actions to maximize the value generated by the asset.

In this chapter we solve the problem with a series of assumptions:

- Only the economic dimension of cost/value space is considered;
- The demand for the asset depends only-and-only on the condition of the asset;

- The maintenance action selected by the model at the end of the current period is applied to the asset before the beginning of the next period;
- There are no constraints on available resources;

The above assumptions don't necessarily restrict the outcome of our models. We plan to relax them in the remainder of this thesis as follows:

- The first assumption is relaxed in chapter 4 by using a multidimensional space for calculating the value of the action/asset.
- The second assumption is relaxed in chapter 5 by considering multiple owner-agents in the system;
- In current stage the demand condition elasticity is considered as given; this assumption will be relaxed in couple of steps. In chapter 3 the sensitivity is calculated based on the preferences of the user on driving time. In chapter 4 by introducing the activity based demand model we will make it possible for demand locations to switch places from one node to the other;

In this chapter we will investigate the differences between the two approaches. The relaxation of the first assumption will expand the solution space and cause optimal solutions move further apart. By relaxing the second and the third assumptions we must calculate some of the information that we are currently considering as given. Relaxing the last assumption will turn the general problem into a specific case and will tie the solution of the problem to its characteristics.

## 2.4. Illustrative Example

A single asset problem is represented here by a two nodes (A and B) connected by a single link ("Link") as shown in Figure 3. The

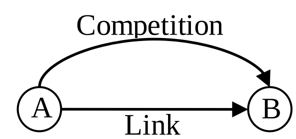


Figure 3: Single asset problem

link is our asset and is used to serve flow (e.g., traffic flow or demand for mobility) from one node to another. There may be one or more competing links (assets) between the two nodes to serve the same demand. We assume that the asset's condition deteriorates over time and that the asset owner has the option of applying maintenance treatments to improve asset condition. The demand for the asset depends on its condition and the owner of the asset has to maintain the asset at a minimum condition to avoid certain penalties.

For the above example we will assume that the following information is known: deterioration curve of the asset, cost of maintenance action, improvement effect of maintenance action, user cost and the demand-condition sensitivity of the asset.

The deterioration curve of the asset is assumed to have a Sigmoid shape with slow deterioration in the early stages of asset life followed by a rapid deterioration in middle life and ending at a slow rate towards the end of life. The base deterioration curve of Figure 4 represents the underlying Sigmoid function. All assumptions for maintenance actions and their life extension effect are made based on expert's knowledge and are presented in Table 2.

Table 2: Maintenance actions

| Maintenance Actions | Life Extension |
|---|---|
| **M1 (do nothing)** | 0 |
| **M2** | 3 |
| **M3** | 5 |
| **M4** | 7 |
| **M5** | 10 |
| **M6 (reconstruction)** | 25 |

The outcome for cost based optimization is shown in Figure 4. Optimal maintenance strategies depend on the definition of the contribution function. The optimization model suggests two different optimal maintenance curves depending on the definition of the contribution function. These can be defined either as *action cost* or *user + action cost*. Asset at perfect condition is rated as 1; with no maintenance actions the asset will deteriorate according to the Base Deterioration curve. If the *agency cost* is the only factor in the contribution function, optimal maintenance actions would be to maintain the asset just enough to keep its condition higher than the minimum service level required at the end of the planning horizon. However, if *user cost* is added as another factor to the contribution function, the optimal performance curve of the asset would change to accommodate this new contributor. Adding *user cost* to the decision making process broadens the scope of the problem and leads to a different solution.

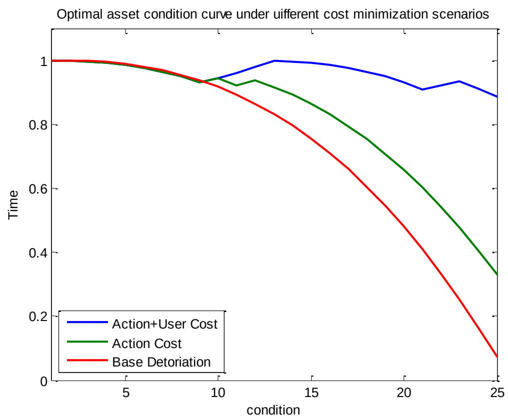


**Figure 4: Optimal Performance Curve for Cost based Optimization**

In the value based optimization the objective is to maximize the economic value that the asset generates. In this approach the asset is an entity, which is capable of providing services in exchange for user fees. The user fee is set in a way to create a 15% return if the asset works at its capacity for the 25 years planning horizon. In this case, users can treat the use of the asset as a purchase of a service with some demand elasticity to quality. The quality-demand elasticity will act as a measure of expected drop in the number of customers to the drop in condition of asset, e.g., a %10 decrease in the condition rating of the asset when the demand condition elasticity is %15 will result in a loss of %1.5 of the demand. The contribution function this value-based approach for a single dimension (economic) problem is shown in Equation 7.

**Equation 7: Single dimenstion valuebased contribution function**

$$\mathrm{P}'(c_t, x_t) = c_t \times \alpha \times r - k_{t,c_t,x_t}$$

With this approach, the expected costumer demand at different conditions is used by the agency as a metric to adjust its decisions and select actions that create the most value for the agency. Different assets have different condition-demand elasticity, i.e., in urban areas drivers have more choices for going from one location to another compared to rural areas. This availability of options and alternatives makes urban drivers more elastic to the quality of services in their roadways than the rural drivers. By considering demand and its elasticity to quality of service, optimal performance of the asset will be more tailored to its specific characteristics, i.e., the agency is expected to maintain a higher level of service when the demand is more sensitive to the quality of the service. As shown in Figure 5, the optimal performance curve of the asset changes based on the quality-demand elasticity of asset to ensure that the maximum economic value is generated. For the case of demand-condition elasticity of 1%, users do not have many options and the best strategy for the owners is to keep the condition of the asset higher than the minimum service level. However, for cases of higher demand-quality elasticity the optimal maintenance and optimal condition of the asset change to best respond to this change. Figure 3 shows that with increasing demand-quality elasticity the optimal maintenance conditions also increase. Clearly with higher elasticity, any drop in the condition rating of the asset will lead to higher drops in demand, thus higher levels of loss in revenue for the owner.

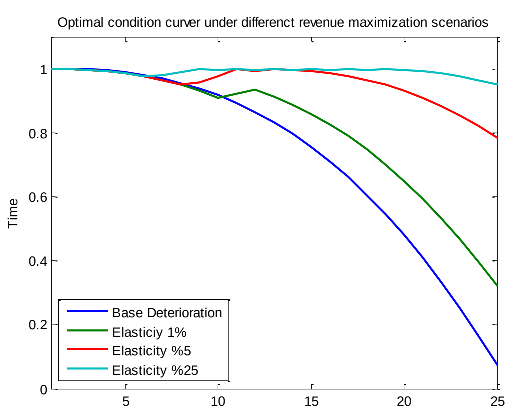


**Figure 5: Optimal Performance Curves for Value-base Optimization**

## 2.5. Impact on Society

These two different maintenance approaches have impacts beyond just the owner and the asset. Any decision made in maintenance and rehabilitation of infrastructure assets will affect the society as a whole. Such an impact is better demonstrated by applying value based and cost based maintenance approaches on assets belonging to the transportation infrastructure of our virtual society (to be explained in chapter 4). The virtual has an underlying grid (flow network), which creates an elastic environment for users with respect to the quality of links. An elastic environment was selected for the operation and the maintenance of a corridor within the grid. The societal effects of optimal maintenance strategy based on agency cost and agency revenue were compared against each other as shown Table 3. In this table the first row is production of hash and bean compared to no deterioration case; the second row is the utility of the society compared to no deterioration case; the third row is the total land price compared to no deterioration case; and the last row is the total travel time compared to no deterioration case. The case value based approach is consistently creating better results (from the society's perspective) for the feedback that is getting through its revenue collection mechanism.

Table 3: Societal impact of different maintenance scenarios

| | Base Case | Agency Cost | 25% sensitivity |
|---|---|---|---|
| **Production** | (100%, 100%) | (85%, 86%) | (101%, 94%) |
| **Utility** | 100% | 91% | 99% |
| **Land Price** | 100% | 82% | 83% |
| **Travel Time** | 100% | 227% | 130% |

## 2.6. Extension to Multiple Asset Optimization

The difference in optimal performance of assets using cost based and value based methods indicates the need for further investigation on these approaches. The cost based approach looks at the network assets independent of each other and aims at minimizing the ownership cost of the network by minimizing the ownership cost of individual assets. This method is fairly simple to apply to large networks just by considering a shared pool of resources for maintenance action along the network.

The value based method, however looks at the system as a whole and creates an optimized maintenance policy that is directed toward achieving that goal. In large scale network applying this method requires understanding of the mechanisms involved in the operation of the network and interactions between different assets of the network. This method is clearly more complex to implement than the cost based method, however by considering the final goal of the system it delivers policies that are more aligned with the goal of the system.

The above single asset model can be expanded and used for selecting optimal maintenance actions in a network environment. The expansion path will be different for value-based and cost-based approaches. In cost based approach the network problem is simultaneous selection of optimal maintenance solutions where the available resource for all assets is shared. In the value based approach the scope of the problem is beyond just individual assets; in value-based approach individual links act as a part of a corridor. In a larger network different corridors have different value generation capacity, and each asset within a corridor has its contribution to this overall value. In addition to assumptions of assets' independence (for cost based) or inter-dependence (for value based), long term changes in demand location should also be considered for multiple asset optimization within a network framework. Current major models (e.g. Four-step model, (59)) work with the assumption that demand generation locations are constant within a network. While valid for short-term estimations, it fails for medium-term and long-run planning horizons. The trip generation location changes over time based on the condition and location of corridors connecting different parts of the network together. Creating a multi-asset optimization framework requires the understanding of the network as well as the interactions between the assets, corridors and network users.

For cost based case, the formulation can be expanded by adding a dimension for assets, i.e., $(a)$ in Table 4. In this formulation $A$ is a set all assets managed by the owner; $x_{at}$ is the maintenance action selected for asset $a \in A$ at time $t$; $R_{t+1}$ show the available resource at time $t+1$ where the total maintenance expenditure at time $t$ is $\sum_{a \in A} k_{t,c_{at},x_{at}}$; $\hat{R}_{t+1}$ is the exogenous change in available resources; $c_{a,t+1}$ is the condition of asset $a$ at time $t+1$ when the asset was in condition $c_{a,t}$, deteriorated $\hat{d}_{a,t}$ and improved $I_{t,c_{at},x_{at}}$ at time $t$. The contribution function of individual asset at time $t$, $\mathrm{P}(c_{at}, x_{at})$, is the sum its maintenance cost ($k_{t,c_{at},x_{at}}$), users cost ($u_{t,c_{at}}$) and penalties ($p_{t,c_{at}}$) occurred at it at time $t$.

Table 4: Expandedcost based formulation

| | |
|---|---|
| Objective Function | $z = \min_{(x_{at})_{t=0}^{T}} \sum_{t=0}^{T} (1+\mathrm{r})^{\mathrm{t}} \mathrm{P}(c_{at}, x_{at})$ |
| Transition Function | $R_{t+1} = R_t - k_{t,c_{at},x_{at}} + \hat{R}_{t+1}$<br>$c_{t+1} = c_t - \hat{d}_t + I_{t,c_{at},x_{at}}$ |
| Contribution Function | $\mathrm{P}(c_{at}, x_{at}) = k_{t,c_{at},x_{at}} + u_{t,c_{at}} + p_{t,c_{at}}$ |

For the value-based case we need to identify corridors with significant impact to the system and create the maintenance plan based on the importance and characteristics of corridors. This will be part of the future research for this thesis.

## 2.7. Cost based vs. Value Based

The question using cost based or value based model is one of the main question to be addressed by owners before adopting a maintenance regime. There is no one single answer to this question and the best approach changes from one owner to the other based on their principle value dimensions and their sphere of influence. For the owners with broader responsibilities value based option where multiple value dimensions are accounted in decision making are better choice and for owners with very simple value space cost based can show to be a better regime. One might argue that looking at adding the opportunity cost to the model would lead to identical results in cost based and value based approaches. This argument is numerically valid; however measuring the opportunity cost itself requires the model to have the ability to measure the net value of making a decision and consequently the lost opportunity of not making that decision. The value based approach to the infra-structure investment should be more look at a new perspective towards the investment which addresses the complexities of the system rather than just a computation approach.

# 3. Chapter 3: Network Flow Formulation of Asset Management

## 3.1. Preliminaries

In the previous chapter we introduced value-based maintenance modeling and discussed the differences between this and a *cost-based* approach over a single asset setting. We also presented the extension to multiple asset problems. A number of assumptions were made, most importantly; no system dynamics was included in the analysis and comparison. Here, "system dynamics" is driven by the underlying flow of "things" or "individuals" ("users" in general) between assets, and depends on the:

- Inter-dependencies between assets and between assets and their users and owners; and
- Behavioral characterization of individuals who use, own and/or operate the assets, and how their behaviors dynamically change with state of assets.

The first step towards relaxing this assumption is to create a modeling environment, which is capable of capturing the underlying flow and replicating the behavior of target environments for further investigation. The integration of flow dynamics into the maintenance optimization model allows us to capture complex behavioral changes of users driven by operation and maintenance decisions. The understanding of these complex behaviors leads to optimal operation and maintenance plans which are specific to a given system and its dynamically changing goals and objectives. In principle, we are creating a closed loop decision-making environment which takes into account feedback from the time-variant behavioral changes of individuals due to asset conditions or other system configurations. Hence, one may classify the decision models of Chapter 2 as "open-loop" models and the models presented here as "closed-loop" models.

The value of maintenance and investment decisions should be measured within the context that they are made. Setting different boundaries for calculating the value of the system can lead to different optimal maintenance strategies. If we look at an asset as a standalone entity the maintenance and upkeep of the asset will be essential to its operation compared to having the asset as part of a larger system. With asset redundancy, keeping all the assets at near perfect condition might not be at the best interest of the overall system. In economic terms, flow generates value, thus, decisions should be directed toward optimizing flow. But at the same time, flow (when is moving slowly) could adversely impact social and environmental milestones. Thus, the general problem of asset management reduces to a multi-objective network flow optimization problem.

To model the underlying flow dynamics we will construct a network flow model where *users* travel or move along links between any two nodes. Generally speaking, this is an open network where flow from outside is also possible, but here, we will only focus on closed flow networks where migration of external users into the system will not be possible. There is no centralized control of flow within this network; each individual runs an optimization model to define its own flow map across the network over a specified time window. In general, such distributed decision making may take advantage of collaboration and information sharing among the individuals. But here we will assume that these decisions are made separately by the individuals and according to their own goals and objectives and by taking into account their <u>perception</u> of network conditions. Each asset (link between nodes) will have an owner, who is capable of running its own optimization routine to determine the best course of maintenance actions for that asset. This owner may apply cost-based or value-based approach, as described in Chapter 2.

The decision-making framework presented in this chapter will be generic and configurable to different application domains, including transportation and production systems. For the transportation systems, the flow between two nodes (origin and destination) will signify traffic flow. A production system can be modeled as a network where work orders come into the network from different initiation points (source nodes) and the final product is produced at the end of production line (sink nodes). Here manufacturing processes are represented as edges in the network, with the direction of these edges indicating the manufacturing process flow. It is assumed that the service time for a given process is dependent on its load and condition, i.e. service time increases with the process load and the deterioration of the process (e.g., equipment wearouts).

## 3.2. Problem Formulation

We can think of our asset network consisting of interconnected nodes and links, where “link”, “node” or both are assets to be maintained and invested on. We assume that two types of agents populate this network: *Owner agents* and *User agents*. *Owner agents* are responsible for the maintenance and upkeep of the assets, and *user agents* use the network. Each agent has its own set of objectives and optimization criteria.

A typical *user agent* wants to minimize the cost of moving from an origin to a destination via a path. The cost terms include travel time and uncertainty in the travel time. Other cost terms such as user fees for network usage can also be added to this cost function. The objective of *owner agent* is to generate the optimal set of maintenance actions to maximize the value that its asset generates. The owner agent can’t create an optimal maintenance policy without understating user responses to its operation and maintenance decisions. In response to the condition of the network, *user agents* select their optimal departure time and path based on their individual characteristics and preferences. The closed loop feedback decision and control is shown in Figure 6.

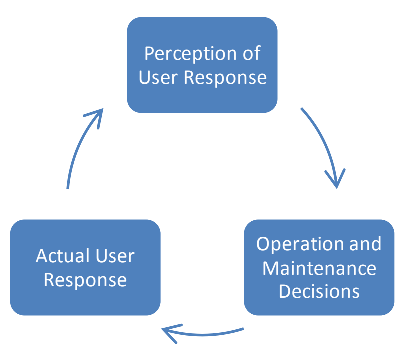

Figure 6: Decision Making Cycle of Owner Agents

The *user* level optimization focuses on finding the optimal path and departure time of *user agents* based on their perception of the network, travel times, costs of travel and lateness. It is an iterative closed loop process (as shown in Figure 7) where *user agents* learn about network characteristics i.e. mean and variance of travel times and plan their optimal actions accordingly. At each decision cycle, *user agents* optimize their path plans based on their perception of the network (historical data). This is followed by the execution of the plan and information update, to be used in the next cycle.

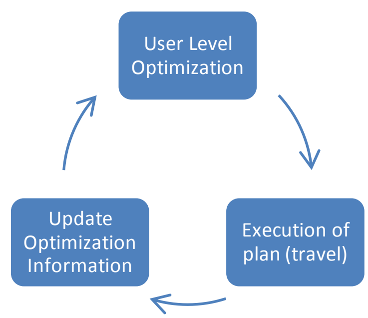


Figure 7: General flow of the user level simulation model

The problem of interest here is to develop a network simulation and optimization environment where the user and owner agents interact and operate (or live) according to their own individual set of optimal rules.

## 3.3. Technical Approach

We start with the flow network definition. Asset networks are composed of links and nodes corresponding to the sources and destinations of flow as shown in Figure 8. There can be more than one link between any two nodes. Each link is characterized by its “Start Node”, “End Node”, “Length”, “Design Capacity”, “Design Service Rate”, and “Deterioration Characteristics”. Each node also has a series of dynamic characteristics such as “Current Load”, “Current Condition” and “Current Capacity”. Here we annotate by $G = (N, A)$ the above network where $N = \{1, \dots, n\}$ represents nodes and $A = \{(i, j) | \; if \; node \; i \; is \; connceted \; to \; node \; j\}$ represents edges.

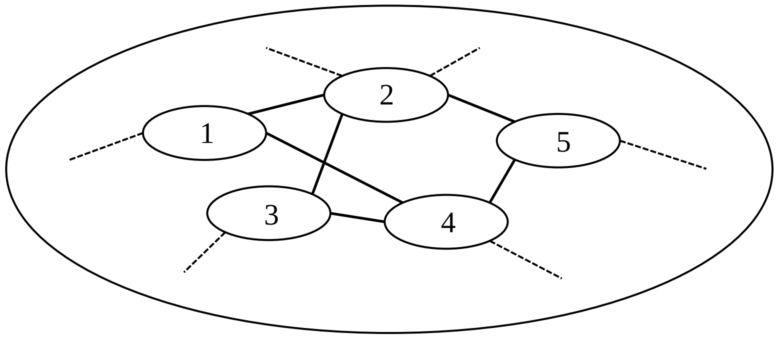


Figure 8: Asset operation network

The network nodes are origin or destination points for the users. Network users have pre-determined arrival times at their destinations. The important factors in users' decision making are travel time and lateness of users as well as the cost of using the network. Travel times are defined as the duration between departure (from the origin) and arrival times (at the destination). The lateness is defined as the difference between the arrival cutoff time at destination and actual arrival time at destination; arrival cutoff time is the latest time that the users can arrive at their destinations without paying any lateness penalties. Travel time and lateness at destinations are defined in Equation 8 and Equation 9 where:

- $AT_{U_k j}$: Arrival Time of user $U_k$ at node *j*
- $DT_{U_k i}$: Departure Time of user $U_k$ from node *i*
- $ACT_{U_k j}$: Arrival Cutoff Time of user $U_k$ at node *j*

Equation 8: Travel Time of user $U_k$ from source $i$ to destination $j$

$$TT_{U_k ij} = AT_{U_k j} - DT_{U_k i}$$

Equation 9: Lateness of user $U_k$ in destination $j$ if the source is $i$

$$L_{U_k ij} = \max(AT_{U_k j} - ACT_{U_k j}, 0)$$

Condition of a link is one of its dynamic characteristics; it deteriorates due to usage and improves by applying appropriate maintenance actions. Condition deterioration of a link leads to its loss of capacity, which not only impacts that link, but also other competing and collaborating links as well. The deterioration pattern used in our research is based on a Sigmoid function with cumulative load ($linksUsage$) as the only independent variable (Equation 10). $linksTotalCapacity$ is a design characteristic of the link and changes from one link to another.

$$condition = \left(1 - \frac{\tanh\left(-5 + \frac{linksUsage}{linksTotalCapacity}\right) * 7}{2} + 0.5\right) * 0.8 + 0.2$$

Equation 10: Base deterioration model

### 3.3.1. User Definition

We create a society of *user agents* each with different characteristics and usage preferences of the network. Consider network $G = (N, A)$ with users $\{U_1, \ldots, U_T\}$, where user $U_k$ is characterized by its Origin, Destination, Arrival Cutoff Time and Risk Aversion factor $(O_{U_k}, D_{U_k}, ACT_{U_k}, RA_{U_k})$. The origin and destination of a user identifies the source node and the destination node on the graph; Arrival Cutoff Time is the latest time that a user can be at its destination and not pay any lateness penalty, and Risk Aversion factor is a measure of user's sensitivity to late arrivals. The risk factor shows the percentage of trips that the user can be late.

Additionally each user has a perception of the network, for user $U_k$ this perceptions is defined as $G_{U_k} = \left(N_{U_k}, A_{U_k}\right)$. This perception model contains user's understanding of the network connectivity which can be a subset of nodes and edges of the original network as well as other edge characteristics such as:

- $ETT_{U_k ij}$ is the Expected Travel Time of user $U_k$ from node $i$ to node $j$;
- $ETC_{U_k ij}$ is the Expected Travel Cost of user $U_k$ from node $i$ to node $j$;
- $VTT_{U_k ij}$ is the Variance of Travel Time of user $U_k$ from node $i$ to node $j$;

#### *3.3.1.1. User Level Optimization*

Based on its perception of the network, each *user agent* solves a shortest path problem to identify the route that it has to take to its destination. The objective function for the shortest path problem is defined by:

$$\text{objective function} = \mathrm{ETC}_{\mathrm{U_k ij}} + \mathrm{f}\left(\mathrm{ETT}_{\mathrm{U_k ij}}, \mathrm{VTT}_{\mathrm{U_k ij}}\right)$$

where f( ) is $\mathrm{costOfTime} \times (\mathrm{ETT}_{\mathrm{U_k ij}} + \mathrm{k}_{\mathrm{RA}_{\mathrm{U_k}}} \times \mathrm{VTT}_{\mathrm{U_k ij}})$.

The best path for each user is obtained using a recursive function with the following parameters for each recursion:

- Current Location
- Visited Nodes
- The mean time to travel to current location
- The variance of the travel time to current location

We have developed an algorithm to finds the best path from the origin to the destination by selective enumeration of all possible choices. At each recall of the algorithm the current position changes from current location to an unvisited neighboring node, and the algorithm is recalled for finding the best path from current location to the final destination with updated recall values. The following notations are used:

- $U^c$ as current user
- $N^v$ as a set containing the list of visited nodes in the order they are visited;
- $UB$ as the upper bound the objective function;
- $N^c$ as the current node
- $NN_k$ as set of neighbors of node $k$
- $CTM$ as the mean time to travel to current location

- $CTV$ as the variance of the travel time to current location
- $CTT$ as Current Travel Time
- $ADT$ as Average Drive Time (calculated based on user perception);
- $VDT$ as Variance of Drive Time (calculated based on user perception);

Each *user agent* finds its best route by going through the following steps:

{

1. Set $N^v = \Phi$
2. Set $UB = 0$
3. $CTM = 0$
4. $CTV = 0$
5. Call the recursive function by passing the following parameters: ($N^c$, $N^v$, $CTM$,$CTV)$
6. Return the best path and the expected travel cost/time for the best path

}

The recursive function is defined as follows:

{

1. Get $N^c$, $N^v$, CTM and CTV
2. If $N^c$ is equal to $D_{U^c}$ and Current Travel Time less than the Upper Bound go to 3 else go to 5
3. Update the UB for Travel Time with the value for the Current Travel Time($\mathbf{UB} = \text{CTT}$)
4. Update the best path with the current value for the $N^v$($\text{bestPath} = N^v$)
5. If UB> Current Travel Time

6. For every node in $\mathrm{NN}_{\mathrm{N^c}}$ (for $\mathrm{k} = 1\!:\mathrm{n}(\mathrm{NN}_{\mathrm{N^c}})$)
7. If $\mathrm{NN}_{\mathrm{N^c},\mathrm{k}}$ is not visited
8. $\mathrm{N^c} = \mathrm{NN}_{\mathrm{N^c},\mathrm{k}}$
9. $\mathrm{N^v}_{\mathrm{length(N^v)+1}} = \mathrm{NN}_{\mathrm{N^c},\mathrm{k}}$
10. $\mathrm{CTM} = \mathrm{CTM} + \mathrm{ADT}_{\mathrm{N^v}_{\mathrm{length(N^v)-1}},\mathrm{N^v}_{\mathrm{length(N^v)}}}$
11. $\mathrm{CTV} = \mathrm{CTV} + \mathrm{VDT}_{\mathrm{N^v}_{\mathrm{length(N^v)-1}},\mathrm{N^v}_{\mathrm{length(N^v)}}}$
12. Recall the best path function with updated values for $\mathrm{N^c}$, $\mathrm{N^v}$, CTM and CTV
13. Go back on level

}

Travel time in the network is not deterministic. In their perception models, *user agents* associate an average and a variance of trip time to each link based on their historical usage data. In the route choice problem different *user agents* use the information on the variance of trip times to avoid lateness penalties. Every user has an avoidance factor toward being late at its destination (this factor can be defined as the percentage of travels that the *user agent* can be late). The average and variance of the trip time and *user agents'* risk aversion determine the departure time of *user agents* from their origins. The departure time of a user agent is calculated by:

$$depatureTime = ArrivalCutOffTime - (expectedTravelTime + safetyTravelTime)$$

For user $g$, $safetyTripTime$ can be calculated by $stt = \sigma_{l,g} \times k_{\alpha_g}$in a link where the variance of trip time over a link is ${\sigma_{l,g}}^2$, and risk aversion factor for user is $\alpha_g$,. When users' path consists of more than one link, the variance for the whole path is used, i.e.,

$$stt = \sqrt{\sigma_{l_1,g}^2 + \sigma_{l_2,g}^2} \times k_{\alpha_g}.$$

where $\sigma_{l_1,g}^2$ is the variance of trip time in link 1 and $\sigma_{l_2,g}^2$ is the variance of trip time for link 2.

$expectedTravelTime$ is defined as the average usage time of a specific link by a user. It is assumed that users make their decisions based on their experience from past (defined on the number of days or decision periods). Similar to variance of drive time, if a trip consists of more than one link, the total travel time will be calculated by summation of trip times in individual links.

#### 3.3.1.2. Simulation

The above network flow model and the formulation of user level optimization are integrated into an agent based *simulation environment*. For *user level simulation*, *user agents* execute their travel plans and interact with each other as well as the environment. To reach their destination each *user agent* has to go through one or more links. The service time for each link is a function of link's capacity, load, maximum service rate and condition. Arrival or departure of *user agents* to/from links is defined as events in the simulation model. The initial event lineup (*eventList*) is created at the end of optimization section by sorting *user agents* based on their departure times. Each event identifies the *user agent*'s next destination and time of arrival at next destination. The following shows fundamental steps of the *user level simulation*.

{

1. If $\text{length}(\text{eventList}) > 0$ go to step 2, else go to step 11
2. $\text{currentEvent} = \text{eventList}(1)$
3. If $\text{currentEvent.nextDestination} <> \text{finalDestination}$ go to step 4 else go to step 9;
4. Set $\text{currentEvent.nextDestination}$ as the next node in the best path
5. Update the arrival time at next destination as a function of load, speed and …
6. $\text{currentLink.load} = \text{currentLink.load} + 1$
7. $\text{previousLink.load} = \text{previousLink.load} - 1$

8. move the event to its location in the event line up, go back to step 1
9. $\text{previousLink.load} = \text{previousLink.load} - 1$
10. remove the event from the event line up list, go back to step 1
11. End

}

As mentioned earlier, the service time is a stochastic function of link's capacity, load, max service rate and service condition. For a given capacity, maximum service rate and condition, the service time would solely depend on the load of the link. For loads below the capacity of the link the travel time is a random variable with the mean of link length divided by the design service rate. For loads higher than the capacity the mean service time for new *user agents* entering the link will be a function of the original mean service time and the current load of the link; the service time will increase proportional to the $linkLoad/linkCapacity$.

At the end of each period *user agents* update their perception of the network and run the optimization for selecting the next cycle's best route and departure time. In addition to the user related information, link related information is also updated in the simulation model. Condition of the link is a function of the aggregate load of the link since its last repair and the link's condition after repair. Condition of the link reduces overtime due to the usage; consequently the $linkCapacity$ reduces from its design capacity proportional to the reduction in the service level.

### 3.3.2. Owner Definition

The *owner agent* mentioned earlier in this chapter operates in a network environment where the poor performance of its assets can lead to loss of demand and possible penalties. To avoid these unfavorable conditions *owner agents* perform maintenance actions on their portfolio of assets. Owner agents use either cost- or value-based maintenance regimes illustrated in the previous chapter to plan their operation and maintenance activities.

## 3.4. Use Cases

The general model described above will be applied to two application domains, namely transportation and production systems.

### 3.4.1. Transportation

For the network $G = (N, A)$ (Figure 9), consider $N = \{1, 2, 3, 4, 5\}$ and $A = \{(1{,}2),\ (2{,}1),\ (1{,}4),\ (4{,}1),\ (3{,}2),\ (2{,}3),\ (3{,}4),\ (4{,}3),\ (4{,}5),\ (5{,}4),\ (2{,}5),\ (5{,}2)\}$. In this example each link is assumed to have the design capacity of 25; starting conditions and service rates are assumed to be 1. Length of links are assumed to be (0.4, 0.4, 0.3, 0.3, 0.3, 0.3, 0.4, 0.4, 0.5, 0.5, 0.5, 0.5), respectively. There are total of 1000 users in the system and the travel demand between any two given nodes is assumed to be proportional to the square inverse of the distance, e.g. the demand for 1-5 is equal to 16 where the demand for 1-2 is equal to 63. User agents have one of the two possible arrival cutoff times (one time unit apart), each selected with probability 0.5. The objective of the user agent is to get to its destination at every time period at lowest possible cost.

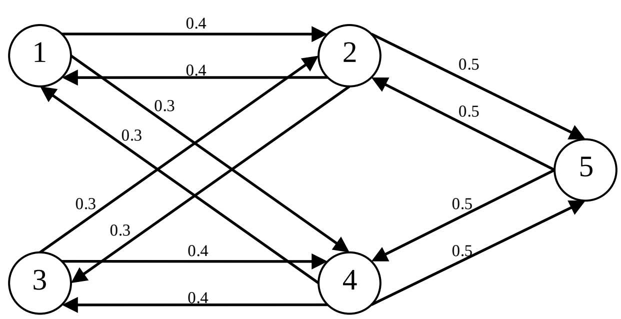


Figure 9: Detailed illustration of the network G

#### *3.4.1.1. Initial Conditions*

It is assumed that users have a complete initial perception of the network, i.e. they are fully aware of the network connectivity. Additionally they have an initial perception of the service time of each link. The initial perception of service time is created at the initialization i.e. filling the memory of the *user agents* with 4 random numbers for the drive time of each link from a normal distribution where the mean is equal to expected drive time ($lengt/speed$) and the standard deviation is equal to $1/5$ of the mean.

Using the initial conditions, the optimization will yield the optimal path and departure time for each user. Table 5 shows the output of the first round of optimization model for user agents 1 and 948.

Table 5: Initial information for user agents #1 and #948

| | User Agent #1 | User Agent #948 |
|---|---|---|
| **Origin** | 1 | 5 |
| **Destination** | 2 | 3 |
| **Arrival_CutOff** | 9 | 9 |
| **Risk_Aversion** | 0.9674 | 0.9190 |
| **Departure_Time** | 8.4279 | 7.9911 |
| **Route_Selection** | [1 2] | [5 2 3] |

At the end of the first simulation period each *user agent* would have an updated perception of the network and travel time which will be used for its trip planning in the next period. The one period updated information for users 1 and 948 is presented in Table 6.

Table 6: Learning over time - One period information for user agents # 1 and # 948

| | User Agent #1 | User Agent #948 |
|---|---|---|
| **Origin** | 1 | 5 |
| **Destination** | 2 | 3 |
| **Arrival_CutOff** | 9 | 9 |
| **Risk_Aversion** | 0.9674 | 0.9190 |
| **Departure_Time** | 8.3636 | 7.8436 |
| **Route_Selection** | [1 2] | [5 2 3] |
| **Lateness** | 0 | 0.3384 |
| **Travel_Time** | 0.5307 | 1.3473 |

At the end first period both agent 1 and 948 have additional information compared to the beginning of the period. These agents use this additional information to update their perception of the network (expected travel time and the variance of the travel time). As a result, agents will depart from their origins earlier in the second period compared to the first period.

User agents update their perception of the network at each period and use the information for planning their route in the next period in order to minimize their lateness (total usage cost in general case). Figure 10 shows the change in the Total Travel Time and Total Lateness of the network. As illustrated in the figure the total lateness reduces in the first 5 periods and stabilizes for the remainder of the simulation.

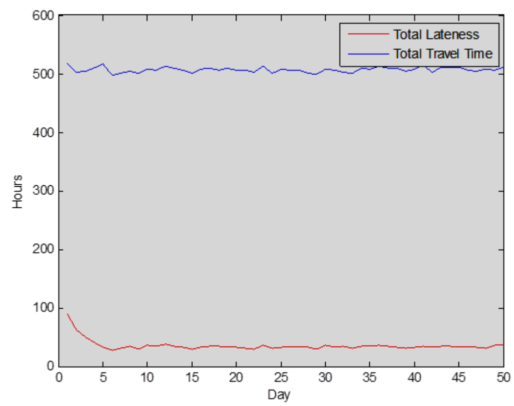


**Figure 10: Changes in lateness and total travel time**

*User agents* use their updated perception of the network to avoid lateness at their destination by changing their departure time or route. The change in the selected route and departure time changes link's load pattern in different simulation runs. Figure 11 and Figure 12 show the change in the load pattern of links $(1,2)$ and $(1,4)$ due to agents' learning. This shift in the usage patter is showing earlier peak usage times of links which is due to earlier departure times of users to avoid lateness.

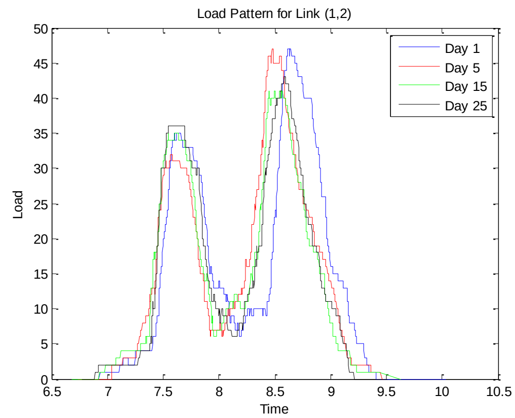


Figure 11: Change in the Load Pattern of Link (1,2)

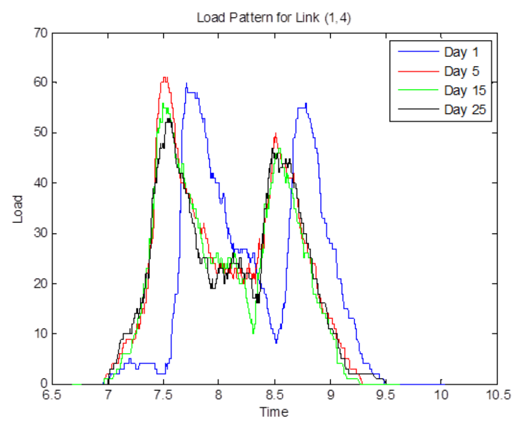


Figure 12: Change in Load Patter of Link (1,4)

As mentioned earlier in this chapter, link condition is a dynamic characteristic and can change over time. Condition deterioration of a link leads to its loss of capacity, which not only impacts that link, but also other competing and collaborating links as well. The deterioration pattern used in our model is based on a Sigmoid function with cumulative load (linksUsage) as the only independent variable where the $llinksTotalCapacity$ (total number of link users before the condition reaches its minimum, as introduced in Equation 10) is assumed to be 3000 () (Equation 11).

$$condition = \left(1 - \frac{\tanh\left(-5 + \frac{linksUsage}{3000}\right) * 7}{2} + 0.5\right) * 0.8 + 0.2$$

Equation 11: Deterioration pattern

The simulation model assumes that link (1,4) starts to deteriorate at period 10 based on the above Sigmoid pattern. All other links are assumed to remain at their initial conditions. The resulting deterioration pattern is given in Figure 13. The exogeneity in the asset deterioration makes it impossible to have complete information on deterioration pattern of the process; however it is possible to have an estimation of the deterioration pattern of the process based on the available historical condition information and the shape of the deterioration function.

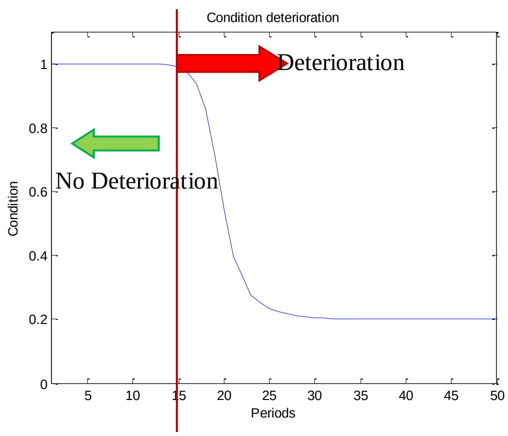


Figure 13: Condition Deterioration of Link 3

The change in the condition of a link leads to a loss of capacity, which causes an increase in the travel time of *user agents* and changes in its load pattern of the deteriorating link as well as other non-deteriorating links. The change in the usage pattern due to condition deterioration of the link (1,4) is shown in Figure 14. The link starts to deteriorate in period 10 and reaches its minimum condition in period 35.

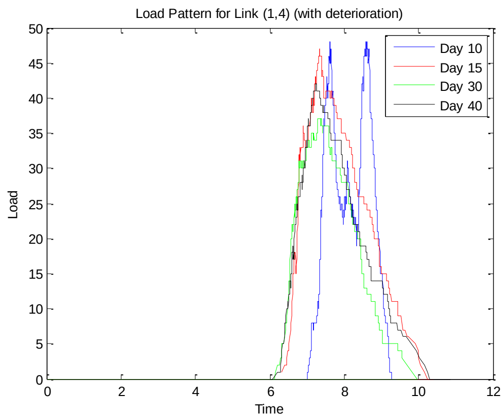


**Figure 14: Load Patter for Link (1,4) (with deterioration)**

In addition to the loss of demand and change in the usage pattern of link (1,4), the deterioration of link (1,4) affects the load patterns of other links in the network as well. Path 1-4-5 is the substitute for path 1-2-5 for agents who want to travel from node 1 to node 5. Reduction of capacity and increase in the travel time of path 1-4-5 forces agents for switch to an alternate path to get to their final destination. As a result of this behavior the load of link (1,2), as shown in Figure 15, increases with the loss of capacity of the link (1,4).

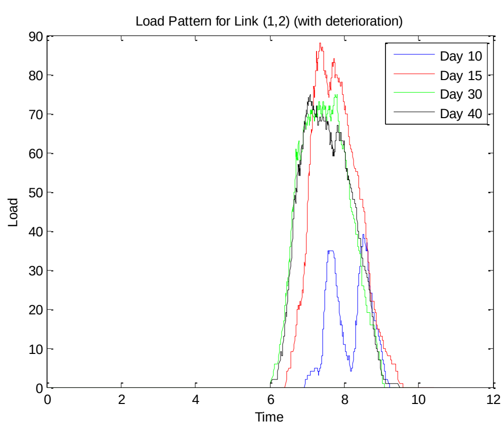


**Figure 15: Load Pattern for Link (1,2) (with deterioration)**

The changes in load pattern and link usage are the *user agents'* response to the increase in the drive time due to condition deterioration of the link. The deterioration in link (1,4) also affects the total travel time and lateness of the users. As shown in Figure 16, during the 10$^{th}$ period the total lateness of the network is stabilized after the initial learning period. The change in the condition of the link (1,4) increases the total lateness of the network. Adjustments made in the departure time and route selection made by the *user agents* will reduce and stabilize the total lateness however these adjustments lead to an increase in the total travel time of the network.

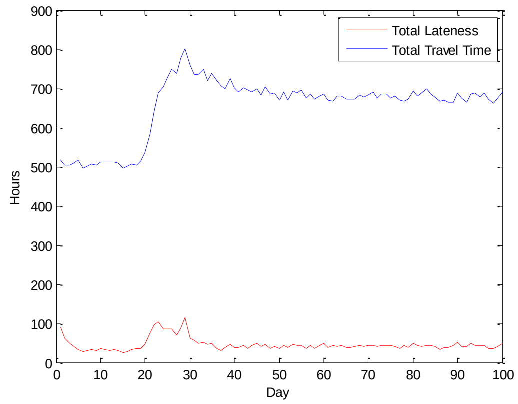


Figure 16: Total Travel Time and Lateness (Deterioration)

In addition to the load pattern, the condition deterioration of the link affects the daily usage of the link. Figure 17 illustrates how the changes in the condition of the link (1,4) affect the usage in link (1,4) as well as the usage in link (1,2).

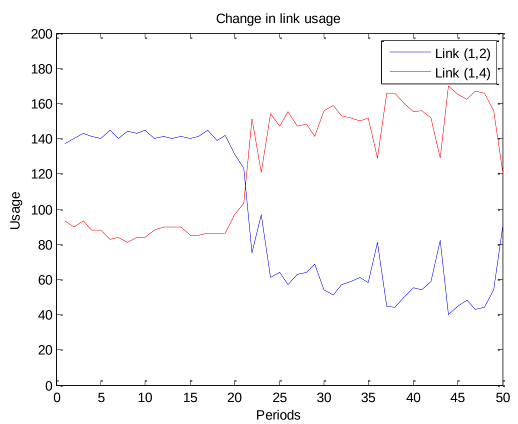


Figure 17: Usage change in two competing links

#### *3.4.1.2. Owner Level Problem*

##### 3.4.1.2.1. Cost based:

In the cost based approach the asset owner aims at maintaining a standard service level for its asset portfolio at minimum cost. For illustrative purposes we assume that *user agents* update their optimal path every period while *owner agents* update their optimal sequence actions every 3 periods (in general the frequency of *user* level optimization is higher than the frequency of the *owner* level optimization).

Likewise *user agents*, the *owner agents* create perception models of their network behavior and deterioration pattern for the assets they control. It is assumed that *owner agents* don't have complete information on underlying deterioration model of the asset, however they have general knowledge of asset deterioration pattern and they can calibrate their perception based on the historical data. In this case it is assumed that the owner agents are aware of asset's base deterioration function; however they don't have all the parameters required for precise prediction of asset condition in the future. *Owner agents* periodically calibrate their condition prediction model as well as the error in the condition prediction of the asset. In this chapter assets deteriorate based on usage according to Equation 11. The *owner agent* periodically observes the condition of the asset and fits the best Sigmoid curve over these observed points to be used for condition prediction in the future.

At each decision period, the *owner agent* creates a maintenance plan based on the length of its maintenance horizon and executes the first action in the plan. The result of the optimal maintenance actions is shown in Figure 18. This figure shows the condition curve of the asset under the optimal maintenance policy identified using a cost based model. As it is illustrated in the figure, the *owner agent* leaves the asset at minimum acceptable condition at the end of its operation period.

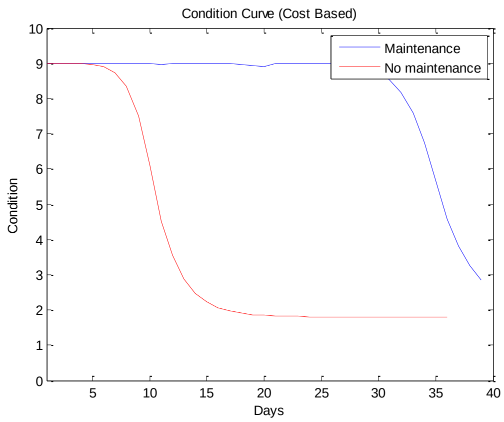


**Figure 18: Optimal Condition Curve Cost Based**

### 3.4.1.2.2. Value Based:

In the value based method, it is assumed that every unit of load generates revenue for the asset owner and the asset owner's objective is to select a set of maintenance actions to maximize the profit generated by the operation of the asset. Here, maintenance actions contribute to the operational cost and the traffic flow to the revenue.

Here, in addition to the condition curve, the *owner agent* must also have an estimate of the demand at different condition levels. This estimation can be made by the *owner agent* using the available condition-usage data. By combining the condition curve and the demand curve the *owner agent* can estimate the impact of its maintenance strategies on the demand for the asset. Figure 19 shows the optimal performance curve of the asset where the value based method is used for management of the asset.

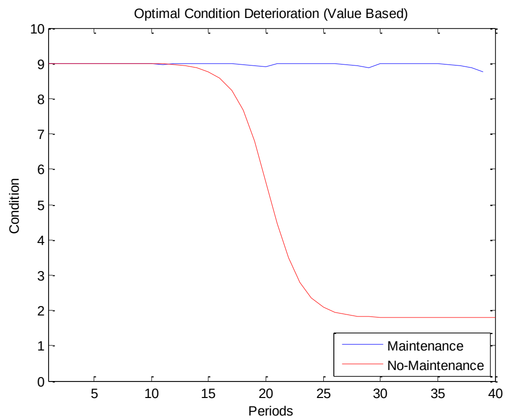


Figure 19: Optimal Condition Curve Value Based

This difference in the maintenance approach impacts the users' decisions in selecting their optimal paths and departure time and consequently their total travel time. In this example the value based method tends to maintain a higher quality towards the end of the planning horizon. This higher quality keeps the link more attractive to the users compared to the cost based approach, Figure 20.

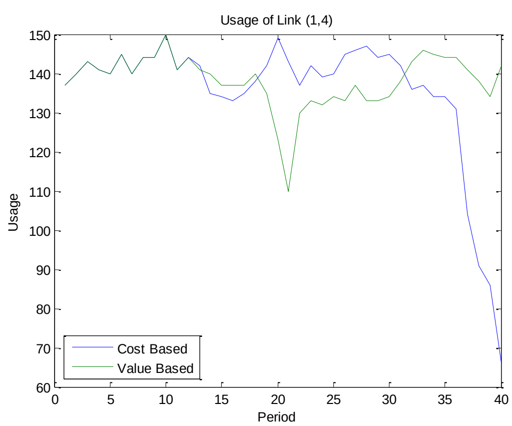


Figure 20: Usage of in (1, 4) in Value Based and Cost Based maintenance approaches

### 3.4.2. Production and Manufacturing applications

The above concept can also be used in maintenance planning of networks with different structure and objectives. A manufacturing facility can be modeled as a network where work orders come into the network from different initiation points (source nodes) and the final product is produced at the end of production line (sink nodes). Here manufacturing processes are represented as edges in the network, with the direction of these edges indicating the manufacturing process flow. It is assumed that the service time for a given process is dependent on its load and condition, i.e. service time increases with the process load and the deterioration of the process (e.g., equipment wear outs). The example network below has one sink node and four source nodes where production orders are initiated in nodes 1,2,3,4 and the final product is delivered in node 5.

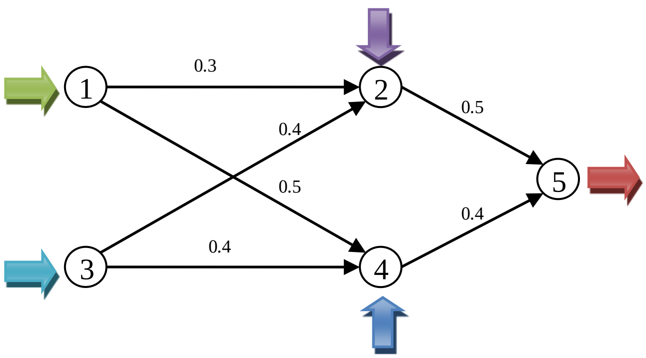


Figure 21: Sample manufacturing system

The above system is capable of producing four product families, with production starting at source nodes and taking different process flows depending on the product family. Clearly, the objective of this system is to produce good products and sell them at some market prices.

The deterioration in the process condition leads to a drop in capacity which increases the manufacturing time/cost of the final products. To avoid the increase in the manufacturing cost, the system owner has to schedule a set of maintenance actions to maintain the condition of its manufacturing processes in some acceptable levels. The owner can take two different approaches to maintenance planning: *local approach* and *system approach*.

In the production problem there are series of cutoff times for availability of products in the sink node for the production system of Figure 21. Additionally let us assume that different lateness penalties and holding costs are defined for each production batch. We assume four arrival cut off times, randomly assigned to production batches (can be explained as the scheduled departure time for transportation from the facility). Lateness penalty and holding costs are also assumed to be uniformly distributed among different production batches. We also consider a production time tolerance for production batches. If the expected production time plus the wait in the sink node before departure is higher than a certain threshold the batch owner decides not to produce the product in the period. This threshold is defined as a percentage of the standard production and safety time and is assumed to be uniformly distributed among production batches from 0 to 30% of the standard production and safety time.

For the illustrative example, we additionally make the following assumptions:

- 4 product families; product families 1 and 3 need a pre-processing and a final processing, product families 2 and 4 need only the final processing; Processes (1, 2) and (1, 4) are main preprocessing operations and processes (1, 4) and (3, 2) are side preprocessing operations;
- Demand for families 1 and 3 is equal 120, and for 2 and 4 is equal to 60;
- Batch tolerance uniformly distributed between 0 and 30%
- Arrival cutoff times: 7+1, 7+2, 7+3, 7+4 uniformly assigned to production batches
- Link Capacity: 20 for pre-processing links and 30 for final-processing links;

Each production batch has a separate owner. Different owners schedule their batches based on the minimum production cost path, similar to the *user agents* in transportation networks. These schedules are made based on the existing perception of the processing times; initial perception of model at first run and historical data for further runs. The actual process time can only be determined when the process is being used under actual load patterns. Owners reschedule their production batches upon receiving new data on process time.

The simulation model developed in this chapter will be used to estimate the actual load patterns of different processes. The arrival and departure of production jobs to/from processes are defined as events. The initial event line-up is created at the end of optimization section based on the initial perception of batch owners. Each event identifies the production batch, next destination and time of arrival at next destination.

Figure 22 shows the production time and lateness in different production periods. As illustrated in the figure, the total lateness has a reducing trend at the beginning (learning period) and stabilizes thereafter and throughout the life of the system. It can be seen in Figure 23 that the usage pattern of processes is changed to meet requirements for production lateness. The cutoff times for production process are 8,9,10 and 11. The blue line shows the number of batches in the system at any point of time in period 1 and the red line shows the same metric for period 20, which is lower than first period's value production cutoff times of 8,9,10 and 11.

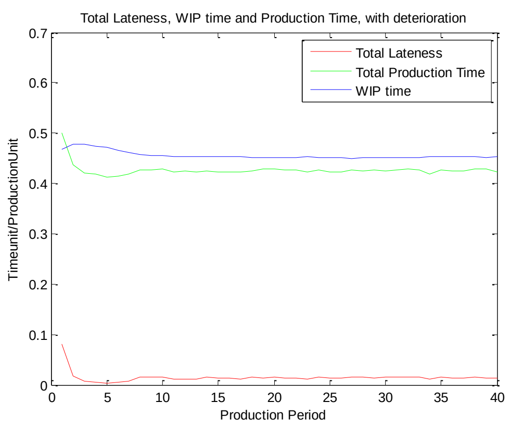


Figure 22: Total Lateness, WIP time and Production Time

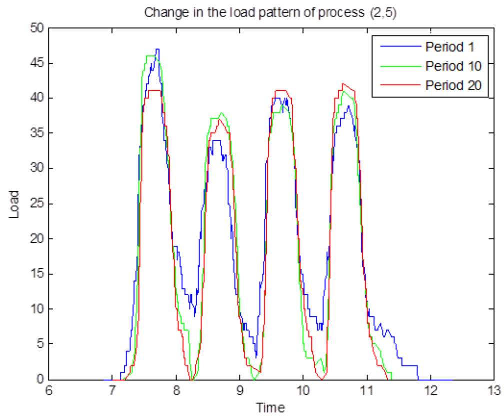


Figure 23: Shift in usage pattern of process (2,5)

Condition deterioration of a process (link) will impact other processes in the network as well. Here we assume a sigmoid deterioration function for the condition deterioration of the manufacturing processes. In the simulation model we set one of the links to start deteriorating at the 20th production period based on a sigmoid deterioration function shown in Figure 24 and all other links stay at their starting condition of 1.

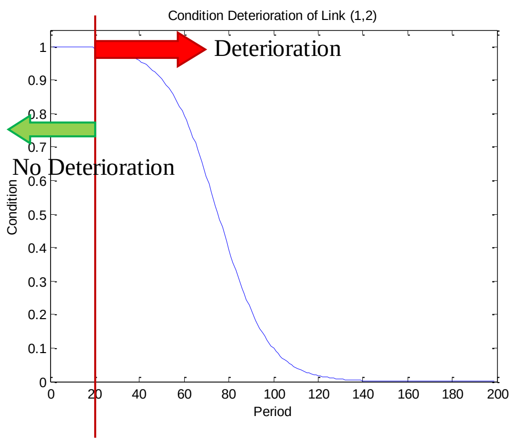


Figure 24: Process deterioration pattern for process (1, 2)

To illustrate the impact of process deterioration on lateness and processing times, processes (1, 2) and (2, 5) are allowed to deteriorate in two separate simulation runs based on the pattern introduced in Figure 24. Deterioration in one process affects the usage pattern and demand both on deteriorating process and non-deteriorating processes based on their characteristics. Figure 25 shows the change in the load pattern of process (1, 2) when process (2, 5) is deteriorating. It can easily be seen that there is a change in the load pattern of the process (1, 2) even though it is not the deteriorating process.

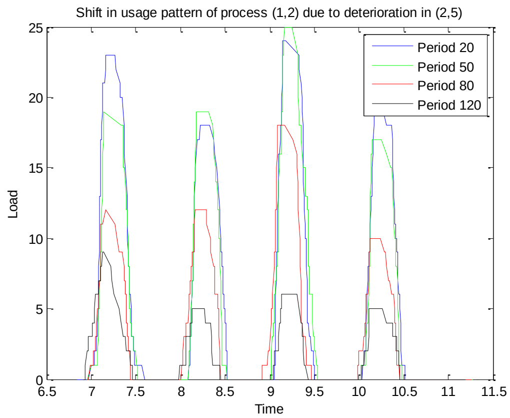


Figure 25: Change in the load pattern of process (1,2) due to deterioration of process (2,5)

Deterioration in the pre-processing stage can also have a strong impact on the usage pattern. If the process (1,2) is the deteriorating one, usage pattern of process (1, 2) as well as other processes will be influenced. Process (1, 2) is a feeding process from process (2, 5) the load lost on process (1, 2) will be passed to process (2, 5) and cause lower utilization of that process as well. Figure 26 shows the impact of deterioration of process (1, 2) on process (2, 5) and (1, 2) itself.

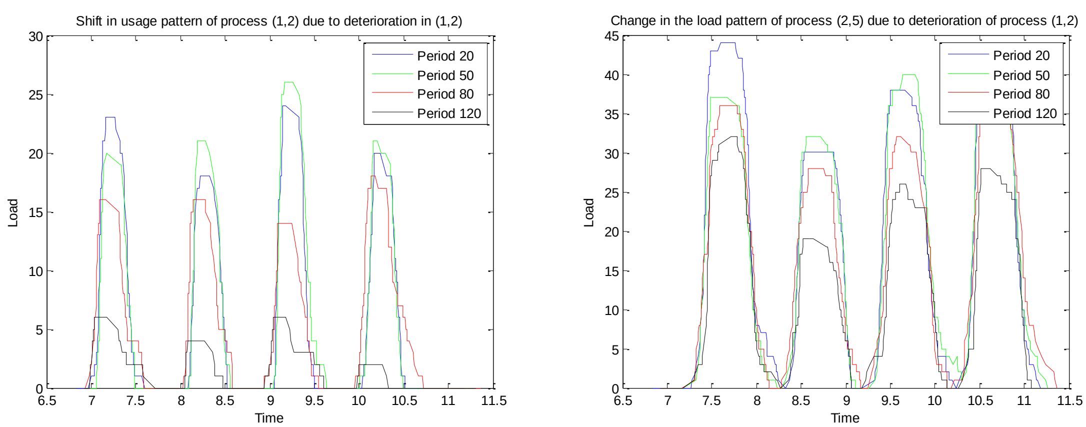


Figure 26: Shift in usage pattern of process (2, 5) and (1, 2) due to deterioration in (1, 2)

In addition to the load pattern, the deterioration of process (1, 2) changes the total usage of other processes in the network. The loss and shift of demand caused by deterioration of the process (1,

2) leads to change in the nominal processing time of the system ($standard\ processing\ time\ *\ usage$) which is a baseline for the revenue generated by the system. As it is illustrated in Figure 27 the total change in the nominal processing time of a production system can be decomposed to change in the deteriorating process and combined change of non-deteriorating processes. In Figure 27 the horizontal axis is the condition of process (1, 2) and the vertical axis is the total revenue. The green line shows the total revenue made by the system at each condition of process (1, 2). This revenue can be broken down into the revenue made by process (1, 2), usage of process (1, 2) times its standard processing time, and the revenue made by the rest of the processes, usage of other processes times their standard processing time. The condition deterioration of process (1, 2) leads to the reduction of the revenue generated by it a slight increase in the revenue generated by the rest of the processes.

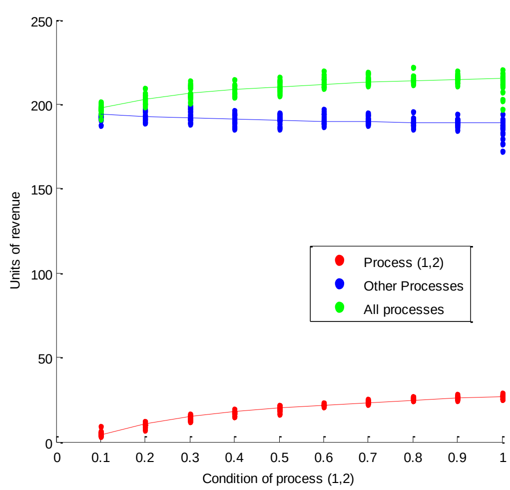


Figure 27: Loss of revenue due to deterioration in process (1, 2)

The logarithmic line ($\mathrm{nominalProcessingTime} = a \times \log condition + b$) fitted over the data (Figure 27) resulted from the simulation shows a positive correlation between condition of the process (1, 2), nominal processing time of process (1, 2) and nominal processing time of the system.

Table 7: Fitting lines for process (1, 2) and All Processes

| | Process (1,2) | All Processes |
|---|---|---|
| ***a*** | 10.0652 | 7.7458 |
| ***b*** | 26.8483 | 215.6088 |
| $R^2$ | 0.97 | 0.71 |

As shown in Table 7 the impact of the change in the condition of the process on the nominal processing time is stronger on process (1, 2) than the system. This is an indication that loss of the capacity in the process (1, 2) can be covered by the other network processes and optimal maintenance processes focusing only on process (1, 2) can be different than optimal maintenance processes designed for the system.

Deterioration of different processes does not necessarily lead to identical impacts on the nominal processing times and consequently the revenue generated by the system. In our production network condition deterioration of process (2, 5) has a greater impact on loss of revenue of the system than condition deterioration of process (1, 2) (Figure 28).

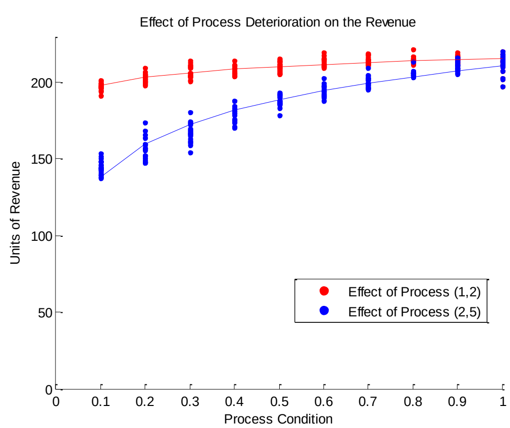


Figure 28: Effect of Process Deterioration on Total Revenue

The impact of condition deterioration on link (1, 2) doesn't just show itself as the loss of nominal processing time in the deteriorating process; It also affects some other processes/parts of the system by increasing the nominal processing time of non-deteriorating processes. Figure 29 shows the ratio of the nominal processing time of non-deteriorating processes at deteriorated conditions the deteriorating processes to the average nominal processing time of non-deteriorating processes at deteriorating processes perfect condition.

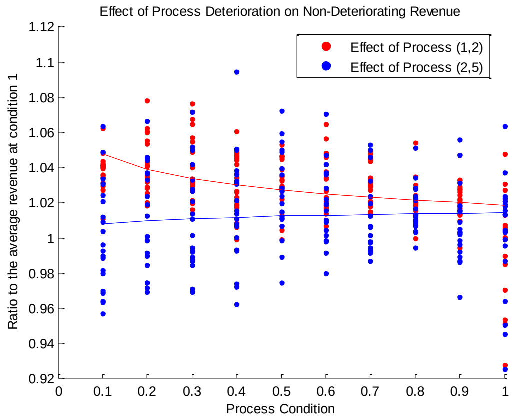


**Figure 29: Effect of process deterioration on the revenue generated by non-deteriorating assets**

Fitted lines of Figure 29 have very low $R^2$, so we have to investigate the existence of a significant difference between performances of non-deteriorating assets in the two cases by creating simple two factor model where the first factor (P) is the deteriorating link, the second factor (C) is the condition of the deteriorating link, the third factor is the interaction effect (PC) and the observed variable (Y) is the revenue ratio.

**Table 8: Factorial Analysis for Non-Deteriorating Processes**

| Model: $Y = P + C + PC + \varepsilon$ | | | | | | |
|---|---|---|---|---|---|---|
| Class Level Information | | | | | | |
| Class | | Levels | Values | | | |
| C | | 9 | 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0 | | | |
| P | | 2 | 1, 2 | | | |
| | | | | | | |
| Dependent Variable: | | Y | | | | |
| | | | | | | |
| Source | | DF | Sum of Squares | Mean Square | F Value | Pr>F |
| Model | | 17 | 0.20669938 | 0.01231688 | 23.74 | <.0001 |
| Error | | 340 | 0.17908522 | 0.00051882 | | |
| Corrected Total | | 357 | 0.3857846 | | | |
| | | | | | | |
| Source | | DF | SS | Mean Square | F Value | Pr>F |
| C | | 8 | 0.19993479 | 0.02499185 | 48.17 | <.0001 |
| P | | 1 | 0.00676459 | 0.00676459 | 13.04 | 0.0004 |
| PC | | 8 | 0.00268765 | 0.00033596 | 13.04 | 0.7375 |

As shown in Table 8, the deterioration of (1, 2) and (2, 5) processes have different effect on the change in the revenue generated by other non-deteriorating processes.

### 3.4.3. Process Maintenance

The maintenance planning of the production system defined above can be done using a similar model used for the transportation system. Each production batch will be treated as an independent user; however there will be differences in the ownership model. Unlike transportation system in which we assumed multiple owners in the network the production system has a single owner. To show the difference in the outcome we will consider two different cases: the deteriorating process is operated and maintained individually; the deteriorating process is operated and maintained as a part of the production system. We will compare *value based* models for these scenarios and compares the outcome.

#### *3.4.3.1. Local Model:*

In the case of *local model* the objective of maintenance planning, as shown in Equation 12, is to increase the wealth generated by process (1, 2) through selecting the optimal set of maintenance actions by taking advantage of condition curves and estimated demand for process (1, 2) at different conditions. The same value based model introduced in previous chapter is used in this section. It is additionally assumed that every maintenance action can be applied only once before applying a maintenance action of higher order.

**Equation 12:Contribution function of local model**

$$\mathrm{P}'(c_t, x_t) = link_{1,2}.usage_t \times usageFee_{1,2} - actionCost_{c_t, x_t}$$

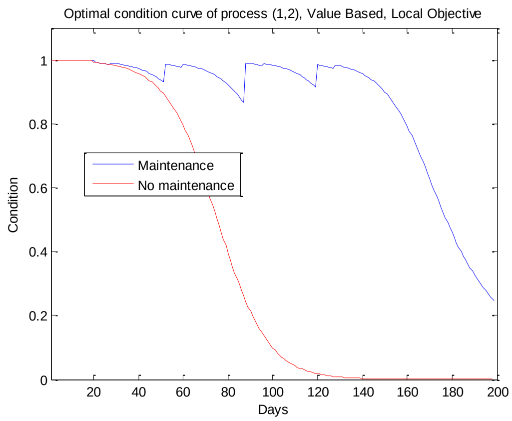


**Figure 30: Optimal condition curve of process (1, 2), Local Objective**

### *3.4.3.2. Global Model:*

In the case of *global model*, maintenance actions are selected to maximize the total revenue generated by the production system rather than the individual deteriorating process. If the change in the nominal processing time of the system has a different pattern than the change in the nominal processing time of the process the resulting optimal maintenance action for the process would be different for the two cases of *global objective* and *local objective*. The contribution function of the global model, shown in Equation 13, is defined based on the number of batches reaching the sink node while the objective function of the local model is defined based on the number of batches going through the (1, 2) link.

**Equation 13: Contribution function of global model**

$$\mathrm{P}'(c_t, x_t) = \left(link_{2,5}.usage_t + link_{4,5}.usage_t\right) \times unitRevenue - actionCost_{c_t, x_t}$$

While in the case of local objective, maintaining process (1, 2) increases the wealth of the system, in *global objective* maintaining process (1, 2) doesn't increase the wealth of the system and loss of capacity of the process (1, 2) can be covered by other processes of the network.

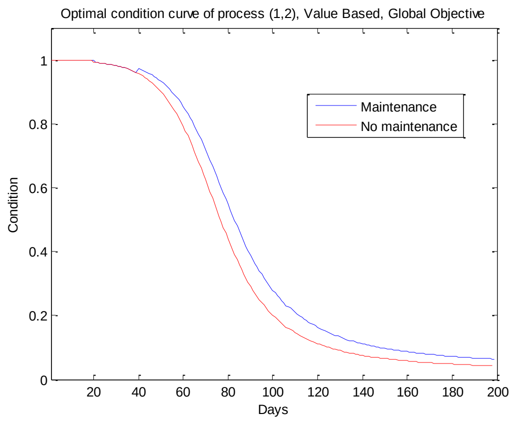


Figure 31: Optimal condition curve of process (1, 2), Global Objective

## 3.5. Chapter Summary and Conclusions

In this chapter we created simulation model as a test bed to verify our finding from the previous chapter on the differences between *cost based* and *value based* models. We've also compared *global* and *local* maintenance focuses for maintenance planning of deteriorating assets and showed that optimal maintenance actions depend on the focus of the optimization and belonging portfolio of the asset.

In the future chapters we expand the scope of the problem by creating an activity based demand model. We empower this activity based demand model with the ability to predict the change in location of population centers through land use model. We will further increase the number of owners in the network and explain the interaction between different owners and the role of the regulator in those interactions.

# 4. Chapter 4: Dynamics of Societal Model

## 4.1. Preliminaries

In Chapter 3 we modeled and studied the impact of infrastructure changes and investments on the flow dynamics of systems with case studies in transportation and production. A network flow model was used to represent the underlying asset network. We showed that flow patterns of individuals (people in case of transportation and products in case of production) are impacted by asset conditions. But we fell short of exploring how these changes propagate across the society. For example, a new or improved roadway impacts the individuals in a society by reducing their travel times and enhancing the QoS. The reduction in travel times increase the available time of the society members who use the improved infrastructure. These individuals now have the option of utilizing their excessive times on building more value for themselves and the whole society, e.g., additional productivity, lower travel related emissions, more family time, etc. Furthermore, the spatial configuration and shape of a society may also change due to changes in travel times and new value-based opportunities. In Chapter 2 we already presented some preliminary results on how different maintenance strategies impact this primal economy.

The objective of this chapter is to capture the underlying dynamics and model the impact of these changes in a simple primal society. The value metrics and the dynamics can be defined in a multiple dimensions of economy, society and environment. We developed an agent based simulation environment for this society which runs on a hash-and-bean economy.

## 4.2. Problem Statement

To properly measure the impact of infrastructure changes on a society we need to create a model that has an endogenous look towards economic, social and environmental characteristics of the society. This model should make it possible to compare different investment and maintenance policies in terms of societal and economical impacts. The model must take a micro view of economics to the point that it captures the main behavioral characteristics of individuals, asset-to-asset, asset-to-individual, and individual-to-asset interactions as closely as possible. Societies are built from individuals who decide and act in some distributed fashion and according to their own utility function, which is essentially variant over time. At the same time, some societal and economical aspects are decided in a centralized manner by authorities. The model must capture both aspects of decision-making, namely distributed for individuals, and centralized for investment on infrastructure assets. While not every real society enjoys a closed loop feedback mechanism between the two levels of decision-making, we will inject into the model this additional requirement. The model must be sufficiently primal to be computationally tractable and generic so that aggregations can be made to real life societal/economical elements. In a real economy, as explained in by Robinson Crusoe economy (60), individuals' main objective is to make a balance between work and leisure (61) while interacting with the economy in terms of buying or selling products and/or services. Personal preferences can vary from one individual to another in terms of preferences over leisure or consumption (62). And depending on the structure of the society and individual's preferences they selfishly or collaboratively attempt to maximize.

To build this society an agent based modeling approach was adopted. In this approach the response of the society on the infrastructure changes is calculated through aggregation of responses of individual agents. This simulation investigates the impact of availability of transportation infrastructure on behavior of agents and the society as a whole.

## 4.3. Technical Approach

For the problem at hand, consider a hash-and-bean (52) economy characterized by: a finite number of profit-seeking agents producing hash, a finite number of profit-seeking agents producing beans. These agents drive utility from the consumption of hash and beans as well as time spent for leisure;

A virtual grid that agents are located on, this grid is analogous to the land that provides resources to its inhabitants. Agents can move within the grid based on the availability of links between different nodes, where links are abstract representation of transportation infrastructure in the grid; Agents can change their location within the grid for better accessibility to grid's resources.

### 4.3.1. Dynamics of Primal Economy

In our primal society each agent is uniquely identifiable and has a set of static characteristics and a set of dynamic properties that changes based on agent's decisions. Agent's static characteristics are its utility and production functions. The utility function shows the relative importance of leisure, consumption of hash and consumption of bean. The production function of an agent identifies the labor effectiveness of the agent in the production process. Dynamic properties of an agent are determined based on the decisions that agents make at each time period. These properties are residence location, work location, occupation, working hours (total production), total consumption and utility.

As mentioned earlier each agent has the objective of maximizing its own utility through a set of decisions. An agent starts each period with its residence location, work location and occupation known from the previous period. At any given time period agents have to make the decision of allocating their available time between production and leisure. It is assumed that agent's available time at each period is some portion (50% for the illustrative example) of the time period minus the work to residence and residence to work location travel times. Agent's allocate part of their available time to production and assign the rest of their time to leisure. Additionally agents act as price takers where they consider the market price of the hash and bean as given and plan their production accordingly. Agents assume that they can sell all of their hash/bean production at market price and buy from the other product at the end of the period. It is assumed that all of the agents participate in one central market and the market clears by setting the prices for hash and bean in the way total supply and demand of hash and beans by individual agents are equal. The market sets new prices for hash and bean and reallocates total produced hash and total produced bean among all of the participating agents. The consumption of this new re-allocated hash and bean along with leisure time will determine the utility of the agent. At the end of each period agents will make payments for their residential and work locations based on their production and utility. To simplify the model and avoid the complications of the economic closure loops there will be no actual payment in this model and agents will only announce their willingness to pay for the land.

Once they have paid off their work and residential land, agents compare their own utility to the utility of all other agents. In this process agents with the utility of lower than two standard deviations from the mean will migrate out of the system. These migrating agents will open space which can then be utilized by other agents who are interested in moving into this society. The number of move-ins in each period is equal to the minimum of available spaces and number of agents with utility of higher than two standard deviations above the mean. New move-in agents are agents who expect to over-perform in this society and consequently are going to have characteristics similar to over-performing resident agents.

In addition to moving in or out of the system, agents can relocate within the grid. In this model it is assumed that a portion (5% for the illustrative example) of agents relocate in each period; Move-ins and relocating agents identify a list of affordable locations and select the best combination of residence location, work location and occupation for the next period. An illustrative schematic of this process is shown in Figure 32.

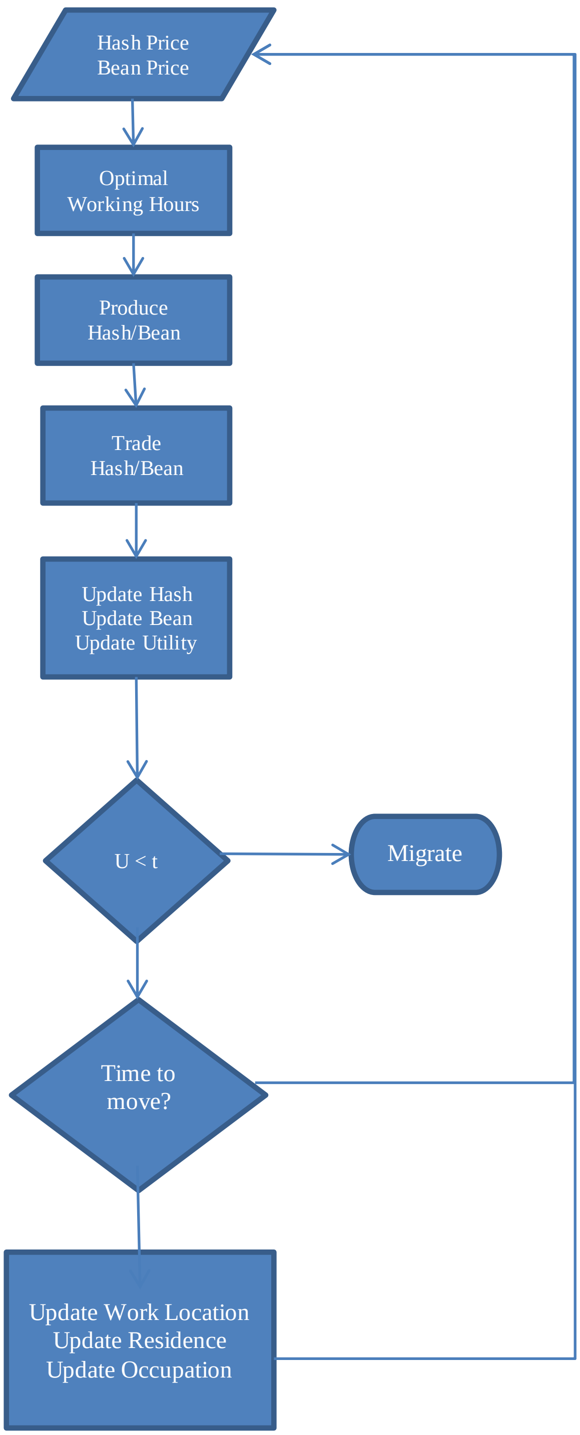


Figure 32: Daily cycle of an individual user

All of the interactions between different agents are placed in the grid mentioned earlier. In this grid each node is connected to all of its neighboring nodes (horizontal, vertical and diagonal). All nodes are homogenous in terms of their capacity but the level of available resources can change from one node to the other. Node capacity determines the number of agents that can live/work on a node and the level of node resource(s) reflects the level of available resources necessary for hash and bean production. This primal economy is a constructive abstraction of a real economy which captures essential behavior and activities of an economy with respect to individual members (allocation of time between productions) and their interactions. While this abstraction simplifies the computational complexity, it doesn't take away the general applicability of our results. Every society can be broken down to its basic functions and studied through the interaction between agents providing those basic functions. Moreover this primal economy can be expanded to contain more of basic functions of the economy for modeling more elaborated societies.

### 4.3.2. Grid

Grid $G$ is defined by: $G = \{N, A, W\}$ where $N = \{n_{ij} | i = 1..m, j = 1..n\}$ is the list of nodes in the grid and $A = \{(ij, kl) | \ (i = k \ \wedge j = l \pm 1) \vee (i = k \pm 1 \ \wedge j = l) \vee (i = k \pm 1 \ \wedge j = l \pm 1)\}$ is the node connectivity and $W = \{w_{(ij,kl)} | w_{(ij,kl)} = 0.1 \ where \ (i = k \ \wedge j = l \pm 1) \vee$ $(i = k \pm 1 \ \wedge j = l) \ and \ w_{(ij,kl)} = \sqrt{0.02} \ where \ (i = \pm k \ \wedge j = l \pm 1)\}$. (Figure 32 illustrates the connectivity of the grid for few adjacent nodes.)

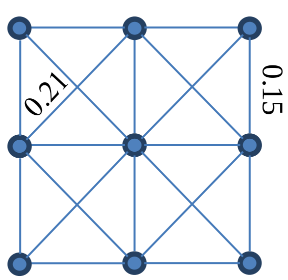


Figure 33: Grid connectivity for adjacent nodes

Each node in the grid has 2 types of resources:

- $R_{rij}$ represents the availability of resource $r \in \{h, b\}$ in node $ij$ and

- $L_{ij}$ represents the total land in node $ij$.

### 4.3.3. Agents

Each agent in the system is an identifiable entity with a unique production and utility function.

#### 4.3.3.1. *Utility Function*

Cobb-Douglass form (63) is used as the utility function. The utility of agent a at time period t is calculated as Equation 14 where $\lambda_{at}$is agent's leisure time, $H_{at}$ is the agent's hash consumption and $B_{at}$ is the agent's bean consumption in the end of period t where $\alpha_{a1} + \alpha_{a2} + \alpha_{a3} = 1$.

**Equation 14: Utility of agent a**

$$U_{at} = \lambda_{at}^{\alpha_{a1}} H_{at}^{\alpha_{a2}} B_{at}^{\alpha_{a3}}$$

#### 4.3.3.2. *Production Function*

Cobb-Douglass form is used as the production function. Agent's production function coefficients represent labor and resource intensity of production processes for hash and bean. $p_{ah} + p_{ab} = 1$ represents the production function coefficient vector of agent a where agent's hash production function is shown in Equation 15 and its bean production function is show in Equation 16 where $\mathrm{w_a}$ represents total working hour of agent a within the planning period.

**Equation 15: Agent a's hash production function**

$$P_{ha} = \mathrm{R_{hij}^{1-p_{ah}} w_a^{p_{ah}}}$$

**Equation 16: Agent a's bean production function**

$$P_{ba} = R_{bij}^{1-p_{ab}} w_a^{p_{ab}}$$

### 4.3.4. Optimality for Individual Agents

A hash producing agent with the residence location of $ij$ and work location $kl$ can maximize its utility by allocating its available time between leisure and hash productions. In this allocation the agent acts as a price taker and uses the price of hash and bean for optimal time allocation between hash production and leisure for maximizing its expected utility.

Each agent needs to make certain number of trips ($n_{rc}$) from its resident location to the grid central location and their work location ($n_{rw}$). $s_{ijkl}$ represents the shortest travel time between residence location at $ij$ and work location at $kl$ and $s_{ijcc}$ represents the total travel time between central grid location and agent's residence at $ij$, total travel time of the agent in a period is shown in Equation 17.

Equation 17: Travel time of the agent who live in location $ij$ and work in location $kl$

$$T_{ijkl} = 2 \times n_{rc} \times s_{ijkl} + 2 \times n_{rw} \times s_{ijcc}.$$

At the beginning of each period the objective of the agent is to allocate the remaining $AT - T_{ijkl}$ hours between work and leisure to maximize its utility, where $AT$ is the agent's available time in period and it is assumed that agents need to allocate a portion (50% for the example) of their 24 available hours in the period on leisure to survive. The reminder of the total time will be agent's leisure time and is shows in Equation 18.

Equation 18: Agent's leisure time

$$\lambda = 24 - \mathrm{T_{ijkl}} - \mathrm{w}$$

If an agent starts the period with 0 Hash and 0 Beans, its end of period utility can be calculated as in Equation 19 where $\Delta H$ is the amount of hash sold, $\Delta B$ is the amount of bean purchased.

Equation 19:End of period utility of an agent

$$U = \lambda^{\alpha_1}(H - \Delta H)^{\alpha_2}(\Delta B)^{\alpha_3}$$

If we substitute $\lambda$ with Equation 18 and $H$ with Equation 15 the agent's utility function will be presented as Equation 20.

Equation 20: Agent's detailed utility function

$$U = (24 + T_{ijkl} - w)^{\alpha_1}(R_{hkl}^{1-p_h} w^{p_h} - \mathit{\Delta} H)^{\alpha_2}(\mathit{\Delta} B)^{\alpha_3} .$$

The individual's optimization model will then be as follows:

$$Max\ U = (24 - T_{ijkl} - w)^{\alpha_1}(R_{hkl}^{1-p_h} w^{p_h} - \mathit{\Delta} H)^{\alpha_2}(\mathit{\Delta} B)^{\alpha_3}$$

$$s.t.$$

$$AT - T_{ijkl} - w \geq 0$$

$$p_h \times \mathit{\Delta} H - p_b \times \mathit{\Delta} B = 0$$

The first constraint assures that the agent is not working more than its total available and the second constraint keeps the wealth of the agent constant.

Each agent in the economy allocates its time between leisure and production based on its estimated future hash and bean consumption assuming that it can sell all of its production to the economy and satisfy all of its demand from the economy at the market price. At the end of each period, agents use their available production of hash/bean to obtain bean/hash from the market. This process sets new prices for hash and bean and reallocates the total produced hash and bean among agents.

### 4.3.5. Market Clearing & Optimality Conditions

This market, like any other market, is a location for exchange of commodities and the sum of hash and bean in the society stays the same before and after the trade, ($\sum \Delta H = 0$ and $\sum \Delta B = 0$). To simplify the problem all agents of the society are forced to use a central market. This central market clears only when the supply and demand for hash and bean are equal at market price. At the end of the clearing process each agent consumes its available hash and bean and ends the period with a utility based on the level of its consummation, leisure and end of the period money. The central market functions based on the following formulation:

- The central market system announces $k$, the relative price of hash and bean $\Delta H = k\ \Delta B$
- Hash and bean producing agents announce their supply and demand for hash at market price of $k$;
- Hash producing agents, $a_h$, maximize their utility by solving $\max_{\Delta H} \lambda^{\alpha_{a_h 1}} \left(H_{oa_h} - \Delta H_{a_h}\right)^{\alpha_{a_h 2}} (k\Delta H_{a_h})^{\alpha_{a_h 3}}$
- Bean producing agents, $a_b$, maximize their utility by solving $\max_{\Delta B} \lambda^{\alpha_{b_h 1}} ({}^{1}/_{k}\, \Delta B_{b_h})^{\alpha_{b_h 2}} \left(B_{ob_h} - \Delta B_{b_h}\right)^{\alpha_{b_h 3}}$
- If $\sum {}^{1}/_{k}\, \Delta B_{b_h} = \sum \Delta H_{a_h}$ set $k$ as the new market price, otherwise if $\sum {}^{1}/_{k}\, \Delta B_{b_h} > \sum \Delta H_{a_h}$ increase $k$, else decrease $k$ and get back to step 2.

Agents' willingness to pay for their residential and work locations is calculated based on their end of period utility and production values. According to Varian 1992 (64), individuals willingness to pay for spatial goods (or lands) is a function of the utility, income and price of other goods, so that the increase in the utility increases the willingness and the increase in the price of other goods decreases the willingness. It is assumed that agents have a higher willingness to pay for a unit of residential location than a unit of work location. The price of each node is calculated as the sum of the willingness to pay of agents using that node as their residence and/or work location. The Equation 21 shows a simplified representation of willingness to pay based on Varian 1992 which adhere to out model's data availability and show similar characteristics without getting into complexities of calculation of price of aggregate good in the simulated society.

**Equation 21: Willingness to pay of agents**

$$residnetial = {}^{(p_h \times H + p_b \times B)}/_{3e^{1-utility}},\ work = {}^{(p_h \times H + p_b \times B)}/_{4e^{1-utility}}$$

### 4.3.6. Migration into and from the Economy

At the end of each period certain changes can occur in the population structure of the society; agents can move in, move out or move within the society. At the end of each period an agent compares its own utility with the utility of the other agents living in the society. The agent decides to leave the society if it is under-performing (it's utility is less than a certain threshold compare to the other agents). These empty spots can be filled by new incoming agents with static characteristics similar to over-preforming agents (agents' with utility higher than a certain threshold). In addition to move-ins and move-outs a portion of agents can change their occupation, work and residence locations within the society.

Every agent (with move-in plans) reviews at all nodes in the grid, retrieves the occupancy price associated to that location for work and residence and creates a list of affordable work and residence locations. The agent then uses the list to find its next occupation, residence and work locations that maximize its expected future utility. In this heuristic selection procedure the agent selects the closest affordable location to the central grid location as its residence and selects the best affordable work location based on its resource availability and proximity to residence location. Once these locations are selected the agent will choose its future occupation by solving the time allocation problem for hash and bean production from these locations and selects the set with higher future expected utility.

If there is enough available space in the destination node for work/residence the agent can simply move in to the destination node. If there is not enough space available at the destination node one of the following scenarios will happen depending on the type of move and land use in the target location:

Agent is changing its residence location and the target location has all residence occupancy: in this case the current resident with lowest pay will be evicted from the target location and the new agent will occupy its space. The evicted agent will select a new residential location before the start of the next period.

Agent is changing its residence location and the target location has mixed residence and work occupancy: work space will be taken away from the current working agent and the space will be allocated to the new incoming agent; (if the partial occupancy is smaller than the residence space by the agent the working agent will be added to the moving list).

Agent is changing its work location: All of the agents currently using the target location will be evicted and the new agent will occupy the location for work. All evicted agents will select new locations before the start of the next period.

## 4.4. Illustrative Example

The individual behavior of agents in the above society will create an aggregate societal behavior, which can be used to measure the societal impact of infrastructure related decisions.

### 4.4.1. Uniform Case

As a base case we start with a society of 100 agents living in a 20x20 grid where central location is in node (10, 10) and hash and bean production resources are uniformly distributed at their maximum level of 1. Agents' are initially assigned random residence and work locations. As shown in Figure 34 initial distribution of work and residence locations don't follow any specific pattern, where $x$ and $y$ axes are the location of the node on the grid and $z$ axis is the number of agent in that location.

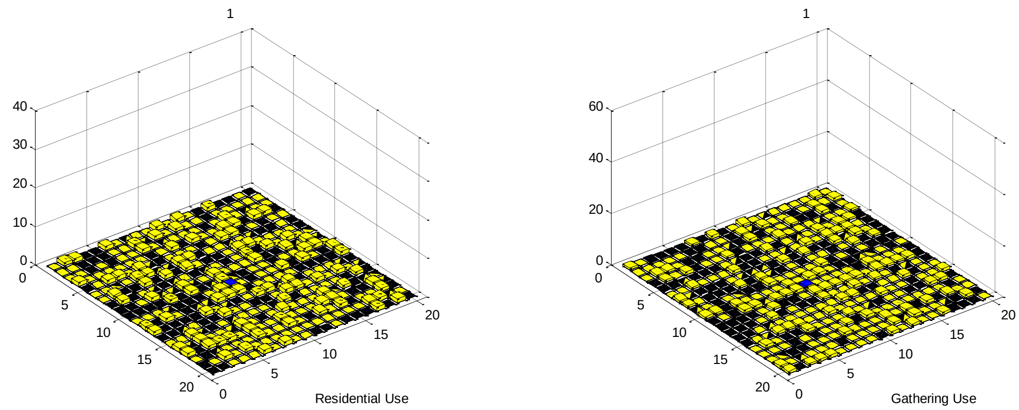


Figure 34: Initial distribution of work and residence locations

In the simulation process agents will change their location and occupation to maximize their utility. One of the main driving forces in this relocation is to minimize the total travel time and allocate the released time to more valuable (in utility terms) activities. This minimization effort will impact the spatial structure of the society leading to population concentration close to the water resource (central grid location for this base case). As it can be seen in Figure 35 agents select the area immediately around the central grid location for residential usage to save on travel time, where $x$ and $y$ axes are the location of the node on the grid and $z$ axis is the number of agent in that location. Agents are generally willing to pay more for a land unit of residence than for work location. This makes the inner circle unaffordable for production of hash and bean and pushes it around the inner residential circle.

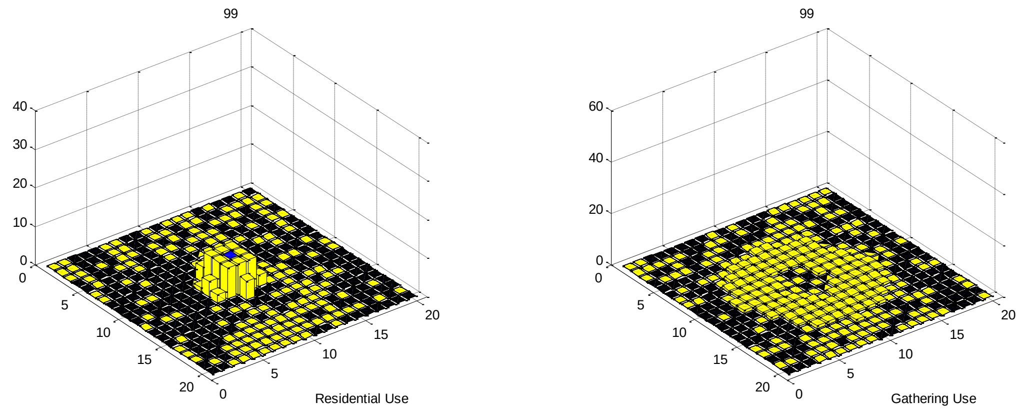


Figure 35: Spatial work and residence patterns

This relocation and change in the occupation will impact other aspects of the society in addition to its spatial pattern. The first impact of this relocation is the reduction in travel times. At the beginning of the simulation, agents are randomly distributed and they spend relatively long time travelling between work and their residence and from there to the central water location. In the simulation environment, as agents relocate to maximize their utility, the total travel time reduces to a steady value. While agents are relocating to their new locations the average utility of agents in the society increases and the gap between slow reacting agents and fast reacting agents widens. At some point in this evolution the gap between slow reacting agents and the others increases to a point that they are forced to move out of the system. In this specific case the steady state travel time, as show in Figure 36, is less than one third of the travel time compared to the starting period. Most of KPIs related to the society show a goal seeking behavior resulted from the equilibrium reached due to interaction of agents. However this equilibrium is not reached instantaneously and when it is reached it is not maintained at a constantan level and major KPIs variate around their long term mean.

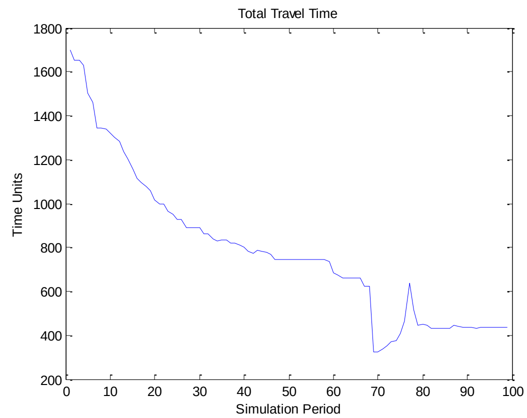


Figure 36: Change in the travel time

Total Travel time of agents is a function of their average speed and total distance travelled. Figure 37 shows the change in the distance travelled and the average speed. The reduction in travelled distance leads means that the population is concentrated in fewer node which consequently leads to increase in the roadway congestion and reduction in the average speed.

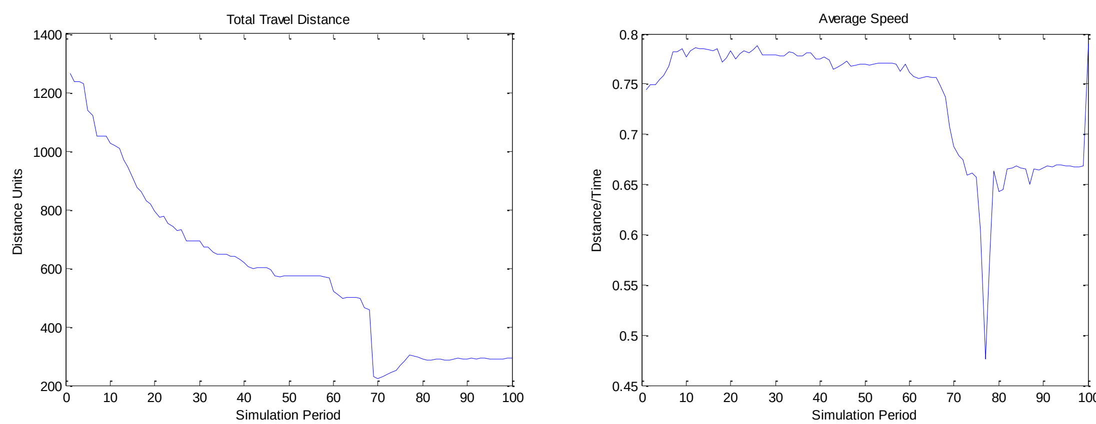


Figure 37:Change in distance travellen and averagespeed

Public utility, defined as the sum of agents' individual utility, is the other societal variable that is subject to change due to decisions made by the individual agents. The sum of utility of all agents in the society, Figure 38, will follow an increasing trend as agents relocate and change their occupations.

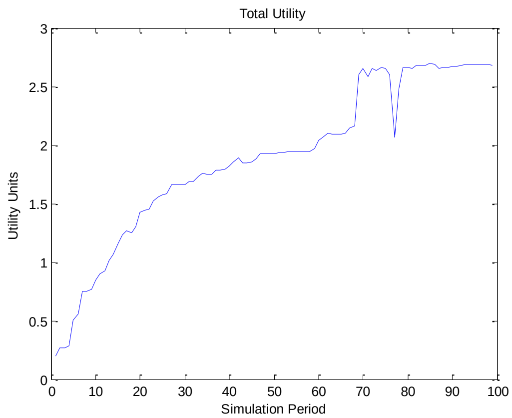


Figure 38: Change in the social utility

Population structure, total production and prices of hash and bean are three closely tied characteristics of the society. With the higher importance of the hash consumption in their utility functions, the agents increase their willingness to pay for hash. This higher willingness to pay leads to the higher steady state hash prices compared to bean. The increase in the price of hash makes the production of hash more attractive and more agents start selecting hash production as their primary occupation (see Figure 37).

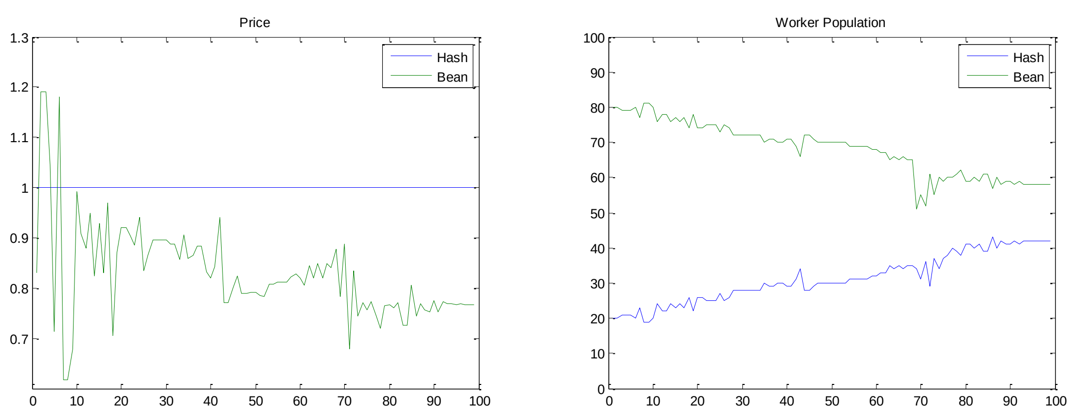


Figure 39: Change in the Price and worker population

The change in the occupation along with in and out migration of the agents will lead to steady level of hash and bean production, Figure 40. The relative importance of hash in the utility function of agents leads it to having a larger share of the total production.

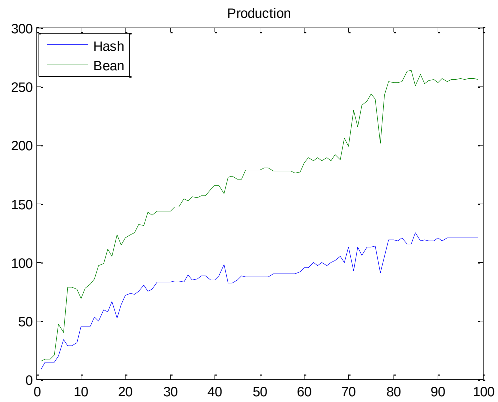


Figure 40: Long-term hash and bean production

One of the important spatial characteristics of the grid affected by agents' decisions is the price of land (total willingness to pay for each node). In the relocation process, agents compete for getting the land that maximizes their utility based on their willingness to pay! This competition leads to increase in prices in locations with higher resource availability or desirability as residence location compared to other locations. At the beginning of the simulation agents are randomly scattered around the grid, and their willingness to pay for their residence and work location is low and doesn't follow and specific pattern, Figure 41, where $x$ and $y$ axes are the location of the node on the grid and $z$ axis is the sum willingness to pay of agents in that location..

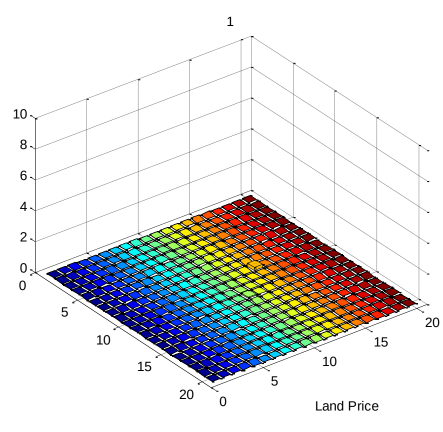


Figure 41: Agent's willingness to pay at the first period

As time goes on and the society moves forward in its evolution, the agents relocate and land prices increase in more desirable locations with higher levels of resource availability. As mentioned earlier in this chapter, locations close to the center of the grid are more desirable; therefore, agents are willing to pay higher prices for these locations Figure 42; the right graph is showing the increase in the willingness to pay of agents over time and the left one is showing the sum of willingness to pay for each node where $x$ and $y$ axes are the location of the node on the grid.

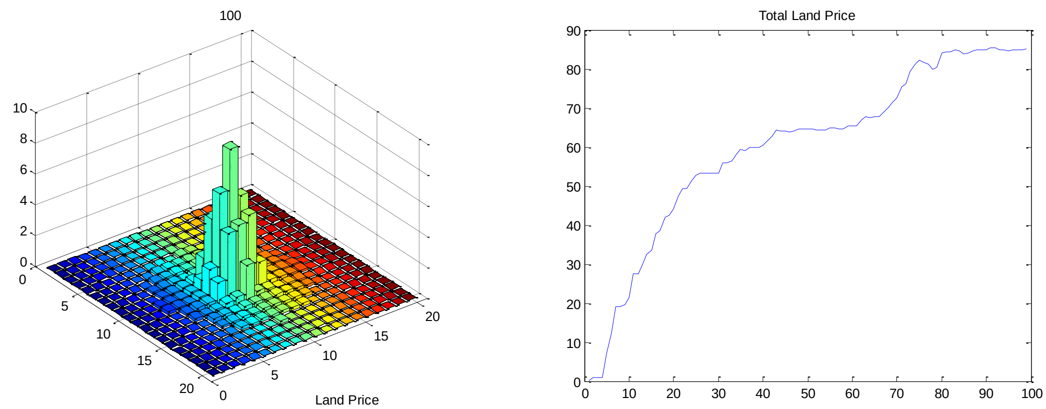


Figure 42: Steady state land price

### 4.4.2. Non-uniform case

In the next example we will relax the assumption of the uniform availability of resources and investigate agent behaviors under this new condition. In case of non-uniform distribution of resources, hash and bean resources are not equally available in both nodes the resource level varies from one location to the other. For the illustrative example it is assumed that the grid has two concentration of Hash production resource on concentration of Bean production resource, Figure 43.

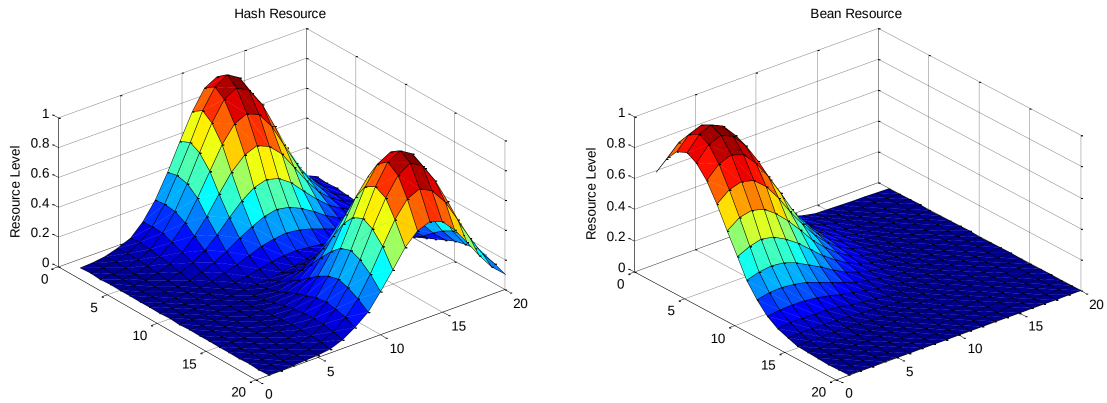


Figure 43: Non-uniform availability of hash and bean resource

In both uniform availability and non-uniform availability of resource case have the same starting distribution and composition of agents. Having these agents placed in different grids agent's individual decisions leads to different aggregate system behaviors endogenous to the system. As Figure 44 illustrates the residential population in non-uniform case is concentrated around the central grid location however production is concentrated in three different clusters (one hash producing cluster and two bean producing clusters.

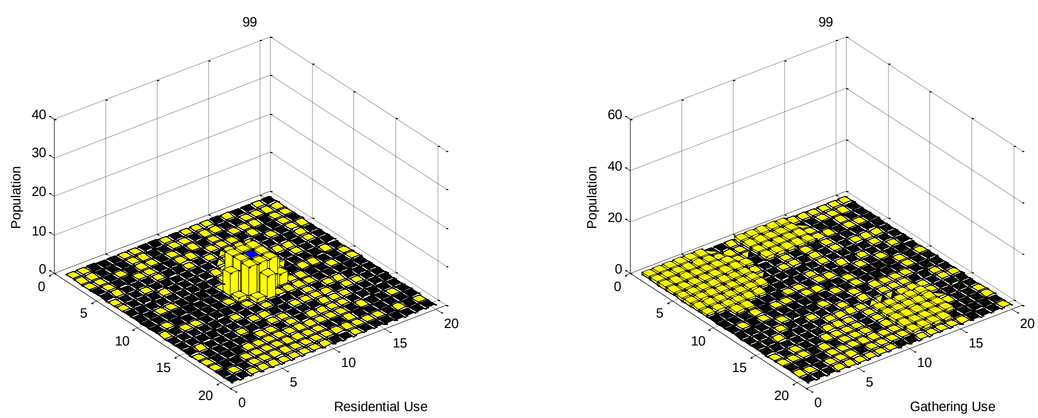


Figure 44: Residential and production clusters in non-uniform cases

Agents' decisions in non-uniform case is driven by the same principals as the uniform case, however the environmental conditions are not as appealing to agents as the uniform case. The steady state utility in this case is less than the non-uniform case, Figure 44. The unavailability of production resources in the immediate surroundings of the residential location leads agents to longer than normal travel times (compared to uniform case, Figure 38) which reduces agents available time to be allocated to production and leisure. This reduction in utility and production will consequently lead to lower land prices, Figure 45.

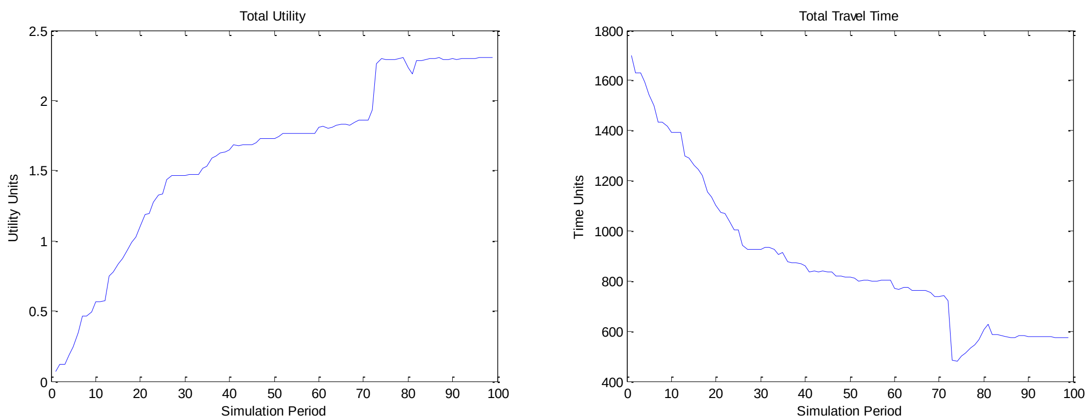


Figure 45: Agent utility and total travel time (non-uniform resource)

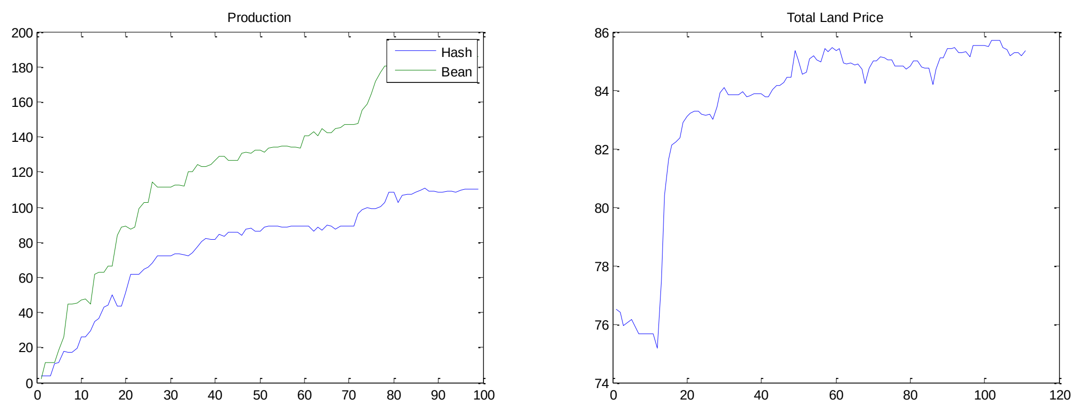


Figure 46: Total production and land price (non-uniform resource)

The impact of changes in the infrastructure of the society can be measured within the same framework. This change can be formulated as reduction in the travel time between two specific nodes or a series of node. Depending on the reduction in travel time and location of reduction agents will adopt to environmental changes. This adaptation will lead to different societal responses which can be measured and used for evaluating those changes. Next chapter discusses models capability for measuring agents responses to infrastructure changes and presents an abstraction for modeling a real life case with the proposed agent-based concept.

## 4.5. Chapter Summary and Conclusions

In this chapter we created primal society using computational agent based economics to model the impact of infrastructure changes. Different values metric were introduced and applicability of model for measuring those metrics was shown.

# 5. Chapter 5: Model Verification and Case Studies

In this chapter possible uses of the model developed in chapter 4 will be illustrated by showing the impact of new investments as well as changes in current service levels of the transportation infrastructure e.g. loss of service.

A basic extension of the model will also be provided to show the impact of regulations on decisions made by owner agents within a complex society (society consisted of more than one economy).

A basic game-theoretic formulation for existence of multiple owner in the system is shown and importance of the regulator is illustrated via an example.

## 5.1. New Investment Optimization - Basic Case

An infrastructure change can be introduced to this society by changing the underlying network connecting different nodes to each other. An example of such change can be creating a corridor from node (10, 1) to node (10, 20) in the illustrative example of Chapter 4 (reducing the travel time between all the nodes in ((10,1)- (10,20)) corridor).

$$W = \left\{ w_{(ij,kl)} \middle| \begin{matrix} w_{(ij,kl)} = 0.01 \; where \; (i = k \; \wedge j = l \pm 1) \vee (i = k \pm 1 \; \wedge j = l) \\ and \; i = 10, k = 10 \end{matrix} \right\}$$

Members of the society will react to this improvement by changing their occupation, work or residence location as well as their time allocation between work and leisure. The new change will make it faster to travel in the corridor as opposed to other routes. This reduction in the travel time will affect the shape of residential and work clusters by stretching them in the corridor's direction, Figure 47. The corridor will reduce the travel time between its nodes into 1/5 of their original value. This change makes the first five immediate nodes in each direction (on the corridor) more appealing for residence than an immediate neighboring node not located on the corridor. As the resident locations of agents spread along the highway, agents relocate their work locations to keep the combination of work/residence location optimal or close to optimal, Figure 47, where $x$ and $y$ axes are location of the agent.

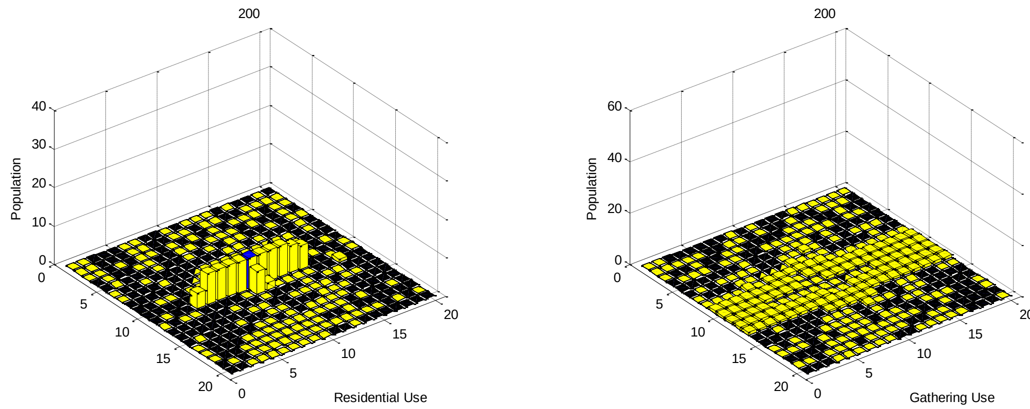


Figure 47: Agent's post highway relocation

Agents' relocation is driven by their objective to maximize their utility through optimal allocation of their available times. As shown in Figure 48 this relocation will reduce the total time spent on the road and consequently increase the agents' available time by reducing their drive time, which can later be allocated to different activities to increase their utility.

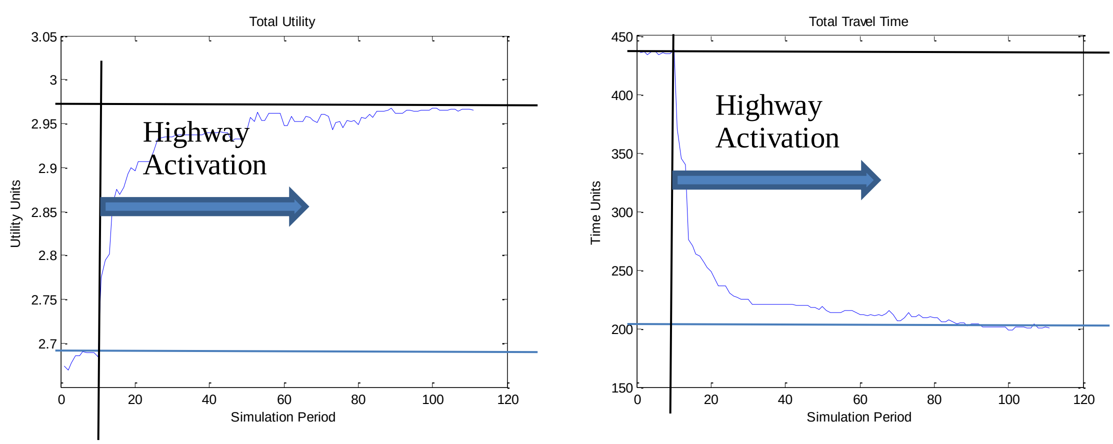


Figure 48: Change in the Total Travel Time and Total Utility

This reduction in total travel time is mainly due to increase in the travelling of agents between work, water and resident location. As shown in Figure 49 adding the corridor will increase to total travelling distance (left) and increase average speed (right), which will result reduction in total time spent in travelling.

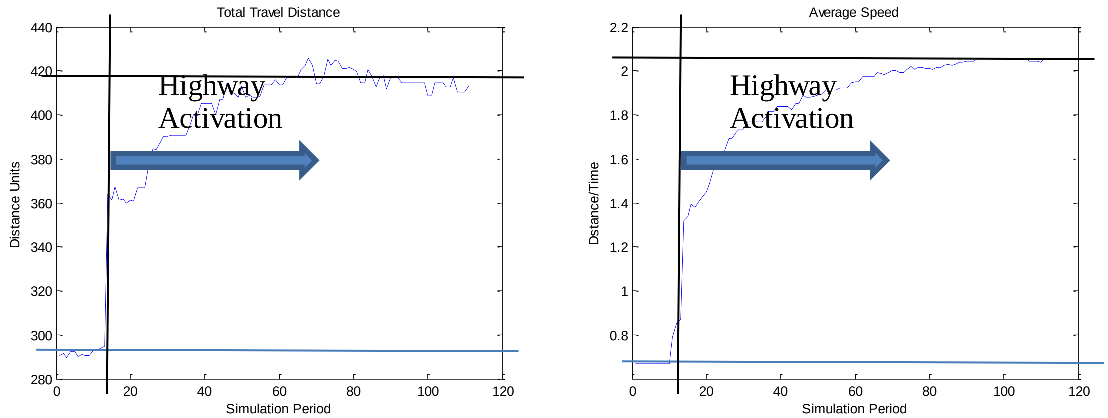


Figure 49: Change in the total distance travelled and average speed

The increase in utility is due to the increased leisure time as well as the increased consumption (production). The construction of the new highway will lead to increase in the total production/consumption of hash and bean. Figure 50 shows about a 10% increase in production of hash and bean due to the construction of the new highway.

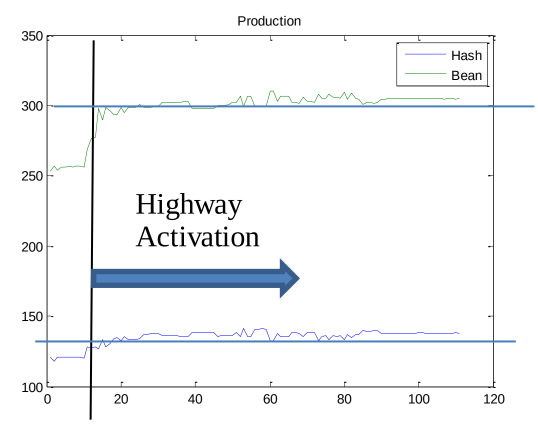


Figure 50: Change in the total utility and total production of agents

Agents' relocation and change in the utility will also impact the land price in addition to the spatial shape of the society. The higher desirability of locations along the corridor will increase the price of land in the area along it, furthermore the increase in the utility of agents will increase their willingness to pay and will consequently increase the total land price in the network, Figure 51.

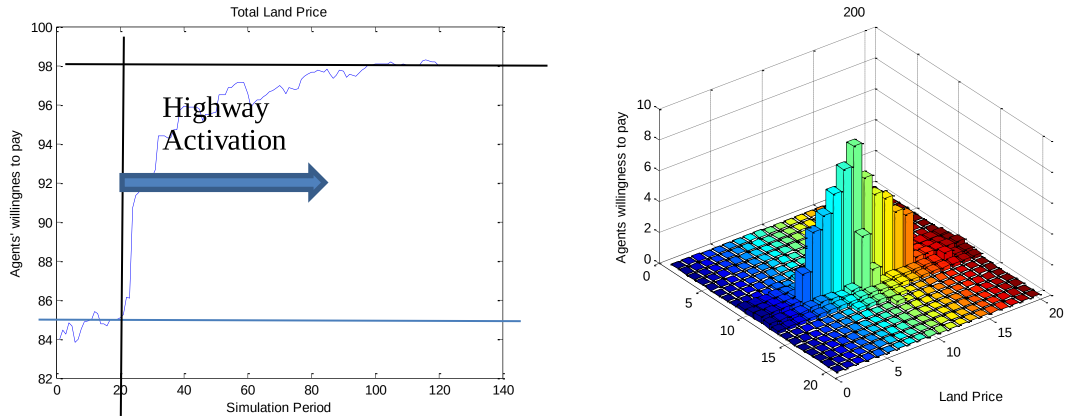


Figure 51: Change in the land price

To estimate the value of the new corridor in the system different aspects of the economy can be measured and quantified using this approach. The economic value of the new investment is evaluated through its impact on total production and total price of land. The social value of investment is measured using the change in the total utility of the community and its environmental impact measured using the change in travel time (versus total miles travelled).

This model can be used to develop a response surface to be used in optimizing infrastructure investments decisions. To create this response surface we incrementally create this (10, 1)-(10, 20) to the base case, starting by creating the ((10, 9)-(10, 11)) corridor and measuring its impact on the society. This ((10, 9)-(10, 11)) corridor is then incrementally expanded from both side to reach its final size; at each step in size increase the impact of the new longer corridor on the society is measured and plotted as the response surface, Figure 52 scenarios.

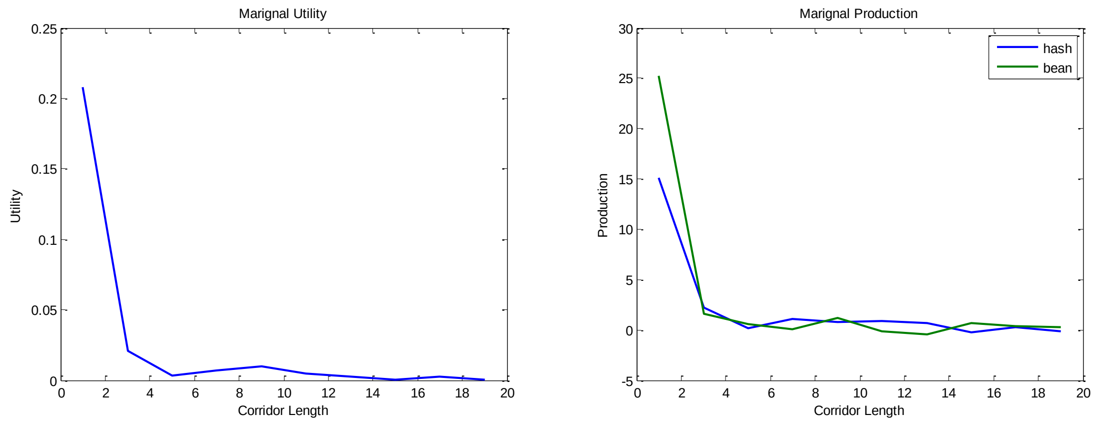


Figure 52: Society's response to incremental construction of the corridor

Response lines in Figure 52 show the diminishing effect of corridor expansion on improvement in utility and production. For this example, the reduction in traffic congestion in the central residential area has the highest impact on improving the utility and production. The magnitude of the improvement reduces as the corridor expands to (10, 1) and (10, 20).

## 5.2. Loss of Service

This model can also be used to evaluate the impact of loss of service on the society. This effect can be measured in terms of change in the production, utility, land price and spatial shape of the society.

### 5.2.1. Real Case

The phenomenon of production shift and other related phenomena can be observed when loss of a major transportation asset (or network of assets) impacts the ability of production centers to transport their cargo to export gateways. US grain production is mainly concentrated in the central USA. However, the main export gateways are located at Pacific and Gulf coasts. Prior to 1997, Gulf ports had the dominant share of the US grain export as shown in Table 9. The lack of proper investment in maintenance of Mississippi water route led to loss of capacity of the river for transporting the agricultural products from central production locations to the southern export gateway. During the same period, increased containerization of grain and improvement to the

Rail Roads serving Pacific ports turned Pacific ports into attractive gateways for grain export. As the result of these changes the share of Seattle has increased from 5% of total export to 10% and brought LA into the list of grain exporter.

Table 9: Grain Export Share of Major Ports

| | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | Gain |
|---|---|---|---|---|---|---|---|---|---|
| **Columbia-snake** | 16% | 19% | 18% | 16% | 17% | 19% | 19% | 18% | 1% |
| **Los Angeles, CA** | 0% | 0% | 1% | 1% | 2% | 2% | 2% | 1% | 1% |
| **Minneapolis, MN** | 0% | 0% | 1% | 2% | 3% | 1% | 1% | 2% | 2% |
| **New Orleans, LA** | 59% | 53% | 50% | 53% | 50% | 45% | 51% | 48% | -11% |
| **Norfolk, VA** | 0% | 0% | 1% | 1% | 2% | 2% | 2% | 1% | 1% |
| **San Francisco, CA** | 1% | 1% | 1% | 1% | 1% | 1% | 2% | 1% | 0% |
| **Seattle, WA** | 5% | 9% | 10% | 9% | 8% | 10% | 9% | 10% | 5% |

The change in the export ports was not the only impact due to the change in the grain export infrastructure. The location of the grain production was also shifted due to the change in the export infrastructure. Simple comparison between intensity of 1997 and 2007 crops production shows that the intensity of production has shifted from central south to northwest, Figure 53. The production has become less intense in the lower part of Mississippi and became more intense in central and west of Illinois, Nebraska and North Dakota.

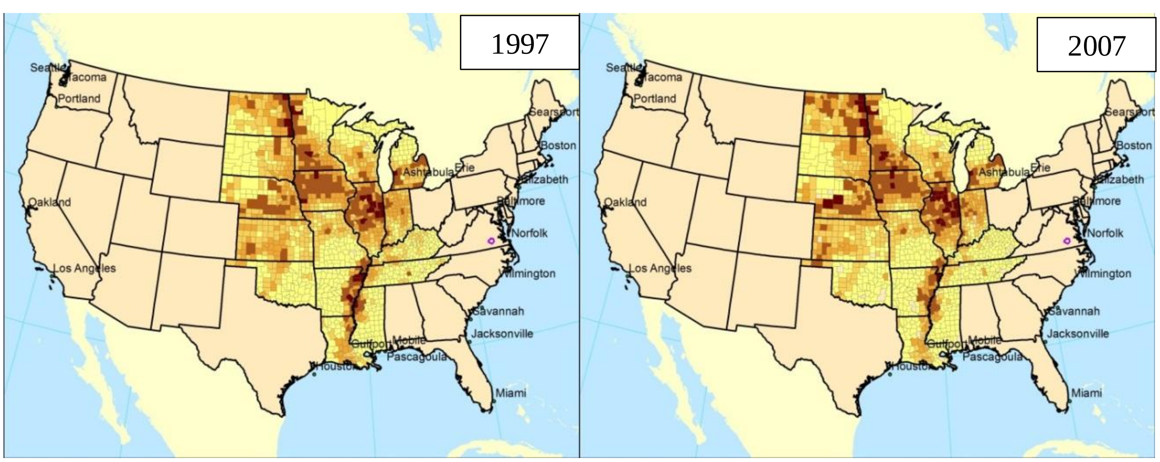


Figure 53: Change in US crops production intensity (1997, 2007)

### 5.2.2. Case Study

Such a case can be modeled with some level of abstraction using the developed framework. Consider a case where there are three (3) water locations along the north-west, south-west and south border of our example society. Also assume that there is a bell-shaped availability of hash and bean resources at the center of the grid (Figure 54) and there are three water sources are located at nodes: $\{(38,1),(4,1),(40,20)\}$

Furthermore, we assume that there are dedicated corridors between central locations of the grid and water locations at the boarders. These dedicated links are relatively faster and have higher capacity than the normal links. Additionally assume that links connecting nodes around (3x3) water locations have very high capacity and virtually zero length.

Under the above assumptions a 40x40 grid is defined as:

$N = \{n_{ij} | i = 1..40, j = 1..40\}$ is the list of nodes in the grid, $A = A_0 \cup A_1 \cup A_2 \cup A_3$and connection weighting is defined by: $W = W_0 \cup W_2 \cup W_3 \cup W_4$ where:

$$A_0 = \{(ij,kl) |\, (i = k \wedge j = l \pm 1) \vee (i = k \pm 1 \wedge j = l) \vee (i = k \pm 1 \wedge j = l \pm 1)\}$$

$$W_0 = \left\{ w_{(ij,kl)} \middle| \begin{matrix} w_{(ij,kl)} = 0.05\, where\ (i = k \wedge j = l \pm 1) \vee (i = k \pm 1 \wedge j = l) \\ and\ w_{(ij,kl)} = \sqrt{0.005}\, where\ (i = \pm k \wedge j = l \pm 1) \end{matrix} \right\}$$

Three corridors connecting the central location of the grid to border water locations are defined as:

**Southern Connection:**

$$A_1 = \{((21,20),(22,20)),((22,20),(23,20)),((23,20),(24,20)),((24,20),(25,20)),((25,20),(40,20))\}$$

$$w_1 = \{w_{((21,20),(22,20))} = 0.0050, w_{((22,20),(23,20))} = 0.0050, w_{((23,20),(24,20))} = 0.0050, w_{((24,20),(25,20))} = 0.050, w_{((25,20),(40,20))} = 0.075\}$$

**Northwest Connection:**

$$A_2 = \{((21,20),(20,19)),((20,19),(19,18)),((19,18),(18,17)),((18,17),(18,16)),((18,16),(4,1))\}$$

$$W_2 = \{w_{((21,20),(20,19))} = 0.0071, w_{((20,19),(19,18))} = 0.0071, w_{((19,18),(18,17))} = 0.0071, w_{((18,17),(18,16))} = 0.0050, w_{((18,16),(4,1))} = 0.1040\}$$

**Southwest Connection:**

$$A_3 = \{((21,20),((22,19)),((22,19),(23,18)),((23,18),(24,17)),((24,17),(23,16)),((23,16),(38,1))\}$$

$$W_3 = \{ w_{((21,20),((22,19))} = 0.0071, w_{((22,19),(23,18))} = 0.0071, w_{((23,18),(24,17))} = 0.0071, w_{((24,17),(23,16))} = 0.0050, w_{((23,16),(38,1))} = 0.1040\}$$

The availability of hash and bean production resources follows the bell-shaped curve where the maximum resource is available at the center of the grid (21, 20), as shown below:

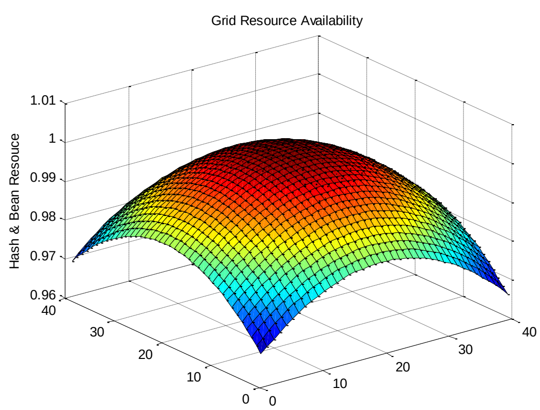


Figure 54: Availability of Hash and Bean resources

If the society starts with the same combination of agents as the previous example, as shown in Figure 55 at the steady state, residential population will be more concentrated around the southern water source compared to the western ones (left figure). At the same time shape of the production location is gravitated towards the southern water location due to shorter distance and higher capacity for the corridor between the central grid location and the southern water location compared to western grid locations. This pattern resembles the pre 1997 spatial shape of grain production Figure 53.

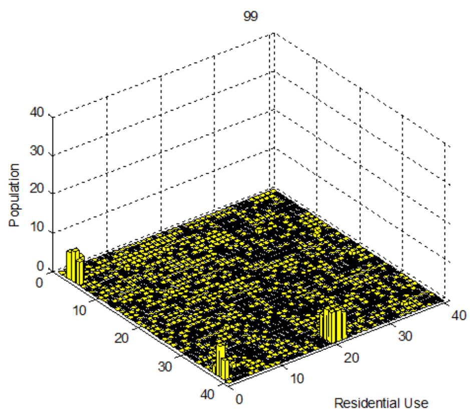


Figure 55: Pre-disruptions shape of society

To replicate events happened in grain transportation between 1997 and 2007 a disruption of service is introduced to the grid by reducing the capacity of the southbound links and increasing its travel time. At the same time the western corridors are improved by increasing their capacity and reducing their travel time. As shown in Figure 56, the post disruption steady state of the system shows the shift of the residential population from the southern water location to the western ones (left) and gravitation of the production center towards the western water locations (right)

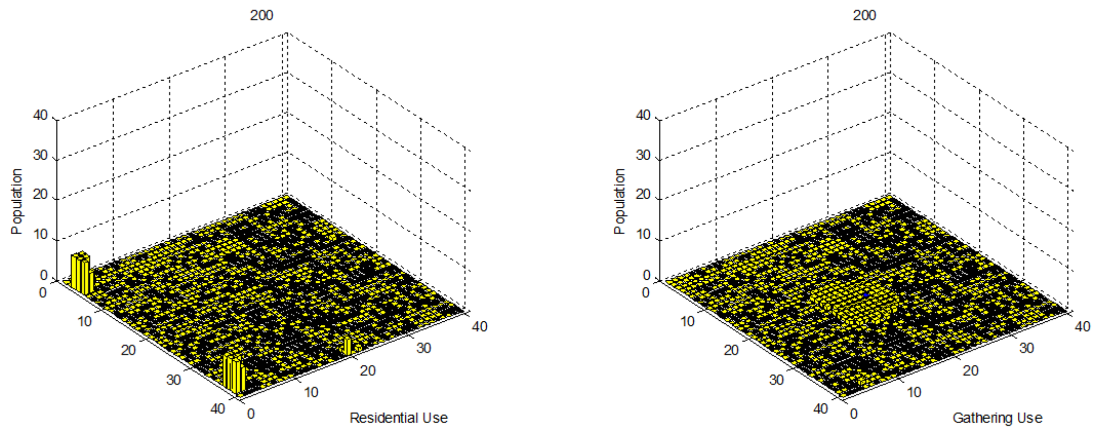


Figure 56: Post-disruptions shape of society

The disruption in service affects the total travel time will which would lead to lower production and utility levels. However the response of the westbound corridors to the loss of in the southbound service, led to sustained production and travel patterns in the post disruption state of the society, Figure 57.

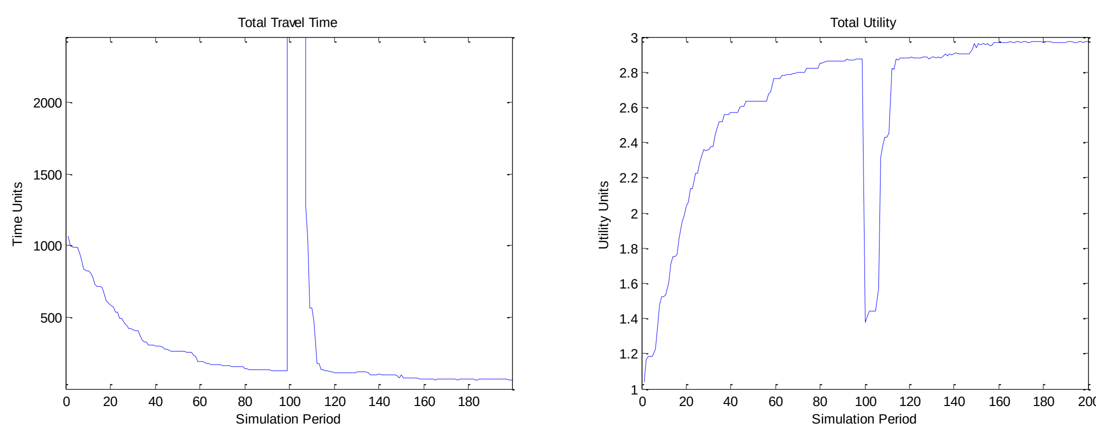


Figure 57: Effect of disruption on travel time and utility

## 5.3. Extensions to Two-Economy Model & Beyond

Our framework can be expanded to model a complete society by breaking it into its building blocks (sub-societies). To explain this extrapolation we construct a 20x40 grid using 2 separate 20x20 sub-grids with central water locations and uniformly distributed hash and bean resources.

Each agent in this new society belongs to one sub-society identified by its water location. This new grid is detached from the external environment in the sense that population of the grid is constant and doesn't change. Agents can only migrate from one sub-society to the other based on the future expected utility realized from living in that sub-society. At the end of each period agents compare their maximum future expected utility of living in these societies and select the one with maximum utility.

Initially, the transportation assets are assumed to be the same in two sub-societies, leading to identical steady state spatial patterns for production and living clusters in two sub-societies, Figure 58. Additionally the steady state utility, travel time, and production in these two sub-societies will be almost equal.

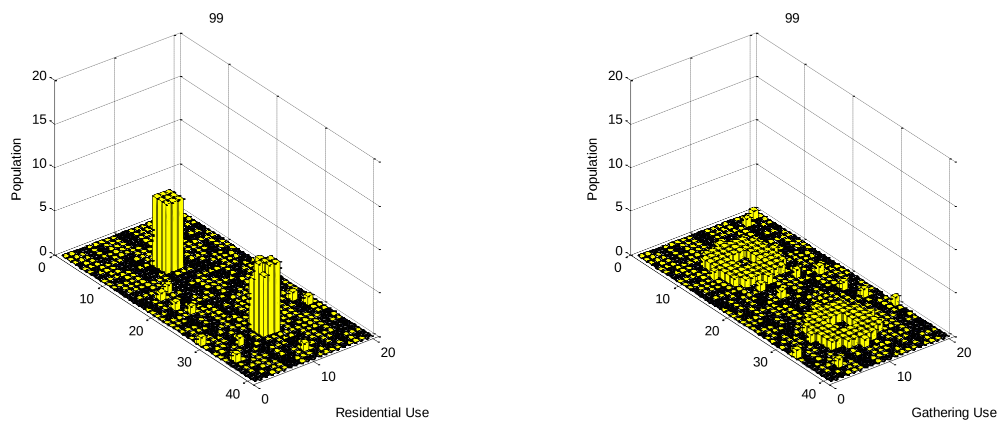


**Figure 58: Production and Residential land use (two sub-societies)**

A change in the underlying infrastructure in any of these sub-societies will disturb the balance, and will make one sub-society more attractive than the other. This change will impact both societies by causing within society relocations as well as in-between society migrations. Once the infrastructure change is made the expected average utility per agent in the sub-society with the new infrastructure will be higher than the other sub-society without the infrastructure. Agents from the intact society will realize the potential improvements from moving to the new sub-society and move to the improved society to the point that no additional utility improvement can be realized. . Figure 59 shows the migration of agents between societies after investing on a new corridor.

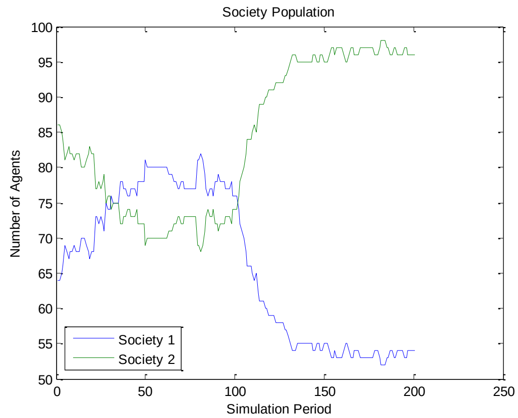


Figure 59: Change in the society population

The migration of agents to the improved sub-society will lead to more sub-societal production, and change in the land use patterns with is strongly tied to increase in land prices of the improved sub-society, Figure 60.

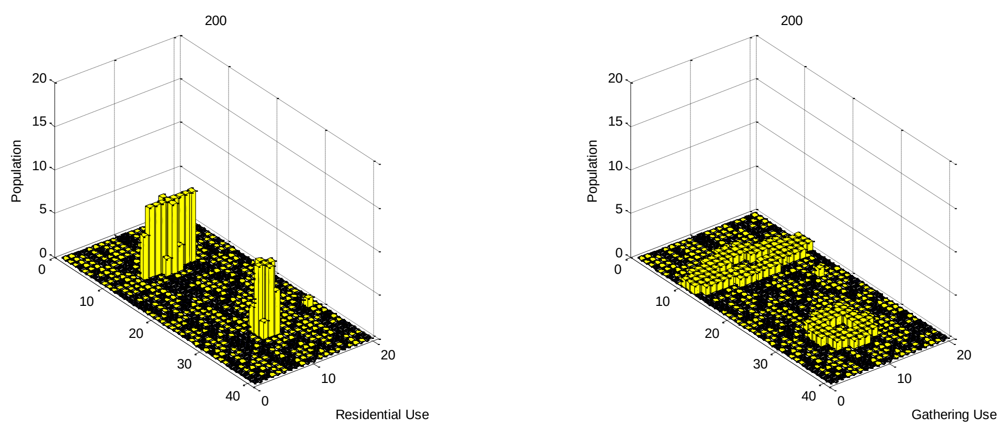


Figure 60: Change in the spatial shape of the investing society

This framework can also be extended to model a complete society consisting of multiple sub-societies by improving between sub-society trades. We can also use this multi-economy society to show the impact of regulations on owner and user agents.

## 5.4. Case of Multiple Owners

Assume that the network of assets within the society mentioned above is controlled by two different owner agents having identical functions. These owner agents are only interested in the revenue generated by their assets in evaluation of their investment decisions as opposed to societal gains. While some investment strategies can be beneficial to user agents no direct benefit can be realized by owners through those strategies. In such scenarios regulator can create an environment that leads to sharing societal gains with owners and lead the owners to decisions that are maximizing societal gains. Figure 61 shows the hierarchy and interaction between these elements.

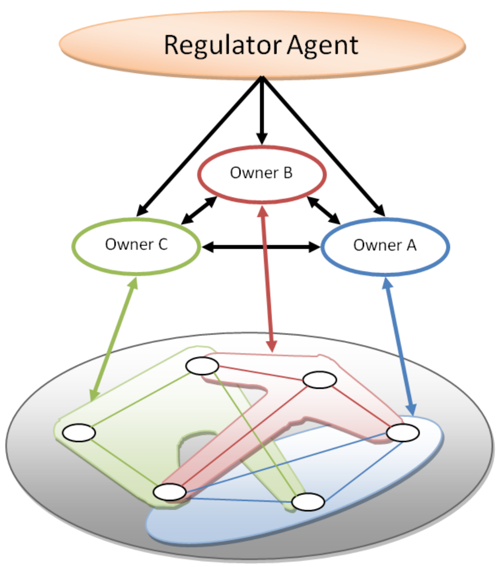


**Figure 61: Structure of the problem**

The interaction between owner can me modeled using applications of the game theory. Rasmusen (65) identifies players, actions, payoff and information as essential elements of a game (rules of the game). In his definition *Players* are the individual who make decision with the objective of maximizing their own utility; *Nature* is a pseudo-player who takes random actions at specified point in the game with specified probabilities; *Actions* are choices that player make; *Payoff* is the either utility that the a player receives after all other players and Nature have picked their strategies and the game has played out, or the expected utility that a player receives as a function of the strategies chosen by itself and other players.

In game theoretic modeling the objective is to describe a situation in terms of rules of the game to explain what will happen in that situation. To maximize their own payoffs player formulate plans know as strategies to select an action based on the available information. The combination of different strategies is known as equilibrium which can be used to predict the outcome of the game.

The interactions the case multiple asset owners fall within the game theoretic modeling framework. In this repeated game owners are players, actions are players' decisions on whether or not to invest in the infrastructure and the payoff is the expected revenue generated by the asset. In the two owner case the owner revenue is generated by the traffic flow passing through the assets that they control. Each one of these owner agents has the option of making an investment (I) or not making an investment (N) which leads to 4 different action combinations: (I;I), (I;N), (N;I) and (N;N). For (N;I) and (I;N) cases the asset owner who makes the investment will experience an increase in total usage (distance travelled on the asset) while the other owner will see a decrease. In (I;I) case, both owners will experience an increase in their traveled distance but its value is smaller than the (I;N) or (N;I) case. Table 10 shows the payoff matrix of owners in absence of the investment cost.

Table 10: Payoff Matrix - no revenue sharing

| | **I** | **N** |
|---|---|---|
| **I** | 60, 60 | 6, 81 |
| **N** | 81, 6 | 7, 7 |

Given this encounter each agent will select the strategy that maximizes payoff. The current payoff structure for this game is show in Equation 22 and Equation 23, where $o_1$ is the horizontal player and $o_2$is the vertical player.

Equation 22: Payoff preference for the horizontal player

$$I; N >_{o_1} I; I >_{o_1} N; N >_{o_1} N; I$$

Equation 23: Payoff preference for the vertical player

$$N; I >_{o_2} I; I >_{o_2} N; N >_{o_2} I; N$$

Equation 22 and Equation 23 are showing the existence of a dominant strategy for this game. A dominant strategy is a strategy in which the payoff of the agent is always higher than other strategies. In the payoff matrix shown in Table 10 investing (I) is the dominating strategy for both agents and consequently in lack investment costs both agents will choose to create the corridor. At existence of an investment cost the payoff matrix of the game will change from Table 10. For illustrative purposes assume that this cost is higher than 60. If we set this new cost at 65 the new payoff matrix for our problem can be re-written as Table 11.

Table 11: Payoff Matrix - revenue sharing

| | **I** | **N** |
|---|---|---|
| **I** | -5, -5 | 6, 16 |
| **N** | 16, 6 | 7, 7 |

This payoff matrix doesn't have a dominating strategy for neither of the agents. In absence of dominant strategies the outcome of the game can't be deterministically predicted. The new payoff matrix shown in Table 11 is an example of a case where no dominant strategy exists. Equation 24 and Equation 25 show payoff preferences of owners the presence of investment costs.

Equation 24: Payoff of the Horizontal Agent

$$I; N >_{o_1} N; N >_{o_1} N; I >_{o_1} I; I$$

Equation 25: Payoff of the vertical agent

$$N; I >_{o_2} N; N >_{o_2} I; N >_{o_2} I; I$$

Payoff preferences shown in Equation 24 and Equation 25 showing the existence of the Game of Chicken (66) were no equilibrium exists and the outcome of the system can't be predicted. This structure is neither beneficiary the owner nor users because of its embedded uncertainty of outcome. Decisions made by regulators can impact the action/reward space of owners and shift their decisions to toward decisions that are more favorable to the society. As shown in previous chapters, creating new infrastructure investments will impact different societal key performance indicators such as production/land value and ….. The societal gain is at its maximum in (I;I) scenario followed by (I;N) or (N;I) and (N;N). A value sharing policy set by regulators will change owners' gain from the actions and change the investment (I) into the dominant strategy for both agents. If $a$ is the value shared by asset owner under (I;I) and $b$ is the value shared by owners under (I;N) or (N;I), where $a > b$ the new payoff matrix will be written as Table 12.

Table 12: Payoff matrix under value sharing policy

| | **I** | **N** |
|---|---|---|
| **I** | -5+a, -5+a | 6+b, 16+b |
| **N** | 16+b, 6+b | 7, 7 |

By properly setting values for $a$ and $b$ the regulator can change the preferences of owners to Equation 22 and Equation 23 and ensure that (I;I) is dominant strategy selected by the owners.

# 6. Chapter 6: Conclusion and Future Work

Selection of proper investment and maintenance strategies requires the understanding and closed loop modeling of users and operator actions. In this research we took a closed loop approach to the problem of infrastructure asset management by looking at assets as an integrated part of a society. Through looking at the problem as complex dynamical system we were able comprehensively measure the value of an infrastructure investments and close the loop to show the effect of transportation infra-structure investment social systems and economic activates.

Our model includes the impact of decisions made by the asset operators or owners on the underlying flow dynamics and on the behavior of asset users. We first explained cost-based and value-based approaches to the infrastructure maintenance for a standalone asset and showed the differences in optimal maintenance policy of the asset under cost-based and value based regimes.

We then added the physics of the underlying network to the decision-making framework and showed the impact maintenance decisions on an asset within a network. We showed the structure of the network and the boundaries for which the value is defined, are important factors in the selection of optimal policies. Consequently, we illustrated through examples that a policy that maximizes the value of a single asset may not necessarily optimize the value of the whole network.

To evaluate the impact of investment decisions on different value dimensions of the society we created an agent-based society. These autonomous agents have the objective of maximizing their utility through leisure and consumption and reacted to changes that were made to the infrastructure. We showed the impact of availability of transportation infrastructure on the "spatial" shape of the society and on the key performance indicators of the society such as production, travel time and utility. We also showed that some aggregate societal behaviors can be modeled through the simulation approach created by explaining the change in the intensity of US grain production and showed how policies and regulations can impact infrastructure investment decisions.

Artificial societies and agent-based computational economics are fairly new concepts in transportation infrastructure management. In this research we created a simplified model that addressed the relationship between different elements of the society and its underlying transportation infrastructure. We emphasize that the primary goal of introducing primal economy into our analytics is to better understand and capture the closed loop dynamics that exist between asset management decisions and the underlying society and economy that use these assets. Clearly, only simplified abstractions of these economies can be made due to the fact that real economies are too complex and too large to be fully modeled. However, it is important to include in these abstractions the necessary ingredient so that conclusions are as real as possible. The work thus far, and the expansions that will be described shortly, are only a leap forward toward this very important goal.

Our primal society model did not include transactions in monetary terms, i.e., money flow was not directly included in the flow dynamics of the society. In this chapter we extend our results to include monetary terms. The societal aspect of the model can be improved by substituting the centralized market with distributed market where agents search for the best value of products and services and allow for trading products.

Introducing money to the society will be a major step up in the evolution of our primal hash-and-bean economy. Adding money to the society will require expanding agents' utility function to include it as a contributing factor. At society level mechanisms must be put in place to control the flow of money against the flow of goods. For a single agent a at time t, the new utility function will be defined by Equation 26. This equation has one additional term compared to Equation 14 to indicate to total money held by the agent.

Equation 26: Utility function of agents with money

$U_{at} = \lambda_{at}^{\alpha_{a1}} H_{at}^{\alpha_{a2}} B_{at}^{\alpha_{a3}} M_{at}^{\alpha_{a4}}$ where $\alpha_{a1} + \alpha_{a2} + \alpha_{a3} + \alpha_{a4} = 1.$

For a hash producing agent a who starts period $t$ with amount of money $M$. At the end of the period utility would be equal to $U = \lambda^{\alpha_1}(H - \Delta H)^{\alpha_2}(\Delta B)^{\alpha_3}(M + \Delta M)^{\alpha_4}$ where $\Delta H$ is the amount of hash sold, $\Delta B$ is the amount of bean purchased and $\Delta M$ is the change in the money level of the agent.

By substituting $\lambda$ with $(12 - T_{ijkl} - w)$, H with $R_{hkl}^{1-p_h} w^{p_h}$ and $\Delta M$ with $p_h \times \Delta H - p_b \times \Delta B$ where $p_h$ and $p_b$ are prices for hash and bean the individual utility maximization problem of the agent can be written as Equation 27.

Equation 27: individual utility maximization problem of the agent

$$\text{Max } U = (12 - T_{ijkl} - w)^{\alpha_1}(R_{hkl}^{1-p_h} w^{p_h} - \Delta H)^{\alpha_2}(\Delta B)^{\alpha_3}(M + p_h \times \Delta H - p_b \times \Delta B)^{\alpha_4}$$

$$\text{s.t.}$$

$$M + p_h \times \Delta H - p_b \times \Delta B > 0$$

Where the constraint assures agents can never spend more than what they have available.

The other suggested improvement to current modeling scheme is the substitution of the centralized market with multiple distributed local markets where agents can chose to trade their products. In this new approach the producing agents will create trading coalitions for exchange of commodities. The society is then partitioned into collations of two and more agents ($A = \bigcup_i A_i$ *and* $\bigcap_i A_i = \emptyset$), which exchange hash, bean and money to gain higher utility. Agents will have a limited discovery time to find the best possible trading partner through whom they can maximize their utility. Within each collation, the trade happens only when the minimum utility of participating agents is maximized. For agent $a \in A_i$ this notation can be presented as follow:

$$\max \min_{a} U_a$$

$s.t.$

$$U_a = \lambda^{\alpha_{a1}}(H_{0a} + \Delta H_a)^{\alpha_{a2}}(B_{0a} + \Delta B_a)^{\alpha_{a3}}(M_{0a} + p_h \Delta H_a + p_b \Delta B_a)^{\alpha_{a4}}$$

$$\sum_a \Delta H_a = 0$$

$$\sum_a \Delta B_a = 0$$

$$\sum_a \Delta M_a = 0$$

where $U_a$ is the utility of the individual participating agents and constraints ( $\sum_a \Delta H_a = 0$ , $\sum_a \Delta B_a = 0$ and $\sum_a \Delta M_a = 0$ ) ensure that the amount of hash, bean and money stay constant before and after the trade. These local markets can also be expanded for adding services to the society. Services are different from commodities for they have to be consumed in the location of their production. Each service provider will also have a local market for which commodity producers will go to exchange their money/products with services to maximize their utility.

Inter-society trade is another important element in converting our primal hash-and-bean economy into a universally applicable framework. The current model assumes that the trades between agents are happening simultaneously without taking into account the physical distance between production and consumption geographical locations. The suggested expansion into multiple markets will work the best for agents which are in close proximity of each other. By allowing the intra-society trade each society can specialize in production of specific commodities and purchase the remainder of its needs from other societies.

The virtual society of this model is built using different types of agent who convert resources to products and consume them. Such a perspective can for extrapolating this frame work to a real society for expansion and calibration. This model can be calibrated on a sub-economy level within a bigger economy (one state or coalition of states compared to the whole country). In this isolated society model can be calibrated to represent the behavior of basic production activities such as farming. US department of census categorization of industries can be used for creating different classed of agents; Bureau of Economic Analysis Input-Output tables can be used for connecting consumption of resources to production of different products; and US department of labor has time use surveys that shows the amount of time spend on various activities which can be used as inputs for creation of the representing virtual society and taking it out of abstraction.

These directions will lead this framework towards a more realistic way of modeling the transportation infrastructure investment problem by having a closed loop look towards the problem and modeling the social, environmental and economic impacts of the transportation infrastructure investments.

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