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Examining the efficiency of multimodal transportation systems: a systems dynamics approach

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EXAMINING THE EFFICIENCY OF MULTIMODAL TRANSPORTATION SYSTEMS: A SYSTEMS DYNAMICS APPROACH

by

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ABSTRACT

With international trade becoming a big part of the worlds economic activity, the demand for good freight transportation systems has grown substantially. The appropriate use of transportation is an integral part of the supply chains effectiveness. Therefore, the continuous economic globalization, the growing demand for speed-to-market product delivery, and the need to manage global supply chains more effectively, has led to the sustained increase in demand towards multimodal transportation systems (MTS).

MTS play an essential role in corporations competing in global markets in the 21st century. In transportation, the effectiveness and efficiency of the whole system depends upon the interconnectivity of its elements. Because disruptions in the supply chain are costly, this research will look at improving the efficiency of MTS by looking at disruptions that have a negative impact on the elements that make up the system. Although past research classifies disruptions in MTS as: congestion, demand fluctuations, time delays, capacity limits, scheduling and, connectivity between the different modes, limited research address the relationship between these failures and the system.

This research presents a Systems Dynamics (SD) approach to model MTS, which will let us iterate and mitigate a system to be able to forecast scenarios and meaningful hypothesis of a systems behavior over time. The SD model will aid to identify and understand those major elements and disruptions that altogether impact the efficiency of the MTS. The model will help determine how the disruptive factors of the supply chain are related to the efficiency of the system and will suggest decision-making strategies that will improve MTS performance over time being able to enhance customer satisfaction.

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ABBREVIATION LIST

ICT	-	Information and Communications Technology
MTS	-	Multimodal Transportation System
U.S. DOT	-	U.S. Department of Transportation
SD	-	System Dynamics

1. INTRODUCTION

An industrialized society cannot exist without an efficient transportation system if trying to compete in global markets in the 21st century. Even before Thomas Friedman suggested that the world was flat in 2002, the worldwide phenomenon of globalization, brought by modern communication and the Internet; had inevitably already encouraged a rapid pace of change towards consciously opening cross-border links in international trade and finance. Trade globalization, outsourcing, and supply-chaining, had changed the world permanently (Friedman, 2002). With international trade becoming a big part of the worlds economic activity, good freight transportation systems grew substantially and became even more significant in any supply chains success.

Transportation suggests the movement of freight from one location to another as it goes from the beginning of the supply chain to the customer (Chopra, 2000). Five modes of transportation, each with advantages and disadvantages, carry freight in the U.S.: water, air, rail, road and pipeline. Water transport is the least expensive mode but is also the slowest and although carries bulk cargo, has limited destinations. Air transport moves cargo in limited quantities but fast and to a limited number of destinations. Rail transport is able to carry rather fast, large quantities of cargo over long land routes for a low value but to limited destinations. Road transport moves cargo in limited quantities but virtually to any destination. And, pipeline transport is limited to large and predictable demand of liquids and gases at a high-fixed cost and has limited destinations. For further details on the characteristics of the different modes within the U.S. are portrayed in Table 1.1 .

The appropriate use of transportation is an integral part of the supply chains effectiveness. For that reason, the continuous economic globalization, the growing

Table 1.1: Comparison of U.S. Domestic Transportation Modes (Stock, James and Lambert, Douglas, 2001)

Comparison of U.S. Domestic Transportation Modes

	Motor	**Rail**	**Air**	**Water**	**Pipeline**
Economic Characteristics					
Cost	Moderate	Low	High	Low	Low
Market Coverage	Point-to-point	Terminal-to-terminal	Terminal-to-terminal	Terminal-to-terminal	Terminal-to-terminal
Degree of Competition (Number of Competitors)	Many	Moderate	Moderate	Few	Few
Predominant Traffic	All Types	Low-moderate value	High Value	Low value	Low value
		Moderate-high density	Low-moderate density	High density	High density
Average Length of Haul	Short to Long	Medium to Long	Medium to Long	Medium to Long	Medium to Long
Equipment Capacity (tons)	10 to 25	50 to 12,000	5 to 125	1,000 to 60,000	30,000 to 2,500,000
Service Characteristics					
Speed (time-in-transit)	Moderate	Slow	Fast	Slow	Slow
Availability	High	Moderate	Moderate	Low	Low
Consistency (Delivery time variability)	High Consistency	Moderate Consistency	High Consistency	Low-moderate Consistency	High Consistency
Loss and Damage	Low	Moderate-High	Low	Low-Moderate	Low
Flexibility (Adjustment to shipper's needs)	High	Moderate	Low-Moderate	Low	Low

demand for speed-to-market product delivery, and need to manage global supply chains more effectively, has led to the sustained increase in demand towards multimodal transportation systems (MTS). Multimodal transportation system refers to the modal coordination or integrated use of two or more modes of transportation for delivering freight from origin to destination in a seamlessly linked and efficiently coordinated flow. MTS has grown considerably in the last decades making it an essential constituent of the whole global distribution process.

Historical patterns show how a nations economic strength and competitiveness depend on an efficient, sustainable and secure freight transportation system. For example, between 1970 and 2001, U.S. international freight trade grew by over 20 times, resulting for the U.S. economy to grow over 10 times over that period of time (Chopra, 2000). That transportation activity denoted more than 10 percent of the gross domestic product (GDP) of the U.S. in 2002 (Bureau of Transportation Statistics, 2002). Also, in 2002, over 19 billion tons of freight worth over $13 trillion, were transported in the United States (Table 1.2). This results in 325 pounds of freight moved daily for every citizen of the United States (Dobbins et al., 2007) and the volume is expected to double by 2035 (U.S. DOT, 2006). In todays globalized

Table 1.2: Top Commodities 2002 (U.S. Department of Transportation, 2006)

Tons (millions)			**Value ($ millions)**	
Total	**(P) 19,326**		**Total**	**(P) 13,120**
Coal n.e.c.1	2,687		Machinery	1,866
Gravel	2,048		Electronics	948
Cereal Grains	1,330		Mixed Freight	944
Crude Petroleum	1,284		Motorized Vehicles	855
Coal	1,261		Coal n.e.c.1	729
Nonmetal min.prods.2	1,138		Textiles/leather	545
Gasoline	1,090		Pharmaceuticals	519
Waste/Scrap	926		Unknown	458
Fuel Oils	560		Chemical Prods.	444
Natural sands	557		Misc. mfg. prods.	411

world, multimodal transportation forms the backbone of world trade. Therefore, as the demand for MTS grows and becomes more significant to logistics and efficient supply chain, there is need of heightening the significance of multimodal transportation systems, understanding its elements and how to manage them effectively.

In order to manage MTS effectively a profound understanding of the system needs to take place. The major players or elements in the MTS network are the carriers and shippers and the different modes of transport. Shippers are those who generate the demand for transportation, and carriers, those who supply the transportation services for moving the demand. The interactions of these elements constituting the MTS, their individual behaviors, and the cause-and-effect that they have on each other, determine the performance of multimodal transportation systems. Figure 1.1 illustrates the multi-mode transportation network, which is represented as a collection of nodes and links. Transportation of freight originates and ends at nodes and travels on links. The figure also shows how for most modes of transportation, infrastructure such as ports, roads, waterways, and airports are required to exist in both, at the nodes and links. In the figure example, loaded containers leave the shippers facilities by truck to a rail yard, where they are merged into a train and sent to another rail yard. Trucks are used again to transport those containers from that rail yard to the sea container terminal. And then, containers after relocated into the ship, are transported to a port, from where they leave by either air or train to their final destinations. This example previously described is an example of the MTS network.

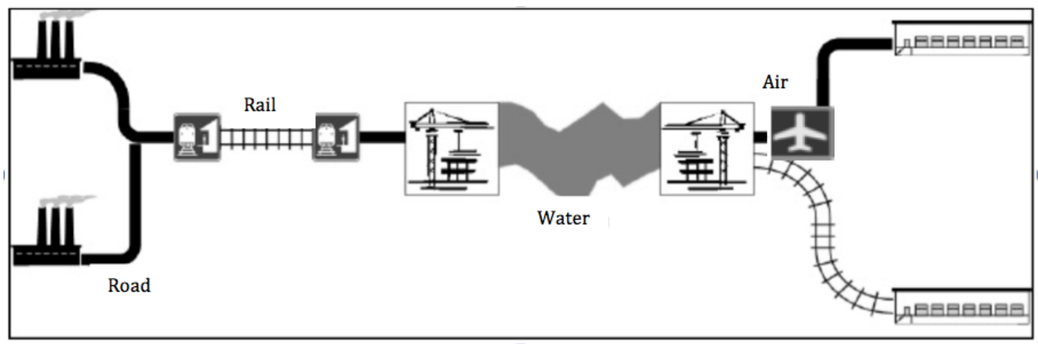

Figure 1.1: A Multimodal Transportation System-Network (Bektas and Crainic, 2007)

Although there are five modes of transportation, this research will only consider the four major modes of transportation, which are: road, rail, air and water. A robust analysis of the combination of all the modes and connections and elements that take part in the system will take place in order to understand the impact towards the efficiency of the MTS, which is critical for sustaining a vibrant economy. Figure 1.2 shows a breakdown of the MTS elements that constitute the system and affect each other because are somehow interrelated to each other by the different means of transportation utilized to move freight from one location to another in the supply chain.

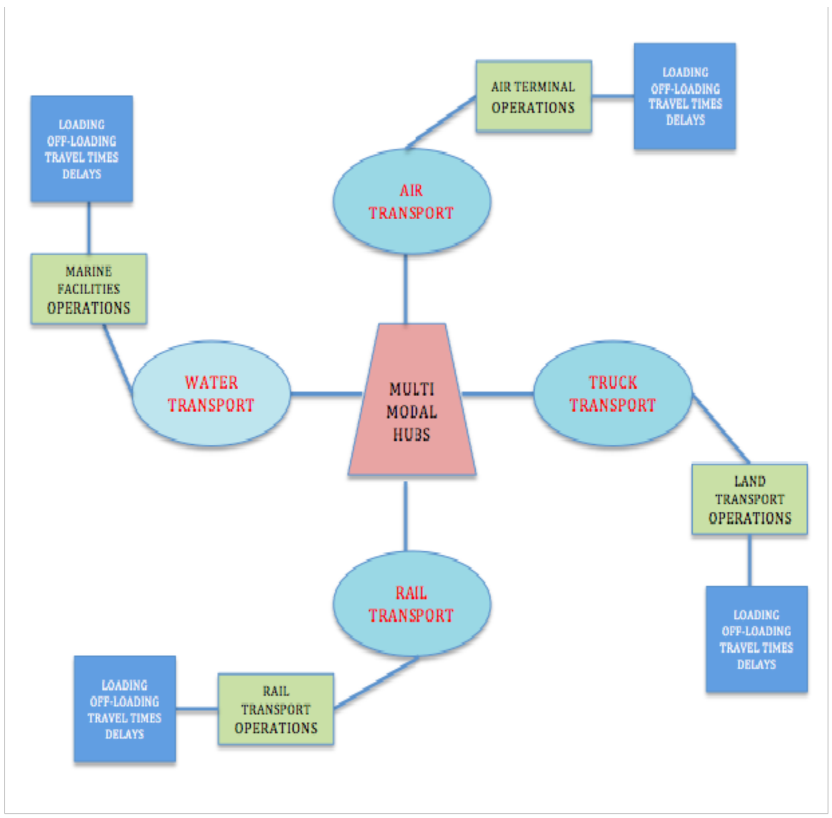

Figure 1.2: Breakdown of MTS Elements

2. LITERATURE REVIEW

As globalization has expanded, supply chain resiliency has decreased making supply chain systems more complex and interdependent. It has become a policy of the United States Government to encourage and promote the development of multimodal transportations systems in the U.S. in order to transport freight in an efficient manner and strengthen the nations ability to compete in global economy (Krebs, 1994). A disruption in any part of the supply chain affects the whole supply chain network. Disruptions are stochastic events that interrupt the normal operations of a multimodal system (Krebs, 1994). For example, the congestion that occurs in the road transport will consequently have a negative impact on the rail transport scheduling. Therefore, interest in understanding the vulnerabilities of supply chains due to these disruptions has become significant in order to increase the efficiency and effectiveness of transportation systems.

Global supply chains of today are subject to more risk factors than localized supply chains of the past. Freight transportation systems have grown, making supply chains success more complex due to factors such as: higher flows, longer distances, and the utilization of different modes of transport; amongst other factors. A global supply chain network is exposed to a variety of risks, including supply disruption, supply delays, demand fluctuations, price fluctuations, and exchange-rate fluctuations (Chopra, 2000). Underestimating risks in global supply chains can result in really painful outcomes. Hence, if appropriate mitigation plan are not in place, these risks can significantly hurt the supply chain performance. For suitable mitigation strategies, it is critical for global supply chains to be aware of the relevant risk factors that must be considered when designing a good supply chain network. Table 2.1 contains a brief categorization of some of the supply chain risks and their drivers which play a significant role in the supply chains proper functioning and which need to be managed to avoid supply chain breakdown.

Table 2.1: Supply Chain Risks to be Considered During Network Design (Chopra and Sodhi, 2004)

Category	**Risk Driver**
Disruptions	Natural Disaster
	War
	Terrorism
	Labor Disputes
	Supplier Bankrupcy
Delays	High Capacity Utilization at Supply Source
	Inflexibility of Supply Source
	Poor Quality of yield of Supply Source
Forecast Risk	Inaccurate forecasts due to long lead times
	Seasonality
	Product variety
	Short Life Cycles
Inventory Risks	Demand and Supply Uncertainty
Capacity Risk	Capacity Flexibility

Risks faced by supply chains are quite diverse, arising from sources both, within and external to the supply chain. These include delays, information and network forecasting, procurement, customers, inventory, capacity, resource allocation, material handling, queuing, maintenance planning, scheduling, congestion, demand fluctuations and connectivity between modes, among others. Since supply chain disruptions are costly, there is a need to understand how the supply chain is affected by these abnormalities in order to develop appropriate strategies for managing their impact.

The complexity of supply chains requires an assessment of the types of risks involved and the related factors that may cause them. The risks are all interrelated. Therefore, before deciding on global supply chain risk management strategies, Manuj and Mentzer (2008) categorize these risks and also, by performing a survey to more than 400 experts in the field, they range from high to low the probability of those risks factors to cause a disruption on the supply chain. Additionally, they associate with each risks factor a level of mitigation, ranging from uncontrollable, where an actor has no influence on an event and must thus simply assume the consequences, to controllable where an actor has a good level of influence on the event itself and may thus be able to mitigate more effectively some of its aspects to consequently improve the smoothness of the supply chain.

Menuj and Mentzer (2008) categorize the risks taking part in the supply chain such as: supply risks, demand risks and operational risks (Figure 2.1). Supply risks are those risks that impact elements of inbound supply, implying that a supply chain is unable to meet the demand in terms of quantity and quality of parts and finished goods. Consequently, the outcome is labeled as a supply disruption. Demand risks are those that impact elements of the outbound supply chain where the extent or fluctuations of the demand are unexpected. This is labeled as demand disruption. And, operational risks, which are those that impact elements within a supply chain, impairing its ability to supply services, parts or finished goods within the standard requirements of time, cost and quality. Transportation is one of the most salient operational risks.

The most significant factors impacting supply chain risks as categorized by Manuj and Mentzer are environmental, geopolitical, economic and technological visually portrayed in Figure 2.1 .

The environmental factor is considered to have among the highest probability of occurrence and that can be the least effectively mitigated since they tend to

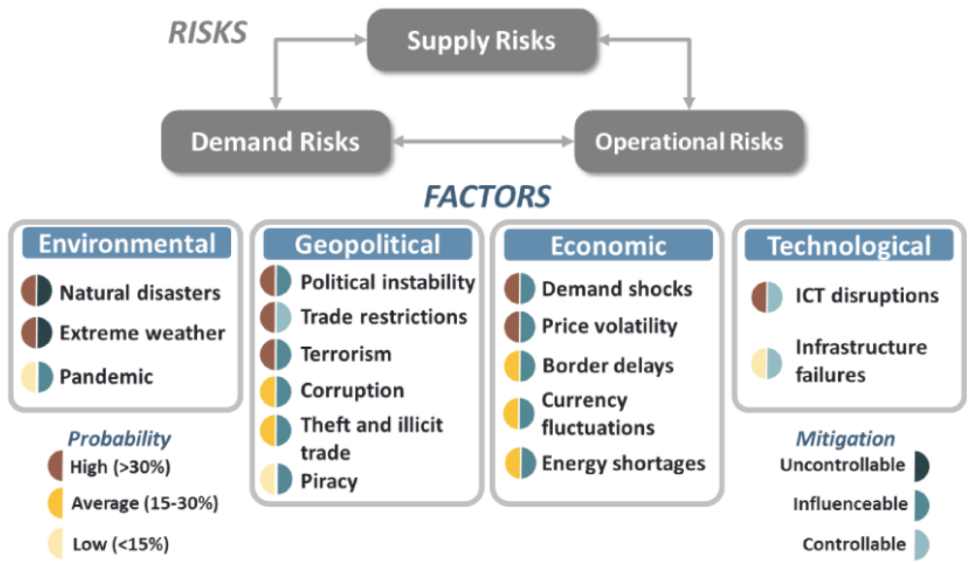

Figure 2.1: The Geography of Transport Systems (Manuj and Mentzer, 2008)

be uncontrollable. Some examples are: natural disasters such as hurricanes and extreme weather are within this category, including potential sea level rises. Pandemics are also a possibility, but their probability and mitigation remains uncertain. The geopolitical factor tends to have a high probability, specifically conflicts and trade restrictions, but supply chain actors have a level of influence on the outcome. The economic factor, which most significantly relates to demand shocks, often associated with political or economic sudden changes. Price volatility is also a concern since it has an important impact on input costs. Like geopolitical factors, supply chain actors have a level of influence on the outcome. For example, trade restrictions randomly imposed by governments can have important impacts, but the industry is able to either comply or to put pressures to have these restrictions change if they are judged to be unacceptable. The technological factor, which although it includes transport infrastructure, these failures are fairly rare. Therefore, the most relevant technological concern involves ICT disruptions. As supply chain management increasingly rely on information technologies for its management and operations, any information system failure has important ramifications. Figure 2.1 figuratively represents the most significant types of risks and their factors that impact the transport supply chain along with legends that show the probability of those factors causing disruptions within global supply chains and level of mitigation associated with each factor. This can be very beneficial in the understanding of how these disruptions affect supply chain transportation systems since it is known that transportation is one of the most salient operational risks.

Transportation related disruptions could be caused by a diverse array of issues such as congestion at ports, airports, and multimodal facilities, etc. At an aggregated level, large-scaled freight transportation disruptions have a significant impact on a countrys economy (Brooks and Button, 2006). Hence, the understanding of transportation disruptions costs, probability, and causes is also of vital importance for governments and policy makers.

Giunipero and Eltantaway (2004) note that a potential transportation disruption is a source of risk, and that it could quickly cripple the entire supply chain. Their discussion is fairly general and does not offer risk measurements or mitigation strategies for transportation disruptions. Other studies that focus on the different disruptions are: Kraman et al. (1998) with their probabilistic model of a port intermodal terminal to prevent delays, Park and Noh with their simulation of a bulk cargo port to study demand fluctuations and Holguin-Veras and Jara-Diaz with their linear programming model of an intermodal container terminal to understand and mitigate capacity limits. Also, research on inventory and capacity planning, demand uncertainty, forecasting and procurement strategies have suggested methods for mitigating risks but do not adequately address the overall impact of all these disruptions on the efficiency of supply chain networks (Lee and Billington, 1992; Levy, 1995; Lee et al., 1997; Chen et al., 2000). All this past research aids in the analysis and understanding of disruptions in transportation supply systems but lack on the overall behavior of the system.

Several studies have successfully applied simulation modeling to understand supply chain behavior. For example, a simulation model was built to investigate the effect of uncertainty (Petrovic, 2001), another simulation was built to understand the impact of order release mechanisms (Banerjee et al., 2001), and even a simulation was built to measure the impact of transshipments on service levels and costs (Banerjee et al., 2003). Towill (1991) and Towill et al. (1992) used simulation techniques to evaluate the effects of various supply chain strategies on demand amplification. The strategies investigated were as follows: (1) eliminating the distribution echelon of the supply chain, by including the distribution function in the manufacturing echelon, (2) integrating the flow of information throughout the chain, (3) implementing a Just-In-Time (JIT) inventory policy to reduce time delays, (4) improving the movement of intermediate products and materials by modifying the order quantity procedures, and (5) modifying the parameters of the existing order quantity procedures. The objective of the simulation model was to determine which strategies are the most effective in smoothing the variations in the demand pattern. The just-in-time strategy (strategy (3)) and the echelon removal strategy (strategy (1)) were observed to be the most effective in smoothing demand variations. Also, Wikner et al. (1991) examined five supply chain improvement strategies, then implemented these strategies on a three-stage reference supply chain model. The five strategies were: (1) fine-tuning the existing decision rules, (2) reducing time delays at and within each stage of the supply chain, (3) eliminating the distribution stage from the supply chain, (4)improving the decision rules at each stage of the supply chain, and (5)integrating the flow of information, and separating demands into real orders, which are true market demands, and cover orders, which are orders that strengthen safety stocks. Their reference model included a single factory (with an on-site warehouse), distribution facilities, and retailers. Thus, it was assumed that every facility within the chain houses some inventory. The implementation of each of the five different strategies was carried out using simulation, the results of which were then used to determine the effects of the various strategies on minimizing demand fluctuations. The authors concluded that the most effective improvement strategy is strategy (5), improving the flow of information at all levels throughout the chain, and separating orders.

As learned from the literature, research in supply chain modeling has only scratched the surface of how supply chain strategies (or decision variables) may affect a given performance measure, or a set of performance measures. Lee and Whang (1993) and Chen (1997) are examples of such research. Lee and Whang (1993) developed a performance measurement system that attempted to match the performance metric of individual supply chain managers with those of the entire supply chain, in an attempt to minimize the total loss associated with conflicting goals. Similarly, Chen (1997) also investigated the relationship between individual supply chain managers and the supply chain as a whole, but does so on the basis of inventory costs. Though simulation has been used, these studies did not use a systems dynamics approach for simulation.

Supply chain is a rather complex, complicated feedback system that is featured with multiple variables, high orders, multiple circuits and non-linear quality. Systems Dynamics (SD) methodology, pioneered by J. Forrester in 1961, has provided insights into supply chain behaviors and has been used to investigate the effect of different policies on supply chain performance. Since the development of Systems Dynamics, it has been applied successfully to a range of complex problems in different areas. Although, relatively little application of this methodology has been implemented towards the field of transportation (Abbas, 1900). Systems Dynamics provides a logical, systematic and detailed technique through which complicated systems can be easily represented. Therefore, it is well suited to model transportation systems since it provides a structured framework through which large-scaled systems can be easily modeled, analyzed and tested.

Previous studies that have applied the Systems Dynamics approach in the transportation field are: Towill (1996) when analyzed how the supply chain responded to various improvements within the system to enhance business performance, Dimitrios et al. (2007) when built an SD model to evaluate dynamic capacity planning of remanufacturing in closed-loop supply chains, and Disney et al. (1996) when established policies to understand how supply chain would respond to robust changes in lead time and randomness in demand. Other researchers have applied Systems Dynamics modeling to study the effects transshipments on supply chain behavior (Hong-Minh et al., 2000) and the effects of Vendor-Managed Inventory on transport operation (Disney et al., 2003).

Previous research on transportation using SD, have demonstrated the capability of this methodology within this rather complex field. Although, SD modeling has been utilized for supply chain modeling, limited research addresses the relationship between risks, disruptions and failures in the supply chain and the systems efficiency behavior over time. In order to be able to determine what will improve the transportation supply chain and how it can be improved, a thorough understanding is needed in what is the effect all these factors have towards the system. How these factors impact the system as a whole?

Since system dynamics focuses on the systems internal mechanism and structure, and stresses the relationship between units and information feedbacks, and also depicts the non-linear logic functions and delay factors inside the system; this research proposes a Systems Dynamics approach to examine how the disruptions of the supply chain are related to the efficiency of the MTS and will suggests decision-making strategies to improve MTS performance over time.

3. PURPOSE OF RESEARCH

As previous research shows, congestion, competition, capacity, scheduling, delivery delays and conservation are some of the major disruptions and challenges faced in the US transportation system that can be met with the adoption of a serious commitment to multimodalism. The multimodal point-of-view involves looking at how individual modes can be connected, governed, and managed as a seamless and sustainable transportation system. That is, the fundamental objective of multimodalism is not to optimize a single mode of transportation but to integrate the modes into an optimal, sustainable, and ethical system. Such a system should promote efficiency, safety, mobility, economic growth and trade, national security, protection of the natural environment, and enhancement of human welfare (NCIT 2013).

A research question emerges from the literature review: What is the effect of disruptions on the efficiency of Multimodal Transportation Systems (MTS) over time? Therefore, this research presents a Systems Dynamic (SD) approach to MTS simulation that enables the user to model the causal relationships (cause-and-effect) of those disruptions and the resultant impact on efficiency of the Multimodal Transportation System. Efficiency is measured as the percent of freight delivered on-time (output/input). Also, data collected from the U.S. Department of Transportation (2011) was used to both validate the model and run the multiple simulations. In the SD model, various disruptions are chosen as the control variables for simulation, and the impact of different policy scenarios on managing these disruptions are analyzed in terms of the measured MTS efficiency. This helps suggest decision-making strategies that will improve MTS performance over time.

Overall, this research:

1. Uses a System's Dynamic simulation approach to model MTS and all the elements and disruption that constitute the system.
2. Develops decision criteria to mitigate disruption and maximize MTS efficiency.
3. Intends to:
   i. Identify the disruptions affecting the different elements of the system
   ii. Monitor how they behave and negatively impact the efficiency
   iii. Analyze through simulation different scenarios

4. METHODOLOGY

Modeling is a feedback process, not a liner sequence of steps (Sterman, 2000). Societies tend to organize themselves with the thought that cause has a specific effect but forget that those two are distant in time and space and therefore are incorrect to look for causes to solve a problem near the events one seeks to explain. The behavior of a system as it evolves over time is often studied by the development of a simulation model. This model usually takes the form of a set of assumptions concerning the operation of the system. A system is an entity in terms of parts and relations between them. Therefore, these assumptions are expressed in mathematical, logical, and symbolical relationships between the entities, or objects of interest, of the system. Often, the challenge to modeling comes when having to deal with complex systems. A system is considered complex when it is composed from relatively many mutually related parts and that are usually hard to describe or understand. System dynamics provides the basic building blocks necessary to construct models that teach us how and why complex real-world systems behave the way they do over time. Systems Dynamics offers a methodology for the understanding of certain types of complex problems as are encountered in todays transportation systems. The goal is to influence this added understanding to design and implement more efficient and effective policies.

Naylor et al. (1996) define simulation as the process of designing a mathematical or logical model of a real system and then accompanying it are computer-based experiments with the model to describe, explain, and predict the behavior of the real system over a desired period of time. The main advantage is that the computer can track the multitude of implications of complex relationships and their dynamic consequences much more reliably than the human mind. System dynamics modeling is concerned with the dynamic behavior of systems. In other words: the behavior of systems over time. In system dynamics modeling, the modeler attempts to identify the patterns of behavior being exhibited by important system variables; and then builds a model that can mimic the patterns. Once a model has this capability, it can be used as a laboratory for testing policies aimed at altering a system's behavior in desired ways.

Advances in simulation methodologies have made simulations one of the most widely used and accepted tools in systems analysis. Some discussion of circumstances under which simulation is the appropriate tool to use have been discussed previously by many authors such as: Vangheluwe (2008), Zeigler et al. (2000), Sonessa (2004), Naylor et al. (1966) and Banks et al. (1996). Simulation can be used for the following purposes: (1) to enable the study of, and experimentation with, the internal interactions of a complex system, or of a subsystem within a complex system, (2) informational, organizational, and environmental changes can be simulated, and the effect of these alterations on the models behavior can be observed, (3) the knowledge gained in designing a simulation model may be of great value toward suggesting improvement in the system under investigation, (4) by changing simulation inputs and observing the resulting outputs, valuable insight may be obtained into which variables are most important and how variables interact, and (5) simulation can be used to experiment with new designs or policies prior to implementation, so as to prepare for what may happen.

This research applies a system dynamics simulation model to study the effects of supply chain disruptions in a Multimodal Transportation System.

4.1. OVERVIEW OF THE MODELING PROCESS

When a problem arises in a system, action must be taken. However, making wrong decisions could propagate the problem, and ultimately collapse the system. For that matter, understanding the behaviors and structures of systems is essential for problem solving. In general, systems contain many complex relationships, which might cause them to be nonlinear, and make it difficult for the human mind to think through the problem. Therefore, many graphical and mathematical modeling methods have been developed as potential tools to understand a system.

In an engineering environment models are made to better understand the real world and real life. With the help of these models, problems can be simplified and the simplified models provide an opportunity for the examination of these problems as well as for the analysis of emerging ideas of solution to these problems. It is desired to mimic a systems structure and imitate its behavior as similar as possible to real life scenarios and captivate its whole essence and functioning in order to simulate the systems behavior. System Dynamics is not the only simulation technique that is targeted at helping to learn about complexity. Different types of models have been in use for decades in order to describe transportation networks. For example, the utilization of Agent Based Modeling (ABM) has helped in the representation and analyses of complex, non-linear or discrete behavior and the interactions of its agents. These models, then make it possible to portray real systems using qualitative and quantitative parameters, so further on they can be examined. Transportation systems are often complex with many different types of parameters and their relationships. Most of the time, those parts are connected in such complicated ways that they form a complex system whose property and behavior is not simply defined. Conventional transportation simulation models are in some cases difficult to use since in complex systems it is sometimes restricted or difficult to attain data or relationships, which are necessary to describe the system. In certain cases, System Dynamics is that strategic approach used in modeling such systems and determining their behavior.

The description and correct interpretation of complex systems are crucial in order to understand the system. The notion of feedback is very important in system dynamics. Feedback is a process in which actions from the past or the present influence the same phenomenon in the present or future. Furthermore, loop diagrams with feedback information are one of the major tools used to determine the structure of a complex system. The system dynamics formalism allows describing the model behavior in terms of cause-effect phenomena. Since, the general behavior of a complex system is always driven by deterministic cause-effect relationships, then a causal loop diagram can be used to consequently portray the feedback relationships.

The cause-effect diagrams are very effective representation of aggregate behavior of the system. They are very useful to express the modeler's idea of the relationships underneath the model. This diagram is not closely related to the model implementation, since it is used as a general documentation schema. It is only a formalism to represent cause and effect loops. Figure 4.1 has an example of a causal loop diagram for the Multimodal Transportation System (MTS).

The causal loop diagram can be two-directional, positive and negative. In the system dynamics literature, positive loops are sometimes called "reinforcing loops" and negative loops are sometimes called "balancing loops" or "counteracting loops." Positive feedback processes destabilize systems and cause them to "run away" from their current position. Thus, they are responsible for the growth or decline of systems, although they can occasionally work to stabilize them. Negative feedback loops, on the other hand, describe goal-seeking processes that generate actions aimed at moving a system towards or keeping a system at a desired state. In the causal loop, shown in Figure 4.1, it is demonstrated that the loop caused by the variables of: shipment, congestion, and state of the system cause a negative feedback loop

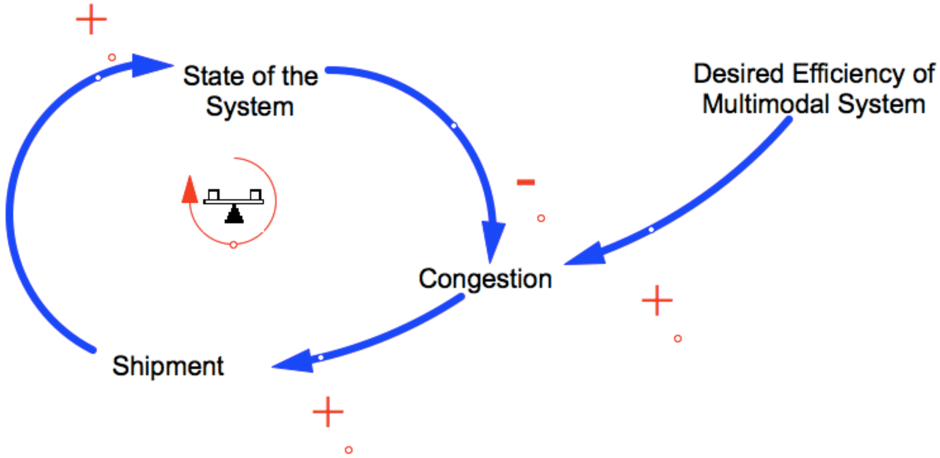

Figure 4.1: Causal Loop of the Multimodal Transportation System

between them resulting in the balance of the whole system and in the long run attaining the desired efficiency of the MTS. What happens in the example in Figure 4.1 is that the negative feedback loop acts to bring the state of the system close to the goal or desired state. The balancing loop counteracts any disturbances that tend to move the state of the system away from the goal. In this particular scenario, the disturbances are the disruptions of congestion and shipment that are taking an effect in the state of the system. While congestion is reduced and decreasing, shipment is efficiently taking place and the state of the system currently taking place will then be efficient and trying to achieve the desired goal. The loop goes on and on for a certain amount of time and the behavior of the variables can be then analyzed. Generally speaking, negative feedback processes stabilize systems, although they can occasionally destabilize them by causing them to oscillate.

As soon as the link diagram is available, thus the functionality of the model is described, the real examination and analysis needs to take place. Because causal loop diagrams fail at quantifying the elements of the system, they must be transformed for further use. Consequently, a Stock-Flow diagram takes place to account for such quantities that the causal loop lacks.

The ability to link the feedback loop structure with the stock and flow structure is critical to effective modeling. Therefore, it is wise to identify the main stocks in a system and then the flows that alter or have an effect on the stocks. But in order to this categorization to take place, an understanding of what a stock and what a flow are, needs to take place. Each stock is thought of as the accumulation of each element size in the system. It is thus said that the system has memory or history. Then, there are two types of flows: inflows and outflows. Inflows are perceived as the rate at which the flow is going to and hence the stock is increasing over time. Similarly, the outflow is the rate at which the flow is going out from and hence the stock is decreasing over time. In other words, inflows and outflows are the rates at which given quantity is being added to or subtracted from the stock. The graphical representation of stock and flow diagram is shown in Figure 4.2 in order to have a better understanding how the stock is the accumulation of the flown in less the flows out.

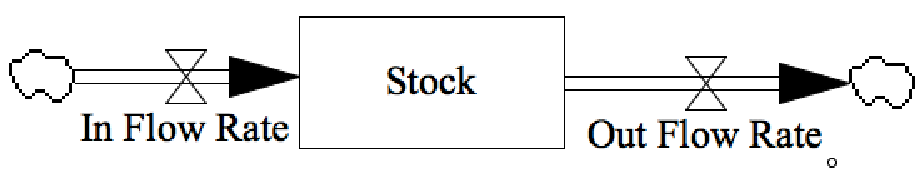

Figure 4.2: Stock and Flow Diagram (Sterman, 2000)

As observed in Figure 4.2 , both inflow and outflow arrows contain a valve that dictates the rate of the flows entering or leaving a stock. Although the diagram is a good visual representation of the problem and its constituents, it is worthy to know that the stock and flow diagram has a precise and unambiguous mathematical meaning. The mathematical model of the overall system dynamics structure is a system of nonlinear, first-order differential and integral equations. Consequently, a stock is the integral of the net flow added to the initial value of the stock. The net flow is eventually the outflow subtracted from the inflow. Mathematically, the net flow is therefore the derivative of the total stock with respect to time. Figure 4.3 , represents the analysis behind the relationship between stock and flows in its integral mathematical notation.

The Stock and Flow diagrams integral equation (Sterman, 2000), stated in Equation (4.1), demonstrates how the flows are functions of the stock and other state variables and parameters. The inflow(s) represents the value of the inflow at any time s between the initial time t0 and the current time t. Equivalently, the net rate of change of any stock, the derivative, is the inflow less the outflow, thus defining Equation (4.2) (Sterman, 2000)

$$\text{Stock}(t) = \int_{t_0}^{t} [\text{Inflow}(s) - \text{Outflow}(s)]\, dt + \text{Stock}(t_0) \tag{4.1}$$

$$\frac{d(\text{Stock})}{dt} = \text{Net Change in Stock} = \text{Inflow}(t) - \text{Outflow}(t) \tag{4.2}$$

In short, stock-and-flow diagrams do not only show the structures components and their relationships but also demonstrate how any stock and flow map posses their corresponding integral or differential equation system in order to express its consequent accumulation and flow processes.

For further understanding of the methodology, the stock and flow diagram for the Causal Loop of the Multimodal Transportation System in Figure 4.1, is represented in Figure 4.3.

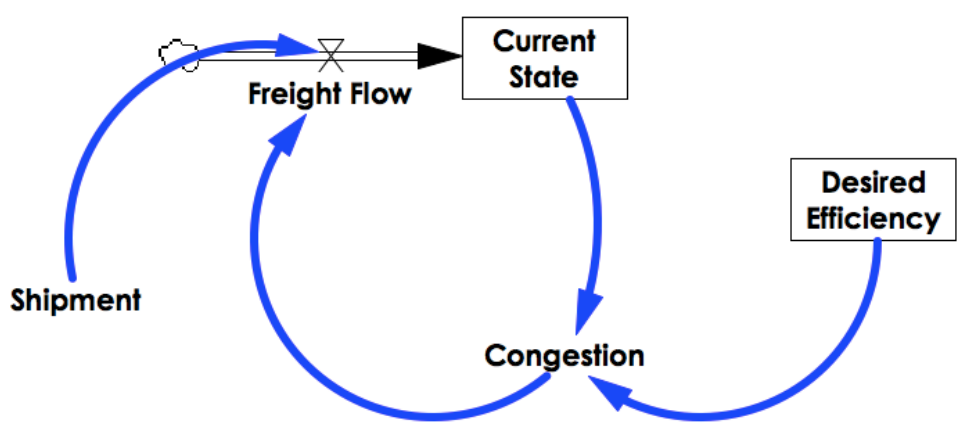

Figure 4.3: Stock and Flow of Multimodal Transportation System

Consequently, since the stock-and-flow diagrams can also be expressed in their corresponding integral or differential equation system. The derivation portrays the equation for the Stock and Flow of the Multimodal Transportation System, as follows:

$$
\begin{aligned}
\boldsymbol{X_t} &= \boldsymbol{X_{t-dt}} * \mathrm{FF}_{t-dt} \\
\boldsymbol{X_t} - \boldsymbol{X_{t-dt}} &= \left(\frac{\text{Congestion}}{\text{SR}}\right) \\
\boldsymbol{X_t} - \boldsymbol{X_{t-dt}} &= \left(\frac{\eta_{\text{desired}} - \eta_{\text{current}}}{\text{SR}}\right) * dt \\
\Delta \boldsymbol{X_t} &= \left((\eta_{\text{desired}} - \eta_{\text{current}})\left(\frac{1}{\text{SR}}\right)\right) * dt \\
\frac{d\boldsymbol{X_t}}{(\eta_{\text{desired}} - \eta_{\text{current}})} &= \left(\frac{1}{\text{SR}}\right) * dt \\
\int_0^t \frac{d\boldsymbol{X_t}}{(\eta_{\text{desired}} - \eta_{\text{current}})} &= \frac{1}{\text{SR}} \int_0^t dt \\
-\ln\left(\eta_{\text{desired}} - \eta_{\text{current}}\right)\big|_0^t &= -\frac{1}{\text{SR}}(t)\big|_0^t \\
\ln\left(\frac{\eta_{\text{desired}} - \eta_{\text{current},t}}{\eta_{\text{desired}} - \eta_{\text{current},0}}\right) &= -\frac{1}{\text{SR}} * t \\
\frac{\eta_{\text{desired}} - \eta_{\text{current},t}}{\eta_{\text{desired}} - \eta_{\text{current},0}} &= \exp\left(-\left(\frac{1}{\text{SR}}\right)t\right) \\
\eta_{\text{desired}} - \eta_{\text{current},t} &= (\eta_{\text{desired}} - \eta_{\text{current},0})\exp\left(-\left(\frac{1}{\text{SR}}\right)t\right) \\
\eta_{\text{current},t} &= \eta_{\text{desired}} + (\eta_{\text{desired}} - \eta_{\text{current},0})\exp\left(-\left(\frac{1}{\text{SR}}\right)t\right),
\end{aligned}
$$

where $\boldsymbol{X}$ is the current state, FF_t is the freight flow at time t, SR is the shipment rate, η_{desired} is the desired efficiency, and η_{current} is the current efficiency.

4.2. MTS SIMULATION

A simulation model was built with the objective of constructing what-if scenarios to understand the impact disruptions in the supply chain have in the overall efficiency of the MTS. Before discussing the steps of modeling in Systems Dynamics in depth, it is important to mention that modeling is an iterative process. Models will go though constant iteration, continual questioning, testing and refinement. Figure 4.4 demonstrates the modeling process as an iterative cycle.

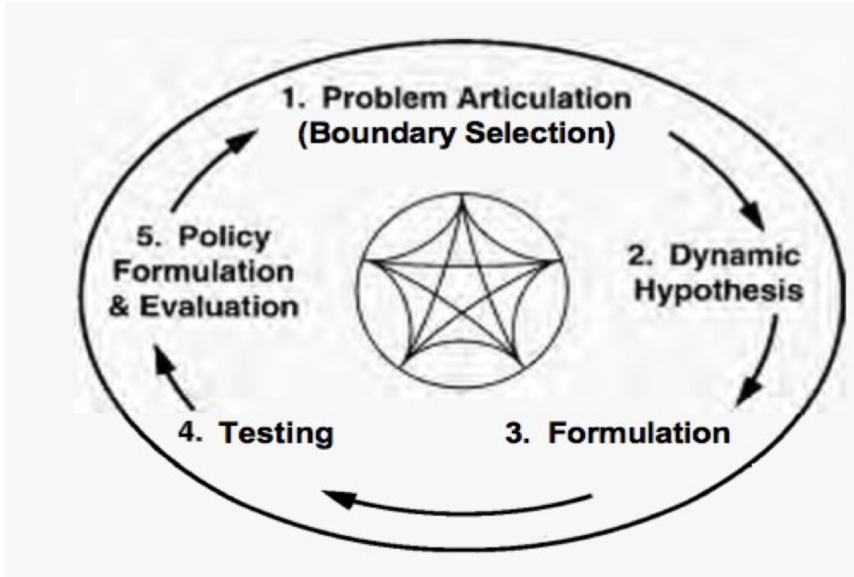

Figure 4.4: SD Steps on the Modeling Process (Sterman, 2000)

The most important step in modeling is problem articulation. What problem are you trying to address? What is the real problem, not just the symptom of difficulty? A clear purpose is essential for a successful modeling study to take place. In this research our problem was to identify the various disruptions that affected the Multimodal Transportation System and see what is the effect of disruptions on the efficiency of MTS over time. Table 4.1 shows the identified disruptions that have a negative impact in the supply chain.

Table 4.1: Disruptions in the MTS

Identified Disruptions	
Congestion	Loading-Unloading Rate
Scheduling	Shipment Rate
Infrastructure Capacity	Transshipment Rate
Mode Capacity	Demand Fluctuations

A model is said to be the mental representation of real-life. Although, one tries to copy as close to real-life as possible, no model is completely perfect. Within problem articulation, a model boundary is selected by the definition of key variables and establishing a time horizon. For the purposes of this research, the time horizon selected was from year 2000 to year 2035 since most of U.S. Department of Transportation data shown in the Appendix, suggests significant increase in transportation in that year; and the key variables, as those disruptions or elements that studies have proven to have a negative impact in transportation industry. Key variables can be divided in three categories that aid in the construction of the model. The endogenous variables are those factors in a causal model or causal system whose values are determined by the states of other variables in the system. Those variables are said to be arising from within and one can control them within the problem and use them to explain how the behavior changes if you alter the structure. In contrast, exist the exogenous variables. These are described as arising from without and are those factors that cannot be controlled but are part of the problem and will explain the dynamics of variables that are relevant and whose behavior over time is under study, in terms of other variables that were assumed. And similar to any other model being built, a limit boundary needs to be established. Therefore, the third category of key variable, the excluded variables which are those who although might affect the problem, will not be looked upon. Table 4.2 described the variables defined for the building of the model.

Once the problem has been defined over an appropriate time horizon, and boundaries and key variables have also been established, the development of a theory, better known as the dynamic hypothesis, should take place in order to model. The hypothesis is dynamic because it must provide an explanation of the dynamics characterizing the problem in terms of the underlying feedback and stock and flow structure of the system. And it is a hypothesis, because it is always provisional,

Table 4.2: Key Variables for Model Boundary Chart

Endogenous	**Exogenous**	**Excluded**
MTS Efficiency (Utilization)	Congestion	Natural Disasters
Mode 1	Infrastructure Capacity	Strikes
Mode 2	Time Delay	Thefts
Demand	Probability Rate of Demand Fluctuations	Terrorist Attacks
Backlog	Out-Freight	
Traffic Volume	In-Freight	
Scheduling	Order Fullfillment Rate	
	Delivery Delay	

subject to revision as you learn more from the modeling process and from the real world. Fundamental modes and structures of dynamic behavior exist in order to explain the behavior of the system that arises from its structure. In order to define the dynamic hypothesis of your model, there is need in understanding its behavior. In this research, the dynamic hypothesis is defined to follow a Goal-Seek Structure. It is desired that the system counteract any disturbances that intent to move the state of the system away from the desired goal. The purpose of the model is to find a way of overcoming the negative impact all these disruptions have on the Multimodal Transportation Efficiency by stipulating a desired goal of efficiency. This will result in that in the case a discrepancy between the desired and actual state of the MTS exists, a corrective action will be initiated to bring the state of the system back in line or close to the goal. Figure 4.5 has a graphical representation of what will happen with the behavior of the MTS over time. The graph portrayed in Figure 4.5 has two lines which represent the behavior the efficiency of the MTS follows over that decided period of time (represented as a green line named the state of the system), and the desired goal for the efficiency of the MTS to behave like (represented as a red line named the efficiency of the MTS). What this graph represents is the theoretical-expected behavior of the overall efficiency (green curve) when managing all the disruptions effectively. The state of the system or green curve represent that expected behavior of MTS efficiency when some disruptions are addressed in the different scenarios such like the scenarios built and demonstrated in the results section where they were managed. As to why that graphical behavior, it depends on the different corrective behaviors applied to overcoming the negative impact all these disruptions have on the MTS efficiency when trying to counteract any disturbances that intent to move the state of the system away from the desired goal which is that one represented as the efficiency of the MTS or red line. In a perfect world scenario, when addressing effectively the different disruptions having a negative impact on the current efficiency of the MTS, the behavior of the current state of the system will try to be similar to that goal established as the efficiency of the MTS.

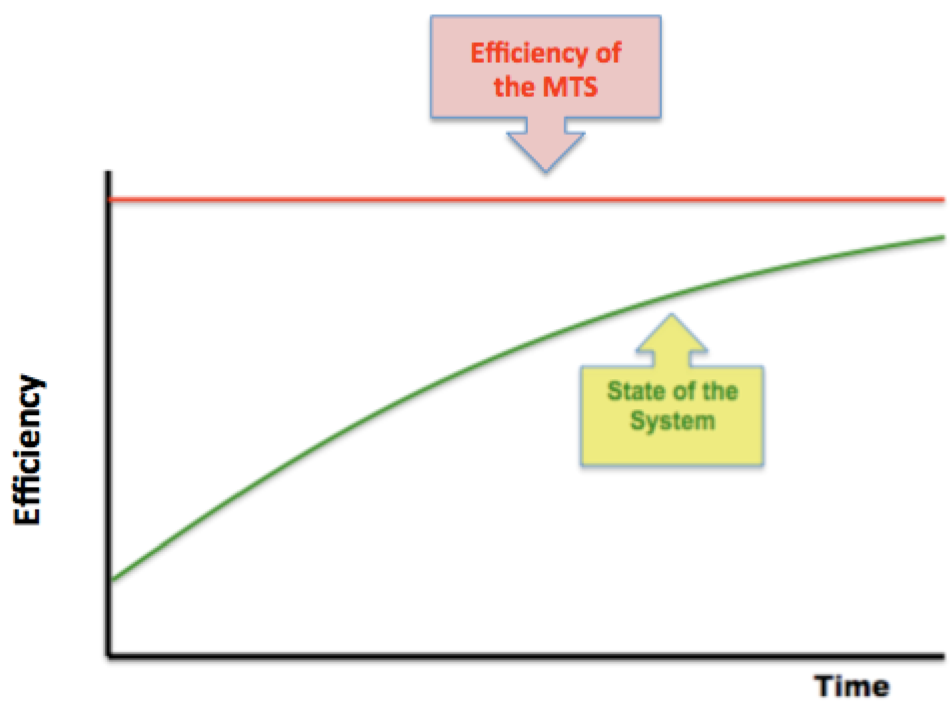

Figure 4.5: Dynamic Hypothesis with a Goal-Seek Structure Behavior

After the defining the Problem Articulation and Dynamic Hypothesis of the study, the next step is the formulation. First, a causal loop diagram is developed in order to understand the relationships among the various main variables in the MTS. Causal loop diagrams are simply a map from the mental model one attains after doing research and studying the MTS system, in order to simplify the building of the stock and flow simulation. In the causal loop, variables are linked with arrows from cause to effect.

Later, with the use of Vensim PLE Software, those relationships in the causal loop diagram are converted into the stock and flow diagram, which is the simulation of the model. Stock variables are those that accumulate over time and provide desired information under study. These stock variables are the ones that characterize the state of the system and are those we want to see how their variation behaves over time. These stocks variables are represented in the model inside boxes. The flows are those variables that represent the amount of change their corresponding stocks undergo during a particular unit of time. And the rest of the variables that are not either flow or a stock, are known to be auxiliary variables because aid in the model for variables to behave as desired or expected over the same period of time. Table 4.3 defines the stock, flow and auxiliary variables used in the MTS model.

One of the benefits of Systems Dynamics approach is that it can be modified in order to attain a better insight and understanding of the behavior of a systems structure over a time period. In this research the model consists of an initial shippers facility where freight is transferred to a terminal and then into a mode of transport. Then, unloaded from that mode of transport into another terminal and into another mode of transport. And last, freight it arrives at its destination and is unloaded. This basic network from origin to destination is affected by the identified disruptions that affect supply chain transportation systems, by delays of transshipments, among other things that negatively impact the efficiency of the MTS. The stock and flow

Table 4.3: Variables for Simulation

Stocks	**Flows**	**Auxiliary Variable**
Demand	Shipment Rate	Probability Rate of Demand Fluctuation
Backlog	Order Fulfillment Rate	Delivery Delay
Congestion	Traffic Volume	Scheduling
Mode 1	Out-Freight Rate	Time Delay
Mode 2	In-Freight Rate	Capacity Limit 1
MTS Efficiency (Utilization)	Mode 1 Freight Exit Rate	Infrastructure 1 Capacity
		Unloading Time 1
		Loading Time 1
		Capacity Limit 2
		Infrastructure 2 Capacity
		Unloading Time 2
		Loading Time 2
		Unloading Time 3

model, shown in Figure 4.6, defines the modes of transport used in the MTS as: Mode 1 and Mode 2. The way the model was designed allows us to easily change corresponding data according to the modes of transport utilized and see how their behavior changes over time accordingly to the impact the different disruptions have on the system. Figure 4.6 is adapted from the stock and flow diagram first developed by Jay Forrester in 1961. For this model, the elements are tailored for an MTS system.

The Table 4.4 demonstrates the integral equations of the stock variables and the equations of the flows and auxiliary variables on the model of the MTS system. Some variables such as fixed capacity limits of terminals and modes, initial demand value, and initial stock values in Mode 1 and Mode 2, vary depending on the modes under study, and it is required for those numerical values to be entered into the model.

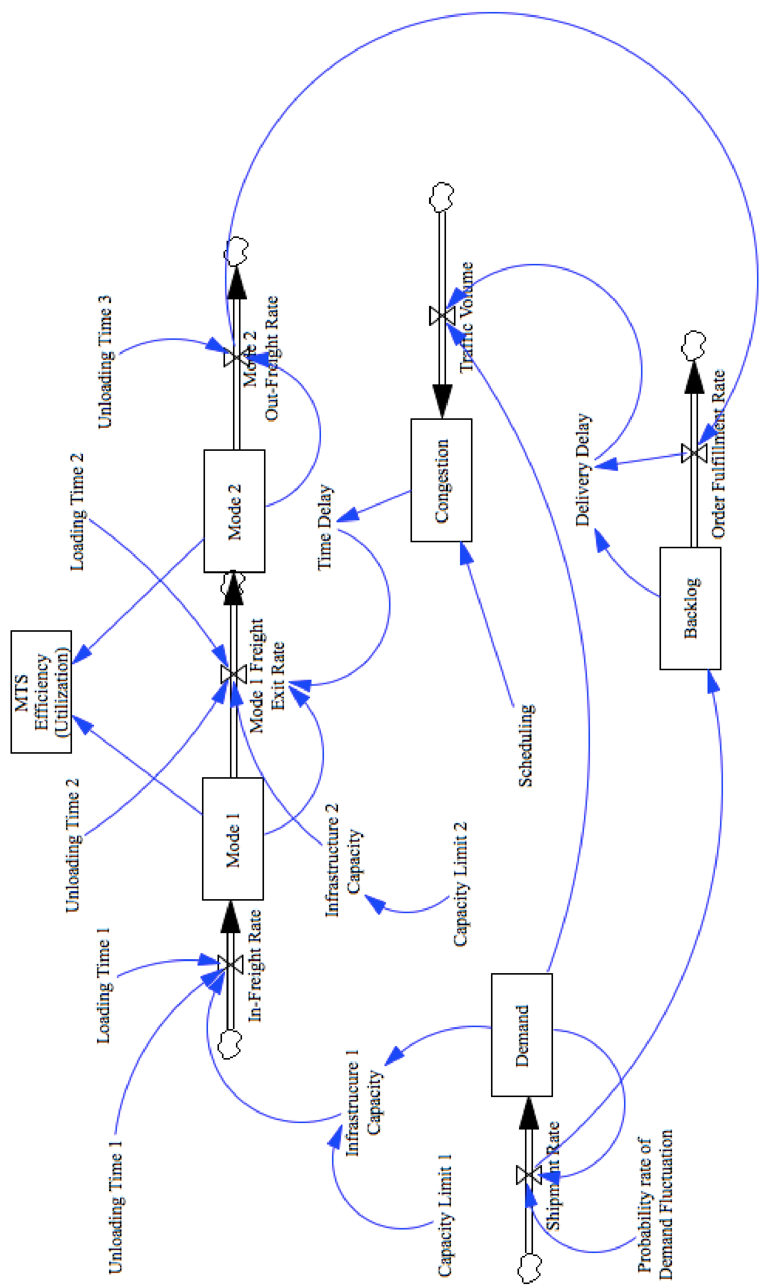

Figure 4.6: Stock and Flow Simulation Model

Table 4.4: Simulation Equations

Variables	**Definition**	**Equation**	**Units**
Probability Rate of Deman Fluctuation	How demand rate fluctuates in a year.	NormDist(0.4,0.3)	1/Year
Shipment Rate	The rate at which demand is satisfied or fulfilled.	Demand*Probability Rate of Demand Fluctuation	Tons/Year
Demand	Tons of freight demanded in a time t.	Initial Demand Value+(Shipment Rate(t)−Shipment Rate(0))$*\Delta t$	Tons
Capacity Limit 1	The fixed caapcity limit of the first terminal.	Fixed	Tons
Infrastructure 1 Capacity	First's terminal capacity at time t.	Capacity Limit 1 - Demand	Tons
Unloading Time 1	Unloading hours in a year from terminal 1.	0.0791	Year
Loading Time 1	Loading hours in a year into Mode 1.	0.0791	Year
Unloading Time 2	Unloading hours in a year from Mode 1.	0.0791	Year
Loading Time 2	Loading hours in a year to Mode 2.	0.0791	Year
Unloading Time 3	Unloading hours in a year from Mode 2.	0.0791	Year
In-Freight Rate	The in-flow rate at which freight moves from terminal 1 to Mode 1.	Infrastructure Capacity 1/(loading Time 1 + Unloading Time 1)	Tons/Year
Mode 1	The transportation mode utilized to take freight from terminal 1 to terminal 2. It transports tons and has a fixed capacity.	Mode Capacity Limit − (Initial Value + ΔFreight Flow) $*\Delta t$ = Mode Capacity Limit − (Initial Value + (Infreight Rate − Mode 1 Freight Exit Rate)) $*\Delta t$	Tons
Mode1-Out Freight Rate	The out-flow rate at which freight moves from Mode 1 to Mode 2.	(Infrastructure 2 Capacity - Mode 1)/(loading Time 2 + Time Delay + Unloading Time 2)	Tons/Year
Mode 2	The transportation mode utilized to take freight from terminal 2 to final destination. Transports tons and has a fixed mode capacity.	Mode Capacity Limit − (Initial Value + ΔFreight Flow) $*\Delta t$ = Mode Capacity Limit − (Initial Value + (Mode 1 Freight Exit Rate − Mode 2 Out Freight Rate)) $*\Delta t$	Tons
Mode 2 Out-Freight Rate	The out-flow rate at which freight moves from Mode 2 to final destination.	Mode 2/ (Unloading Time 3 + Time Delay)	Tons/Year
Time Delay	The time of congestion in a certain amount of time.	Congestion/ dt	Tons/Year
Infrastructure 2 Capacity	Second terminal's capacity at time t.	Capacity Limit 2 - Mode 1	Tons
Capacity Limit 2	The fixed capacity limit of terminal 2.	Fixed	Tons
Congestion	Behavioral response that depends on the type and timing of its delays. It's the bottleneck at a MTS facility. It's a % of the total throughput of the system.	Congestion (t=0) + Traffic Volume/Scheduling)	Tons
Traffic Volume	The flow of freight that is not delivered on time in a certain time t.	Demand/Delivery Delay	Tons/Year
Scheduling	Sceduling issues per tons in a year.	0.2	1/Year
Delivery Delay	The time it takes to deliver the demanded freight from start to finish including that delay at backlog.	Backlog/Order Fulfillment Rate	Year
Backlog	The accumulated demanded freight that due to capacity limits or shipment delays cannot be met.	Initial Backlog + (ΔFreight Flow) $*\delta t$ = Initial Backlog + (Shipment Rate − Order Fulfillment Rate) $*\delta t$	Tons
Order Fulfillment Rate	The rate at which an order is completed from its demand to its delivery in a certain amount of time.	(Backlog/ dt) + Mode 2 Out Freight Rate	Tons/Year

5. DISCUSSION OF RESULTS

5.1. DISCUSSION OF RESULTS FOR THE TRUCK-RAIL MODES

A variety of multimodal combinations are possible. The most common is truck-rail but other combinations could be: truck-air and rail-water. This research modeled all three previously mentioned combinations and studied the resulting behavior of some variables over time.

The first simulation run was the truck-rail multimodal combination of transport modes. According to the data attained by the U.S. Department of Transportation, the shipments by truck in 2002 were 11,539 M tons and for rail were 1,879 M tons. These values were input into the model and the following results were attained graphically, as shown in Figures 5.1 - 5.3.

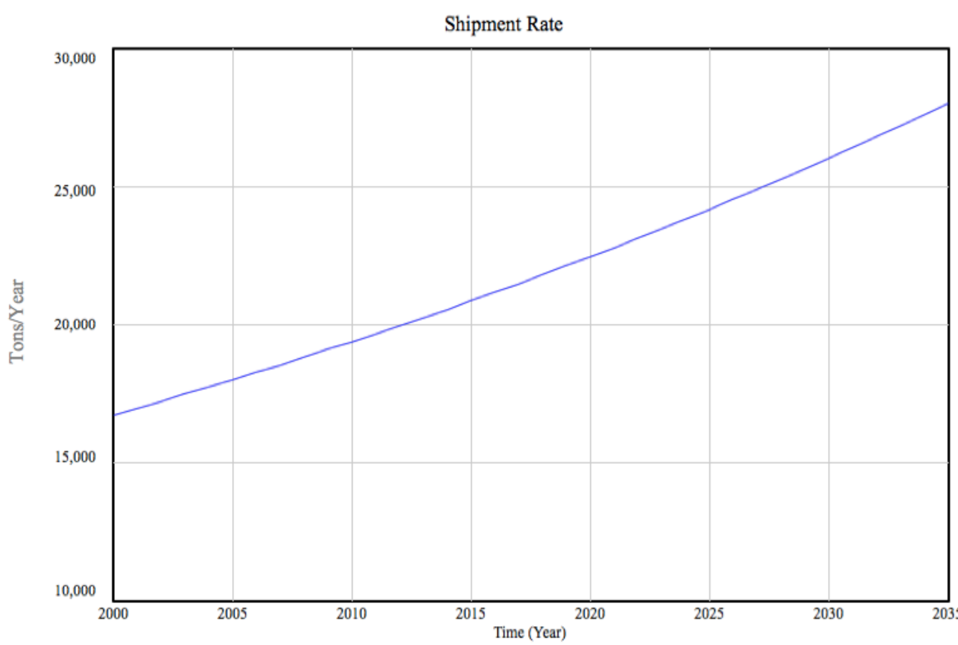

Figure 5.1: Shipment Rate's "Pure" State for Truck-Rail Modes

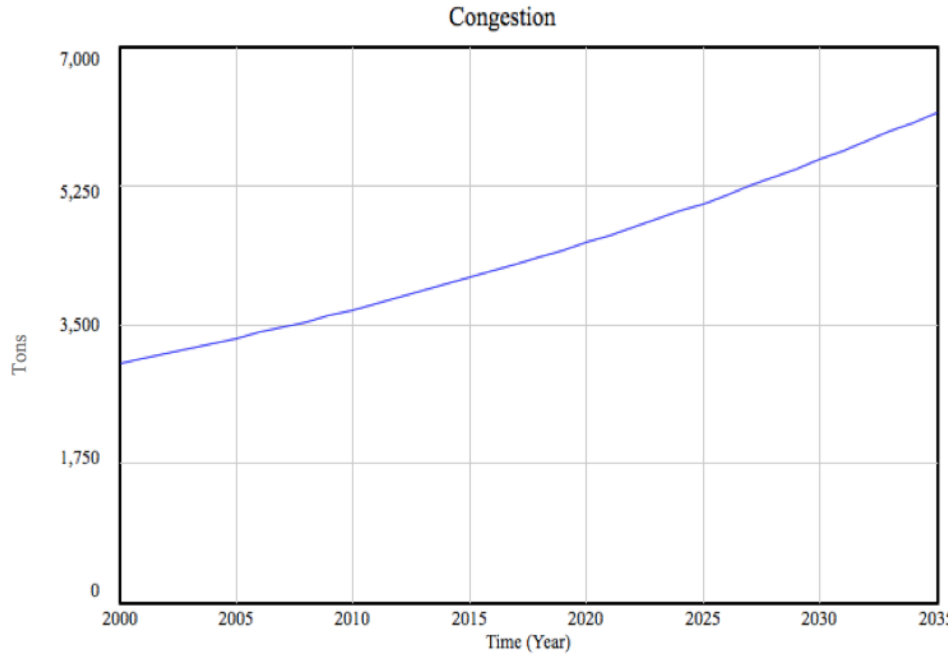

Figure 5.2: Congestion's "Pure" State for Truck-Rail Modes

The model is initialized in equilibrium. The initial value of the current state was set to its desired goal, which in this particular case is the data given by U.S.DOT (see Appendix) for the forecasts of 2035. Then it was shocked out of equilibrium (at time= 1) by a step function that changes the systems goal. This shocking procedure was used because it allows seeing the pure behavior of the system in response to shock. When starting in equilibrium, although is not completely real, can be used as a reference point for analyzing the pure behavior of the model and how it changes over time within the different scenarios. Figure 5.1 represents the simulation of the pure state of the modal connectivity shipment rate before any mitigating behaviors are applied. It is called the pure state because it is an approximation of real world behaviors. It is used then for comparison with changes. As forecasted because of the huge expansion in economic globalization, congestion increased dramatically (Figure

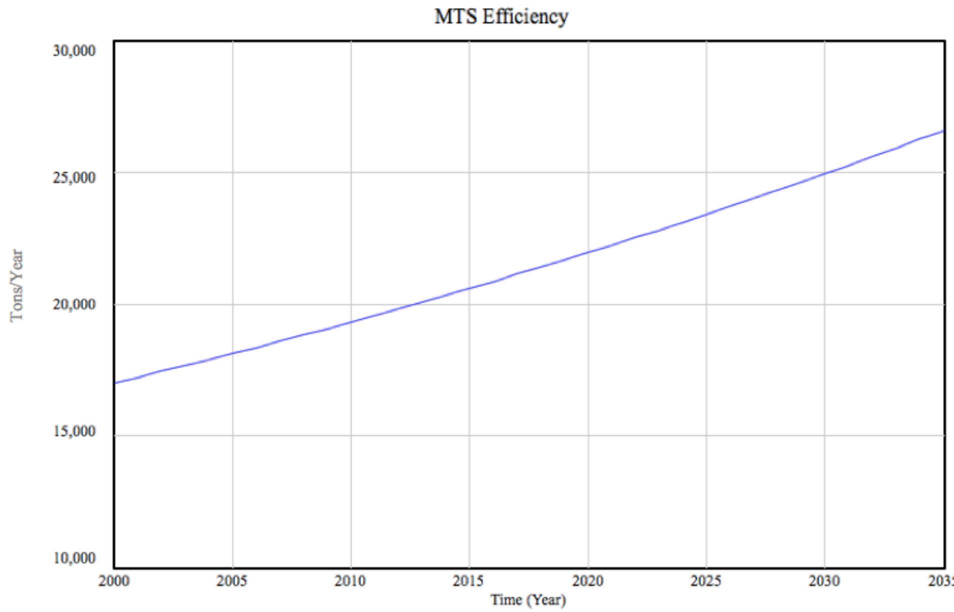

Figure 5.3: MTS Efficiency's "Pure" State for Truck-Rail Modes

5.2). Similarly, Figure 5.3 represents the pure state for efficiency of the MTS. Although congestion increased and demand and its fluctuations increased, it was not that significant. Resulting the state of the whole system to increase its efficiency but not significantly.

The interesting parts were the performance of different policy scenarios in order to understand how all these disruptions are interrelated and affect each other, and consequently, affect the efficiency of the MTS. The first scenario was to mitigate congestion in order to cause it eventually ameliorate. What is interesting is that when comparing shipment rate with the pure system, its behavior does change due to the fact that congestion, although starts with a high increase, in the long run reduces compared to the amount it increased in the pure system. If observe the behavior of shipment rate, it starts behaving similar to the pure state (Figure 5.4), but at the time congestion starts to hold on and not increase drastically, it increases a little. This results in the effective usage of the MTS system and is demonstrated in graphically when increases over time even more than before. Figure 5.6 has a graphical representation of the behavioral effect congestion had in the efficiency of MTS. Figure 5.4 presents a representation of the change in shipment rate when mitigating behaviors are applied to reduce congestion. The upward trend indicates a shift improvement in shipment rate. Similarly, Figure 5.5 presents a reduction in congestion over time and Figure 5.6 presents the results in the effective usage of the MTS system and is demonstrated in graphically when increases over time even more than before. Figure 5.6 is a graphical representation of the behavioral effect congestion had in the efficiency of MTS.

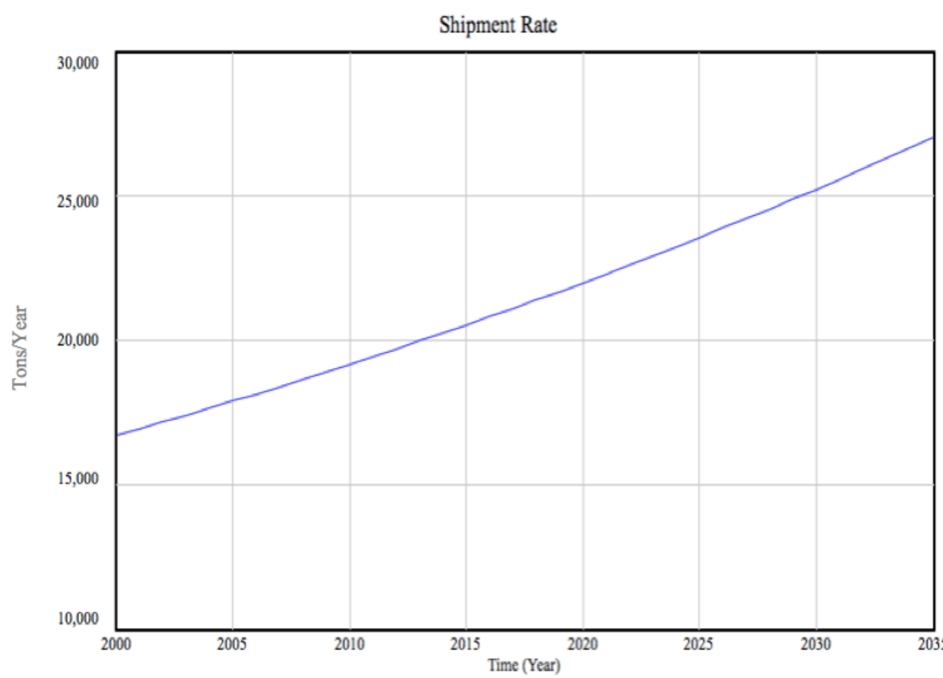

Figure 5.4: Shipment Rate in Scenario 1: Mitigating Congestion for Truck-Rail Modes

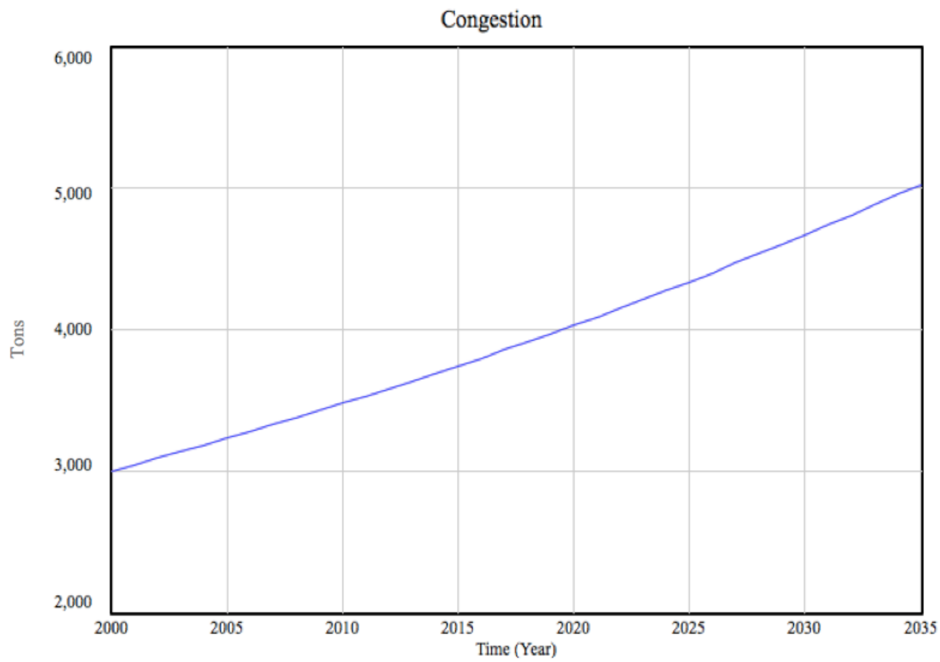

Figure 5.5: Congestion in Scenario 1: Mitigating Congestion for Truck-Rail Modes

It is always good to consider different policy scenarios in order to make decisions on what is best for managing the system efficiently and enhancing customer satisfaction. Another policy scenario that was worked upon in the truck-rail mode combination was the increase of the disruptions of shipment rate and mitigation of congestion altogether to see the effect these two had on other variables and consequently towards the behavior of the MTSs efficiency over time. When reducing congestion just like was done in the previous policy scenario but increasing shipment rate, it is observed how many other variables such as infrastructure capacity and scheduling both affect and are affected, resulting in a decrease in the efficiency of the MTS. Although congestion was reduced, the capacity limitation of the infrastructure managed to create delays and affecting other variables that turned out to negatively impact the utilization of the multimodal trasnportation system. For the second scenario, both congestion and shipment rate were mitigated, and when compared to the

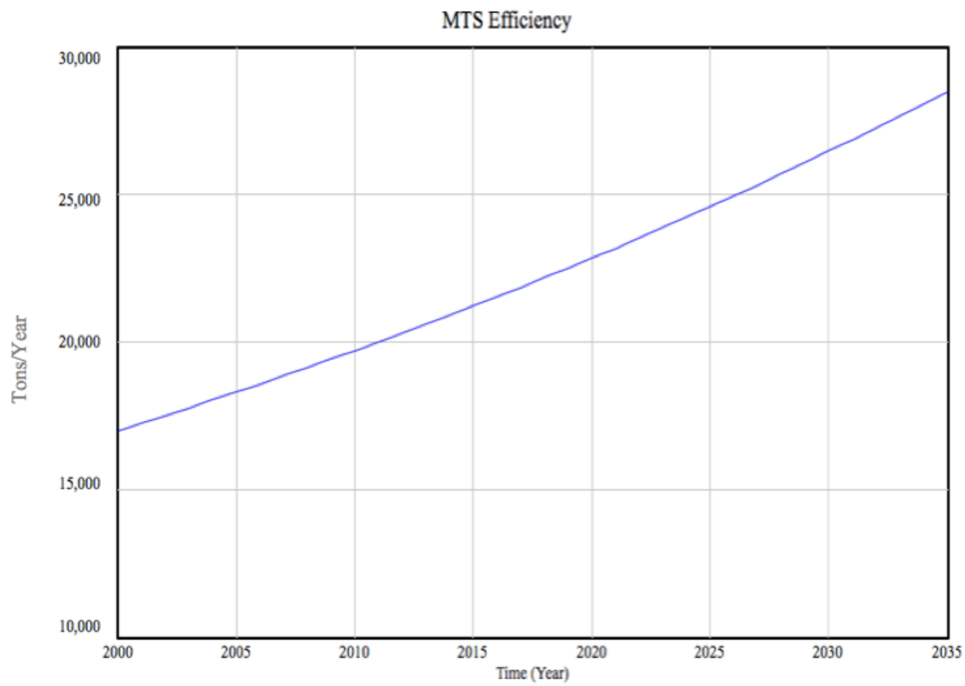

Figure 5.6: MTS Efficiency in Scenario 1: Mitigating Congestion for Truck-Rail Modes

pure state, Figure 5.7 through Figure 5.9 show the effect this decision had on the behavior of the variables. In Figure 5.7 it can be observed how shipment rate decresed over time. Similarly, Figure 5.8 presents the decrese in congestion and Figure 5.9, shows the positive effect this changes had on the efficiency of the MTS. Figure 5.9 demonstrates graphicaly the scenario that was described previously that also, shows to prove that the second scenario is better that the first scenario when improvements in the total efficiency of the system in comparison to the pure state, are higher.

Results have shown that disruptions can be managed to improve the efficiency of the MTS. Table 5.1 shows the summary of the results for the modes of truck-rail and their different scenarios. The research has shown the capability to model impacts and forecast changes to the system. Therefore, decision-making strategies can be attained to improve the MTS performance over time such as: mitigation of congestion

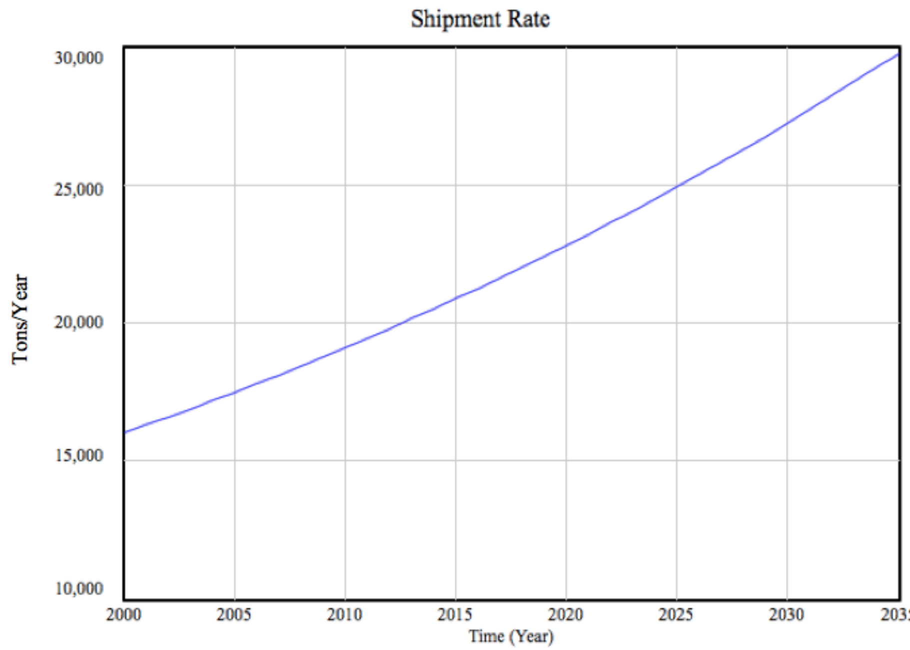

Figure 5.7: Shipment Rate in Scenario 2: Mitigating Congestion and Increasing Shipment Rate for Truck-Rail Modes

to improve efficiency of MTS by an average of 4% with the application of the first scenario. Table 5.1 demonstrates how when mitigating congestion by an average of 19%, efficiency of the MTS improves by 4% and when managing both, congestion and shipment rate by an average of 10% in the second scenario, the efficiency of the MTS improves by a 7% when compared with the pure state.

Table 5.1: Summary of Results Truck-Rail Mode

Year 2035	**Congestion**	**Shipment Rate**	**Efficiency MTS**	
"Pure" State	6,181	27,045	26,603	
Scenario 1	5,029	27,994	27,538	**4%**
Scenario 2	5,029	29,747	28,504	**7%**
%Δ	19%	10%		

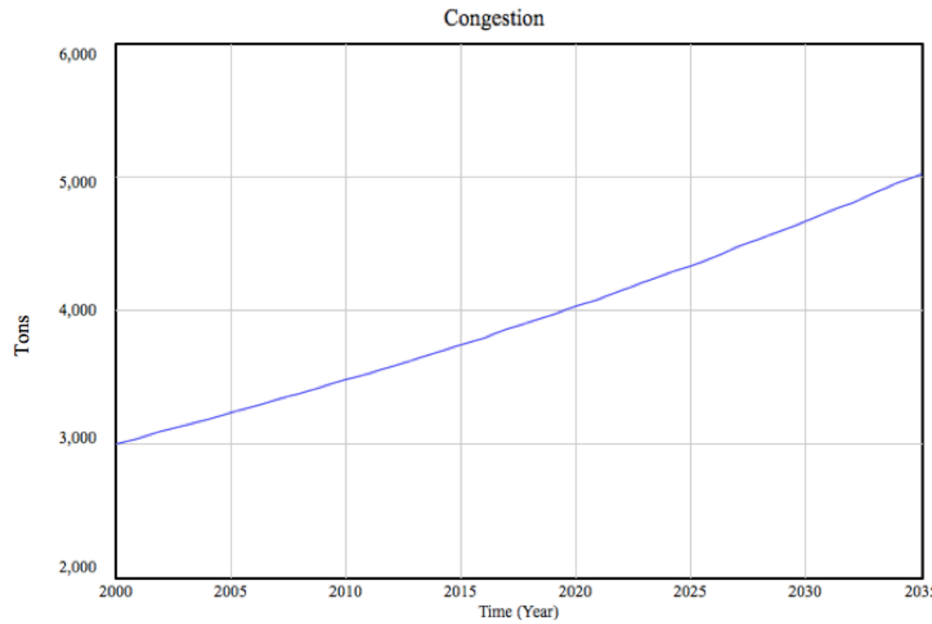

Figure 5.8: Congestion in Scenario 2: Mitigating Congestion and Increasing Shipment Rate for Truck-Rail Modes

Many other scenarios with different policies were carried out for the other combinations of multimodal transportation in order to understand how the efficiency of the MTS behaved under different circumstances and with the utilization of different modes. You can find the other different scenarios for the different combinations of transport modes further on in this discussion. Although some annotations can be made on the different policy scenarios, and patterns can be observed, it is very difficult to select a best alternative for decisionmaking. Policy design is much more profound than changing the values of parameters such as demand fluctuation probability rate or a congestion ratio. Since the feedback structure of a system determines its dynamics, most of the time policies will involve changing the dominant fedback loops by redesigning the stock and flow structure, eliminating time delays, among other. The whole purpose of modeling is to solve a problem. So according to the problem that needs the most attention or the fastest solution, or the less costly,

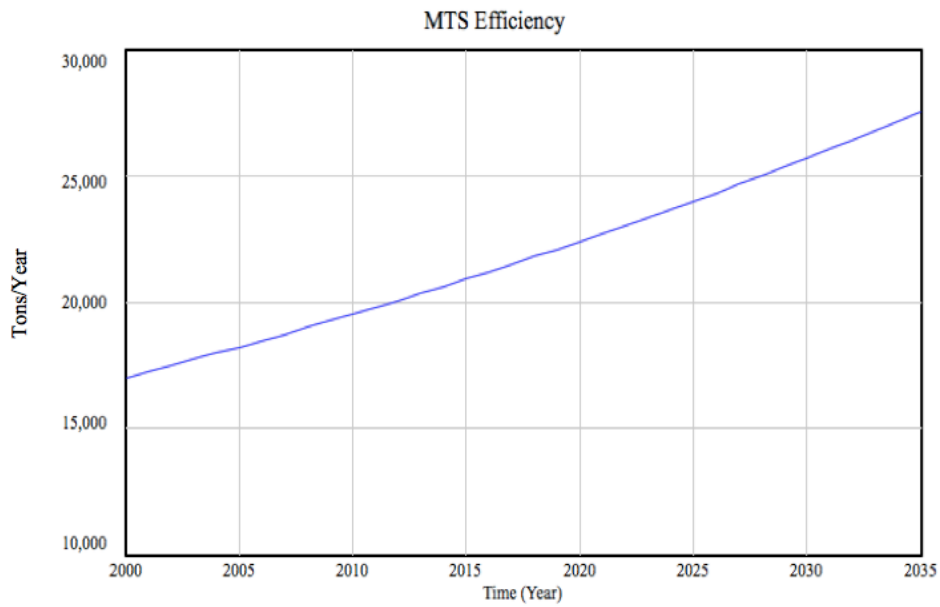

Figure 5.9: MTS Efficiency in Scenario 2: Mitigating Congestion and Increasing Shipment Rate for Truck-Rail Modes

among many other options, need to be taken into account when suggesting a decision to solve a problem.

5.2. FURTHER DISCUSSION OF RESULTS

5.2.1. Results "Pure" State: Rail-Water Modes. Another simulation run was the rail-water multimodal combination of transport modes. According to the data attained by the U.S. Department of Transportation, the shipments by water in 2000 were 941 M tons and for rail were 1,879 M tons. These values were input into the model and the following results were attained graphically. Figure 5.10 presents the behavior of the efficiency of the MTS in its pure state. Similarly, Figures 5.11 and Figure 5.12 show the behavior of congestion and time delays, respectively, in the pure state. It can be observed in Figure 5.11 how congestion increases over time and in

Figure 5.12 how time delays increase over time as well. When these two disruptions increase over time, they have an impact on the total efficiency of the system. But in order to understand what effect they have on the overall efficiency, different scenarios were taken into account and explained further.

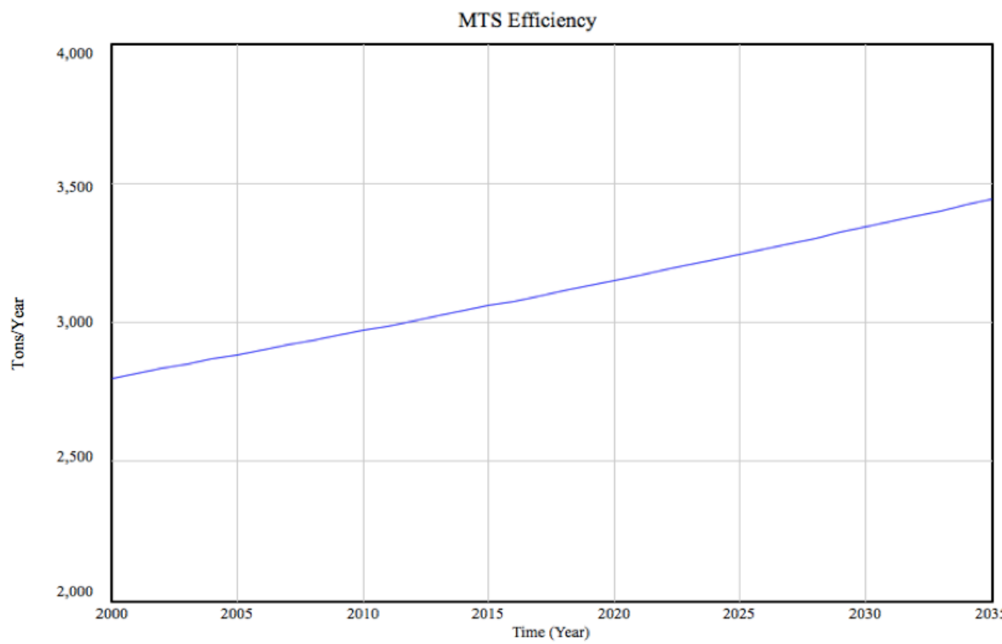

Figure 5.10: MTS Efficiency's "Pure" State for Rail-Water Modes

It can be observed that although the behavior of congestion and delay disruptions is forecasted to increase towards 2035, the MTS efficiency is also forecasted to increase over that same period of time. But can it be improved? A thorough analyzing of all variables in the model took place to understand their behavior. This resulted in the performance of different scenarios in order to visually analyze the impact some variables had on the MTS efficiency. Initially, capacities limits and demand fluctuations were thought to be the factors that were not allowing MTS efficiency to proficiently increase over time. But after trial and error, it was found that

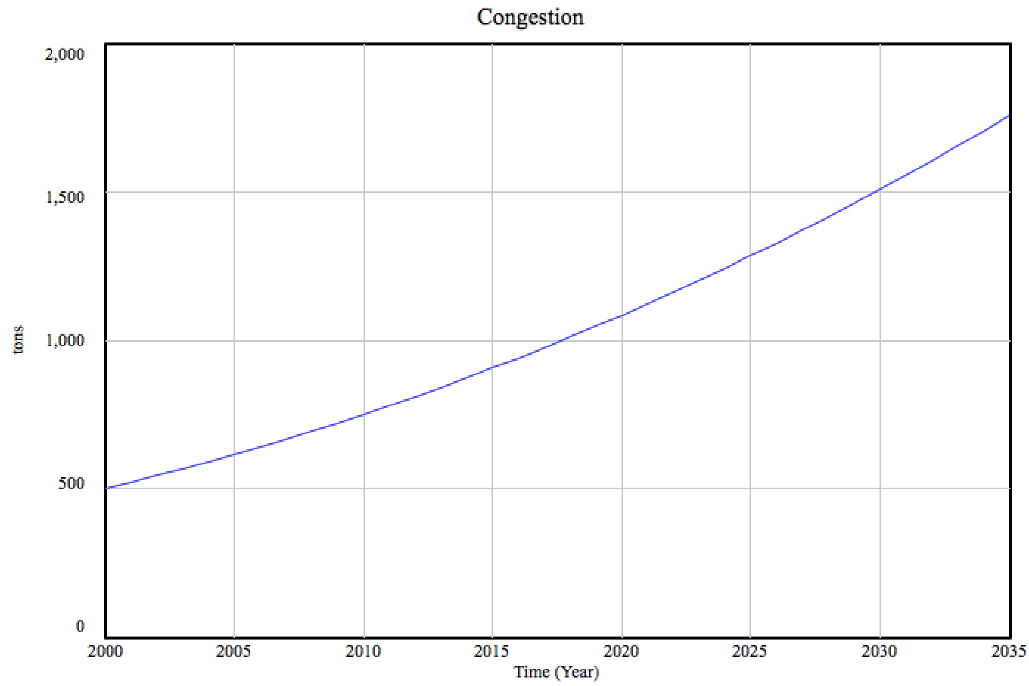

Figure 5.11: Congestion's "Pure" State for Rail-Water Modes

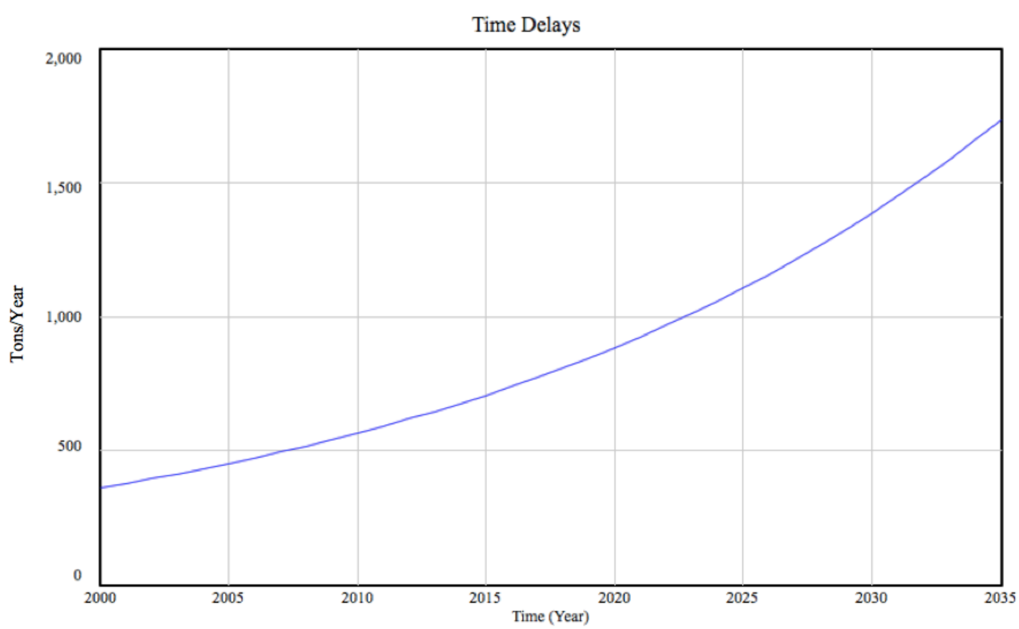

Figure 5.12: Delay's "Pure" State for Rail-Water Modes

although those disruptions had some negative impact, the variables of congestion and time delays had a stronger effect. Hence, the development and effect of the different scenarios are described next.

5.2.2. Results Scenario 1: Mitigating Congestion of Rail-Water Modes. The first scenario that was performed was that of the mitigating of congestion in order to have an understanding on the effect this variable would have on the system. Figure 5.13 represents the reduction of congestion by an average of 30%. This reduction resulted in the reduction of time delays in Figure 5.14 and an overall improvement on the overall efficiency of the MTS of an average of 4%, when compared to those behaviors attained in the pure state.

When mitigating congestion by a range going from 0 to 30%, it is observed how it impacts the efficiency of the system. It is forecasted that when mitigating congestion, other disruptions such as time delays will be ammeliorated and hence will result in a positive impact towards the efficiency of the MTS. In Figure 5.15 it is observed how MTS efficiency can increase up to 4% when the disruption of congestion is allevianated. Although this scenario forecasts an improvement in the efficiency, a curiosity arises as of how can we improve the efficiency a little more? Since an observation was made that the amount of delays due to transshipments were impacted by congestion, what would happen if both were to be mitigated? This question resulted in the creation and performance of scenario 2 explained further along in Section 5.2.3.

5.2.3. Results Scenario 2: Mitigating Congestion and Time Delays of Rail-Water Modes. Before deciding on a second scenario, various alternatives were taken into consideration and by trial and error, it was decided that a suitable best scenario for improving the overall efficiency of the system was that of mitigating both, congestion and time delays. This decision was based on the observations attained when analyzing the different behaviors of the different disruptions and ultimately the

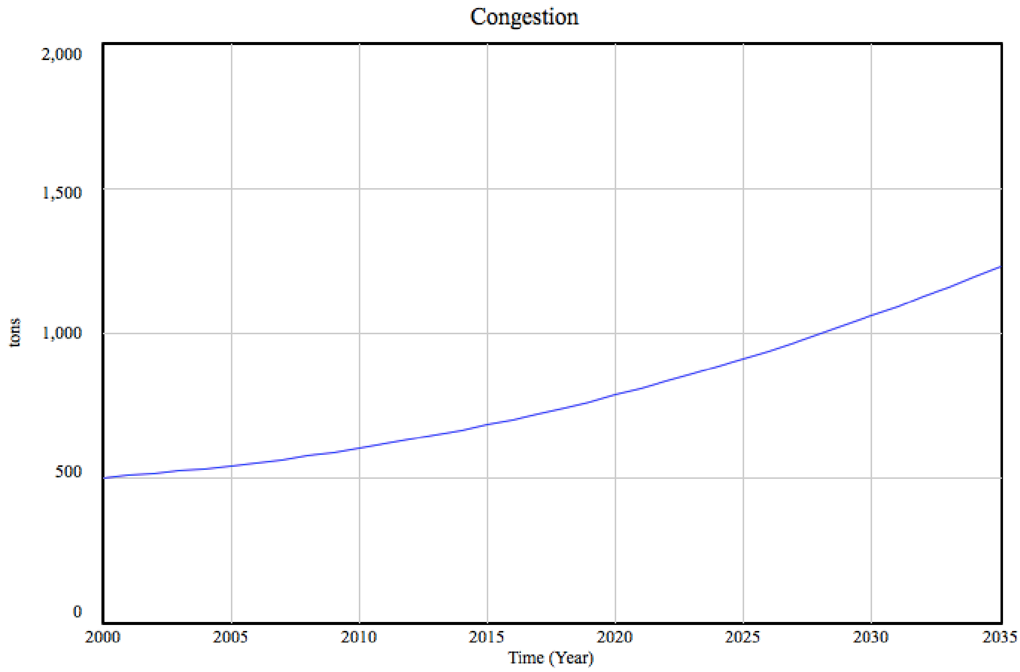

Figure 5.13: Congestion in Scenario 1: Mitigating Congestion for Rail-Water Modes

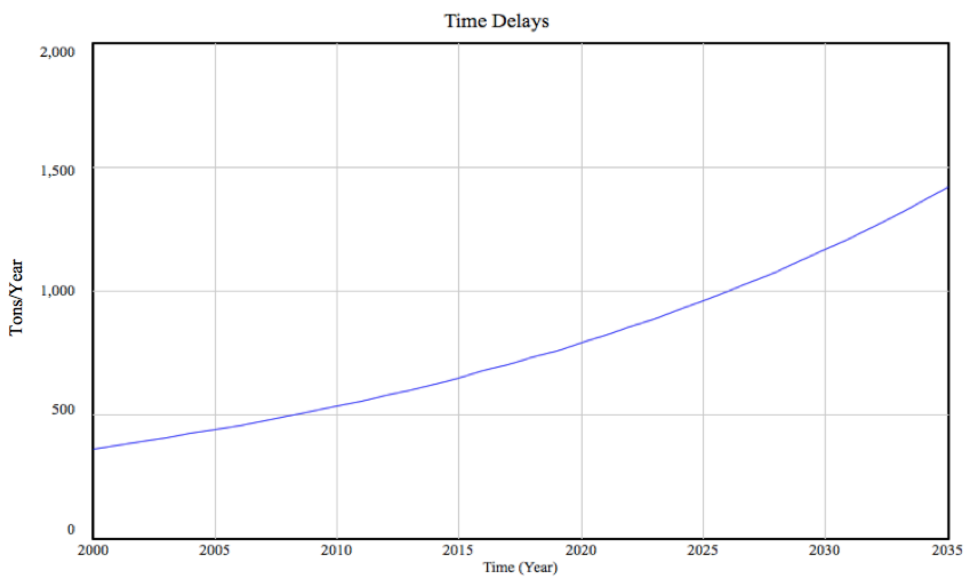

Figure 5.14: Delays in Scenario 1: Mitigating Congestion for Rail-Water Modes

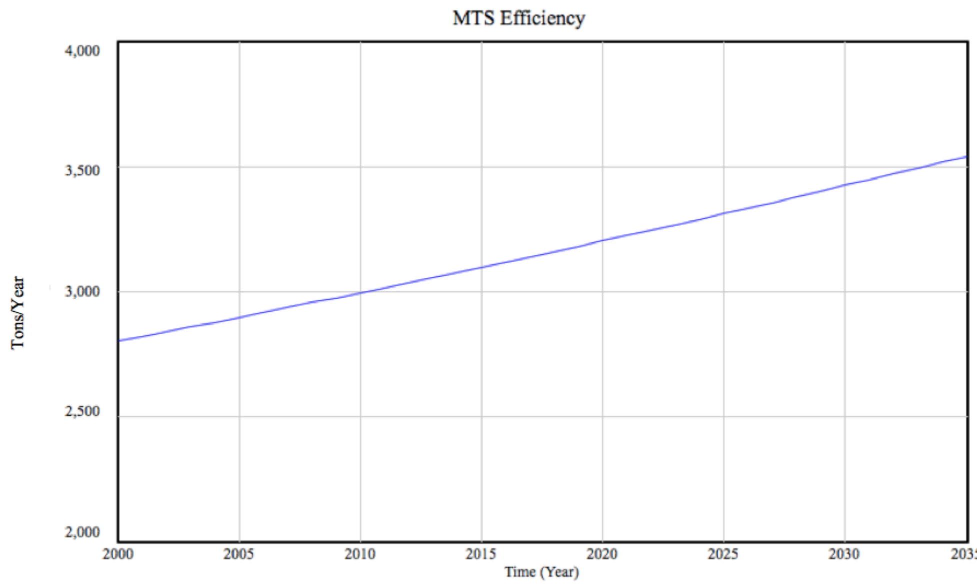

Figure 5.15: MTS Efficiency in Scenario 1: Mitigating Congestion for Rail-Water Modes

behavior of the efficiency. It was observed that even when increasing capacity limits, the efficiency did not improve. It was noticed how backlog kept increasing and the order fulfillment rate was low. Also, it was observed that both the amount of delays between transshipments and delivery delays incremented over time. Due to those observations made, the second scenario will mitigate the amount of delays occurring between transshipments along with the mitigation of congestion to see the effect it had in the MTS efficiency in the long run. Figures 5.16 through 5.18 graphically represents the results of the second scenario.

When mitigating delays in transshipments by a range going from 0 to 31% as observed in Figure 5.18, it is observed how congestion is also ameliorated in Figure 5.17 a little and MTS efficiency is forecasted to improve by 11% s shown in Figure 5.16. It is observed how the disruption variable of transshipment times along with congestion have a greater effect on the MTS efficiency rather than congestion alone over the defined period of time. By running these different scenarios, decision-making

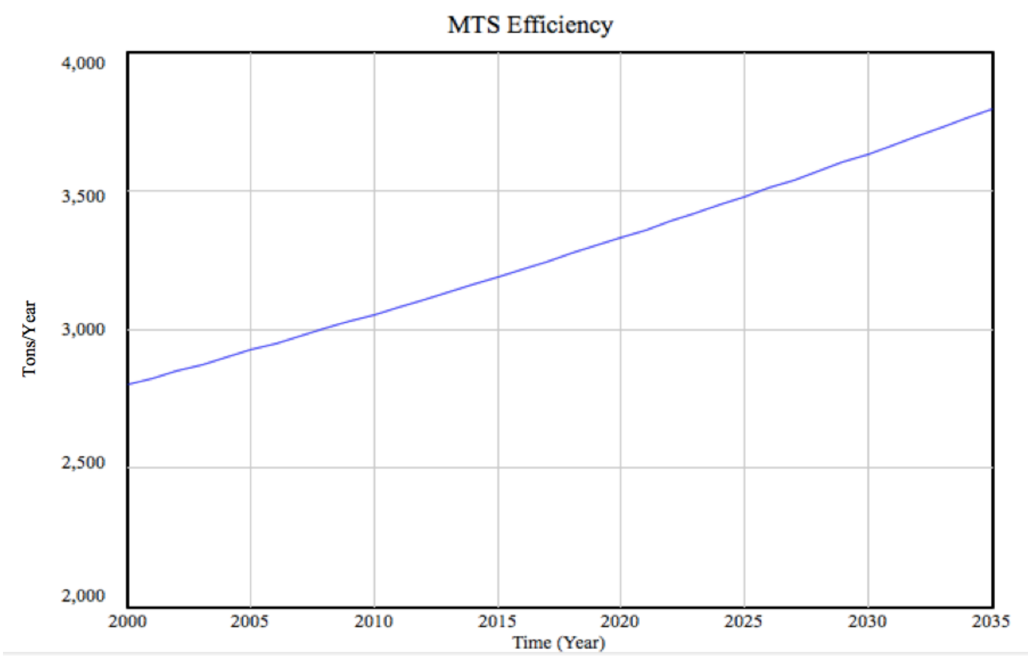

Figure 5.16: MTS Efficiency in Scenario 2: Mitigating Delays for Rail-Water Modes

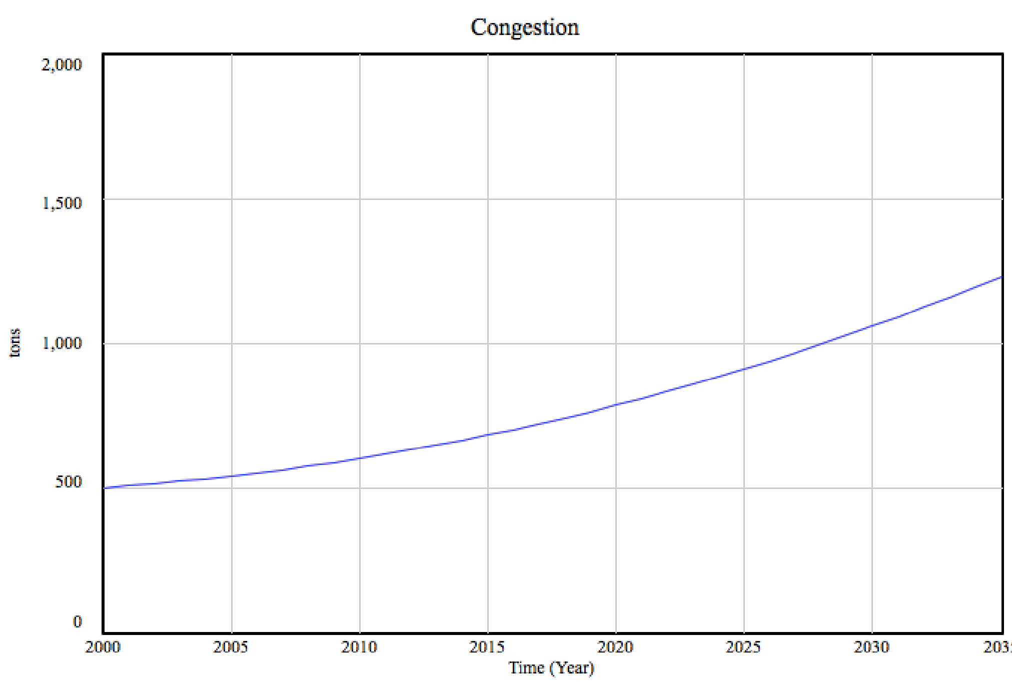

Figure 5.17: Congestion in Scenario 2: Mitigating Delays for Rail-Water Modes

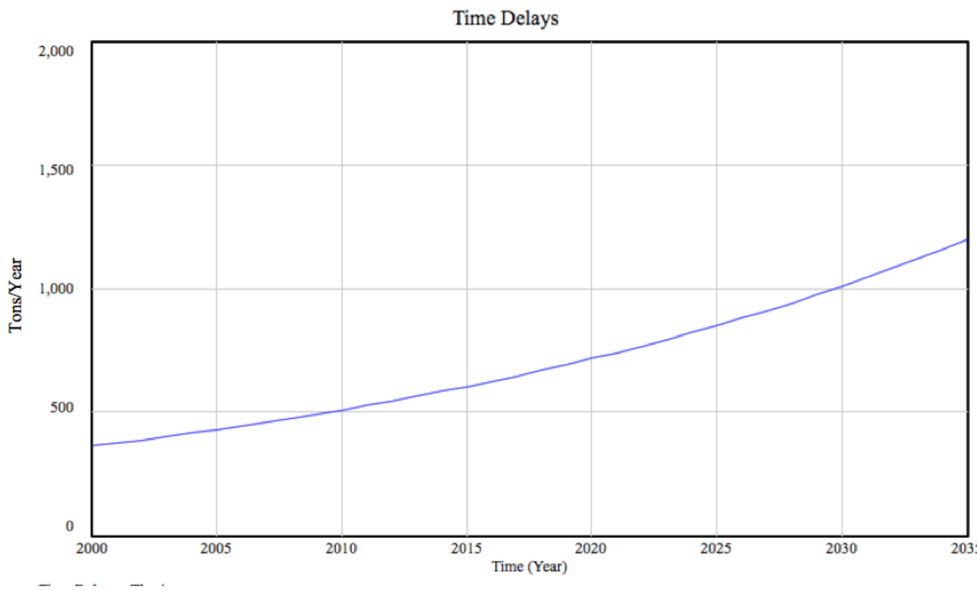

Figure 5.18: Delays in Scenario 2: Mitigating Delays for Rail-Water Modes

can take place as in what can be done in order to achieve the desired efficiency level. Table 5.2 numerically demonstrates the impact these variables have on the efficiency of the system.

Table 5.2: Summary of Results Rail-Water Mode

Year 2035	**Congestion**	**Shipment Rate**	**Efficiency MTS**	
"Pure State"	1,756	1,732	3,418	
Scenario 1	**1,231**	1,416	3,539	**4%**
Scenario 2	1,090	**1,196**	3,794	**11%**
%Δ	30%	31%		

Table 5.2 demonstrates how when mitigating congestion in scenario 1 by an average of 30%, efficiency of the MTS improves by 4% and when managing both, congestion and time delays by an average of 31% in the second scenario, the efficiency

of the MTS improves by an 11% when compared with the pure state. Although the first scenario demonstrated that by mitigating congestion the efficiency of the MTS improves over time, the second scenario demonstrated to be more successful in what desired, which is to improve the efficiency of the MTS the most.

This research has demonstrated that the methodology of Systems Dynamics can be used to simulate the complex-non-linear systems within the transportation field. It has shown how systems dynamics models can make a difference in the understanding and analyzing of a system that undergoes major transitions and different unpredictable changes. And last but not least, it has proven that decision-making strategies can be attained to improve the MTS performance over time.

6. CONCLUSIONS AND FUTURE WORK

A system is a set of things working together as parts of a mechanism or an interconnected network. Many methodologies exist in order to express mathematically, logically and symbolically the relationship between the entities or objects of interest in the system and analyze them. The challenge arises when the system is a complex one. A system is considered complex when it is composed from relatively many mutually related parts and that are hard to describe or understand and in most cases possesses an unpredictable behavior. System dynamics provides the building blocks necessary to construct models that help in the understanding of complex real-world systems and their behavior over time. System dynamics is a useful methodology in the understanding of complex systems such as the ones encountered in todays transportation systems. In this research a SD simulation model was built with the objective of analyzing the MTS efficiency and how its constituents affect it over a certain period of time.

The utilization of Systems Dynamics methodology to understand how disruptions affect the efficiency of the Multimodal Transportation System was a positive one. An advantage to this computer simulation built, is that it not only mimicked, explained and predicted the behavior of the real system over a desired period of time, but also, it tracked the implications of complex relationships and their dynamic consequences within the system when testing different scenarios aimed at altering the MTSs efficiency behavior in a desired way.

A variety of multimodal combinations are possible. The first simulation run was the truck-rail multimodal combination of transport modes. The first run is what is known as the pure state because it allows seeing the pure behavior of the system, which is that close representation to the real-life scenario. This pure state was then used as a reference point for analyzing how the behavior of the system changes over time within the different scenarios. In the truck-rail pure state it was observed how congestion and shipment rate increased over time and even the MTS efficiency increased. The interesting part of performing different policy scenarios was to understand how all these disruptions are interrelated and affect each other, and consequently affect the efficiency of the MTS. The first scenario was to mitigate congestion in order to cause it to eventually ameliorate. As a result to this scenario, it was observed how the efficiency of the MTS, when compared to the pure state, improved by a 4

Another multimodal combination was carried out in the simulation model in order to understand how the MTS efficiency behaved under different circumstances. A pure state simulation run was performed to the rail-water multimodal combination of transport modes. As forecasted by the U.S.DOT, both congestion and time delays increased over time. Consequently, two different scenarios were taken into account in order to understand the impact these disruptions have on the total efficiency of the system. The first scenario performed was that of the mitigation of congestion. Results show that when congestion is reduced by a range going from 0-30

Although some annotations were made on the different policy scenarios performed, and patterns could be observed, it was very difficult to select a best alternative for decision-making. The whole purpose of modeling is to solve a problem, and only considering that specific problem, a decision can be suggested. Since the problem wanted to be addressed in this research was to develop a decision criteria to mitigate disruptions and maximize MTS efficiency, it is suggested that for the simulation run with multimodal combination of truck-rail transportation modes, the second scenario demonstrated to be more successful in increasing the MTS efficiency over time. Similarly, in the simulation run with multimodal combination of rail-water transport modes, the second scenario proved to be more successful in improving the efficiency of the MTS.

Results have shown that disruptions can be managed to improve MTS efficiency. SD simulation has proved to have the capability to model impacts and forecast changes to the system, allowing to the understanding of how the efficiency of the MTS behaved under different circumstances and with the utilization of different modes. Therefore, decision-making strategies could be attained to improve the MTS performance over time.

In spite of the good learning process and understanding of Multimodal Transportation Systems, and the good findings in the research; the study had its limitations. First and foremost by resource constraints in terms of availability and accessibility to data, and also because of the limited literature that exists regarding this type of rather complex system viewed upon the systems dynamics perspective. Also, model limitations regarding the utilization of only two modes, the constant capacity limits, and the exclusion of the specific characteristics of each mode take place, and for future work they can be improved in order to fit world use.

There are quite a few things that can be done in the future to improve the model. Aspects such as costs and environmental impacts should be incorporated into the model to find policies that help improve the efficiency of the MTS from a cost-effective and environmental-friendly perspective.

APPENDIX

Shipment by mode of transport, According to U.S. Department of Transport

Shipment by Mode and Weight (Millions of Tons) Demand		
Year	**2000**	**2035**
Truck	17,799	27,484
Rail	1,879	2,353
Water	941	1,263
Air	13	43

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