# DYNAMICS OF INFRASTRUCTURE

by

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An Interactive Qualifying Project
submitted in partial fulfillment of the
requirements for the degree of

Bachelor of Science in System Dynamics

Worcester Polytechnic Institute

2000

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Project Advisor

Date 3/20/00

Worcester Polytechnic Institute

Abstract

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This project looks at the general method of maintaining systems of public infrastructure and the relationship to overall economic health. Using a generic mathematical model, this project demonstrates that the current pressure based ordering system serves to amplify trends in the economy. The model is then used to develop and test policies aimed at minimizing or eliminating this behavior.

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# INTRODUCTION

**Project Subject**

Looking at the United States economy, one can easily see that there are complex dynamics at work to drive this massive system. Many of the smaller parts to this system are reasonably understood. From a micro perspective, business managers know what their particular business does, they may not completely understand what makes their business fail or succeed but they have a reasonable mental model of its operation. Each of the parts may exactly be understood to the point where the behavior can be simulated and predicted, but multiply the effort to simulate each part by the number of parts and then add the interrelations that occur between them to make the system function and you have a very complex model to say the least. Completely modeling the United States economy is a daunting task, one that, for all intents and purposes, is impossible. We can however, model individual problems. With the use of a generic model of infrastructure and the economy, we hope to make general policy recommendations that could be applied to most systems of infrastructure management.

We posit that current infrastructure investment policy serves to amplify swings in the economic system. This project will attempt to develop new ordering policy guidelines that serve to dampen swings in the economic system. The policies tested and discussed in this paper will give policy makers an additional expenditure related tool to control economic health and stability.

**Goals**

The overriding goal of this project is to better understand how infrastructure investment policy interacts with the economy. From this understanding the goal will be to develop and test policy guidelines that make better use of our resources and serve to encourage economic stability.

**Purpose**

As complexity increases, the ability to understand the behavior of systems will become more and more necessary. Managing a growing economy is something that should not be taken lightly. Each decision could potentially affect thousands upon thousands of people, thus the more we understand about the system we are managing the better equipped we are to make good decisions. Equipping decision-makers with the latest understanding is the overall purpose of this project. This model was developed to capture a generic problem that exists in most economic systems and, to date, has not been thoroughly addressed. As mentioned above, this particular problem exists in the way we allocate resources and maintain a system of infrastructure. It is observed that pressure based ordering combined with an inherently long delivery lead-time, amplifies trends in the economic cycle.

As slow as the traditional democratic government moves from the outside view, there still is not enough time to fully understand the particular problem they are addressing before a decision is made. To "fully" understand the problem one must look not only at the causes behind the behavior, but fanning out, one has to determine what drives each of the causes. Feedback is everywhere, decisions have consequences, and those consequences affect others, which can come back to affect the original condition either positively or negatively. We simply cannot look only at the inputs and outputs when addressing problems. By studying the system that generated the problem, we can design policies that attack the root, the conditions (there is almost always more than one) that lead to the problematic behavior.

Human capacity for mental simulation is impressive and can be expanded with training, however, for problems of this size a more formal method of simulation is necessary to capture the problematic behavior in question. System Dynamics is one of the tools that can be used to capture, simulate, and investigate problems such as this. Developing a System Dynamics model serves three purposes; first, it provides an impetus to explore the actual system in greater detail. As the model is constructed, reproducing the problem is the goal, when what is currently known is not enough to replicate the problem, this lack of complete understanding spurs more research, shining light on parts of the system that before now, have not been considered as a player in the problematic behavior. Secondly, developing the model helps the builders identify policy levers, some that are known and possibly others that have never been considered. Finally, developing the model serves to create a laboratory to test new policies for effectiveness before they are actually implemented, this allows for an added element of security against poor decisions. With all this in mind, the specific purpose of this project is to use a generic model of public infrastructure investment policy, developed by Dr. Khalid Saeed, to better understand the system and produce a set of policy recommendations that use public infrastructure investment as a tool to dampen swings in the economy. This will replace the current pressure driven method of ordering new infrastructure, which at present, acts to amplify swings in the economy.

**Societal and Technical Dimensions**

In terms of the societal dimension of the IQP, this project deals with the management of resources that we as Americans use every day. Imagine life without transportation infrastructure. No roads, rails, or planes, we would be confined to where our feet or a trusty horse could take us, much the same as people of the early $19^{th}$ century. If one thinks carefully however, there have been various modes of transportation for thousands of years, theses devises faired best on roads or at least paths. Travel was very difficult without a system of roads or a transportation infrastructure. Very similarly, the police and fire departments, the state schools, all are under the umbrella of public infrastructure. Without them life as we have come to enjoy it would be much more difficult. Therefore, since we can see that a healthy system of infrastructure is necessary for the well being of the average American citizen, effective management of this system is a requirement. Additionally, since this system is the backbone of the US economy, decisions that are made, have far reaching and potentially drastic consequences.

The interwoven complexity of infrastructure systems in general requires very careful management, but many times decision makers are not fully aware of the effects of a given policy aimed at fixing a problem. The use of computer models helps to better analyze the system producing the problematic behavior, and provide a test bed for proposed policies, thus giving decision-makers a new tool to regulate the economy as well as a greater margin of safety guarding against poor policies. Satisfying the technical dimension of the IQP, this project will use a generic model of an infrastructure ordering and maintenance system, specifically capturing infrastructure policy as it relates to overall economic health. The pressure based ordering of infrastructure is observed to amplify swings in the US economy. The model will be used to analyze the system, and to develop policies aimed at encouraging stability and hopefully producing a policy that will allow infrastructure ordering to act as a stabilizer for fluctuations in the economy.

**Audience**

This project will be of interest to any persons or groups of persons interested in public infrastructure policy as well as policy science in general. The project will also appeal to those interested in using system dynamics to simulate problems in government as well as a wide range of other areas. The results would be of interest to students of economics and public policy as well as to decision-makers who are responsible for infrastructure policy, helping them to better understand how public infrastructure works within the economic system. Additionally, the model can serve as a laboratory for learning, policy formation, and testing, thus giving infrastructure policy-makers the freedom to test innovative policies without the danger of making large and costly mistakes.

**Application of Results**

The recommendations of this paper would be of significant value to decision makers responsible for maintaining and investing in infrastructure. Additionally the results will be of use to policy scientists, researchers, and system dynamicists who are interested in infrastructure policy, giving them further insight into the system and possibly directing further research.

The project will be presented in the form of a paper with the accompanying model used for the analysis.

The general procedures are as follows: Data gathering, model validation, policy experimentation and comparison, and conclusions and recommendations.

*Chapter 2*

# BACKGROUND

## Literature Review

In terms of research, not much has been done to study infrastructure supply chains and their effect on the economy. Near by on the continuum of research, Ali N. Mashayekhi[1] conducted simulations on infrastructure project cost dynamics as they related to the growth of infrastructure production capacity. Along the same lines Edward Roberts[2], conducted similar research using a model of research and development project dynamics. Both of these models concentrate more on the dynamics of projects in the infrastructure supply chain, adding more detail than that used in infrastructure sector in this model. In a paper on maintenance dynamics, Mashayekhi[3] concluded that a lack of systemic thinking or what he called fragmentation, coupled with reactiveness resulted in the demise of preventative maintenance programs where they would oscillate between reactive and proactive maintenance. This correlates especially well with the overall message of this project that complex problems need to be addressed from a systemic point of view. Humans simply don't have the mental capacity to simulate problems of this size. In a highly recognized paper on the limits to short-term memory, Miller[4] identified that humans can hold up to 7 +/- 2 chunks

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[1] Mashayekhi, Ali N., *Development Project Cost Dynamics (draft)*, System Dynamics Group, MIT, Cambridge, MA, 1996.

[2] Roberts, Edward B., *A Simple Model of R&D Project Dynamics*, R&D Management, vol. 5, no. 1, October 1974.

[3] Mashayekhi, Ali N., *Reactiveness and Fragmentation in Maintenance Management*, Center for Organizational Learning, MIT, Cambridge, MA, 1995.

[4] Miller, G. A., *The Magical Number Seven, Plus or Minus Two: Some Limits On Our Capacity for Processing Information*, Psychological Review, 63, 81-97, 1956.

of information in short-term memory for processing at any given time. (Cognitive psychologists currently define a chunk as "a well-learned cognitive unit made up of a small number of components representing a frequently occurring and consistent perceptual pattern (Bellezza[5])). With this in mind it is easy to see why we need to construct mathematical models of complex problems to find truly viable solutions. (For further discussion on the nature of complex systems, the reader is directed to Forrester's[6] book: Urban Dynamics, particularly chapter 6 titled: Notes on Complex Systems.) Returning to the continuum of infrastructure research, using system dynamics Saeed and Honggang[7] explored the efficacy of infrastructure policy for developing countries with decidedly dualist economies. As with the research by Mashayekhi and Roberts, Saeed and Hongang work also looks more closely at the infrastructure sector dynamics particularly in relation to a dual economic system. Looking at traditional economic literature there has been a fair amount of research in recent years exploring the question: Does infrastructure investment have an effect on the economy in general and is there a shortfall in this investment?. This research will be mentioned in the sections to follow, particularly when looking at the past cyclically of investment and the effects of these decisions.

**So what is the problem**

In general, stability is good, and fluctuations are bad, so when a current policy does not serve to promote stable growth, but rather amplifies other disturbances from itself and elsewhere in the system, this is cause for concern. The US system for investing in infrastructure is one such policy.

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[5] Bellezza, F. S., *Chunking.* In V. S. Ramachandran (Ed.), Encyclopedia of Human Behavior, Vol. 1, pp.579-589, Orlando FL: Academic Press, 1994.

[6] Forrester, J. W., *Urban Dynamics*, Ch. 6, Cambridge MA: MIT Press, 1969.

[7] Saeed, K., and X. Honggang, *Infrastructure Development in a Dual Economy: Implications for Economic Growth and Income Distribution*, Social Science and Policy Studies Department, WPI, Worcester , MA, 1999.

Even though the model used for this analysis is generic in nature and deals with a problem that is common to many governments, and thus is not designed to replicate the performance of a specific economy, research on past economic behavior still had to be conducted when applying this generic case to the US system of infrastructure investment. Ample data over the past one hundred years points to the existence of a long-term periodicity in the economy which corresponds well to bulges in the investment in non military infrastructure as a percentage of the gross domestic product. In a paper presented at a conference held to address the question, "is there a shortfall in public capital investment?", Economist George Peterson of the Urban Institute successfully identified cyclical patterns in US infrastructure investment.[8] Simply put, the model demonstrates that these trends in the gross domestic product are the result of over-buying when demand for infrastructure is high, and then under-buying when there is an oversupply. This unstable order stream produces bulges in the stock of infrastructure, and thus down the road when these large groupings of infrastructure begin to wear out the supply drops quite rapidly, creating an undersupply that has not been anticipated and will continue until new orders make their way through the channels to replace the large collection that has now become obsolete. As one can see, these pulses continue through time, and if there was only one shock to the system to produce the initial jump in investment, then the system would exhibit damped oscillations between oversupply and undersupply until finally coming to rest at equilibrium. However such is not the case in any economy, and especially not that of the US. Instead, there are many pulses of varying size. One large pulse in particular was the huge infrastructure investments designed to pull the nation out of the great depression in the early part of the twentieth century. This large-scale investment produced

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[8]Peterson, G., *Is Public Infrastructure Undersupplied?* In: Is There a Shortfall in Public Capital Investment:?: Proceedings of a conference held at Harwich Port, Massachusetts, June 1990, p116, Boston, MA: Federal Reserve Bank Boston, 1990.

disproportionate mass of infrastructure and so, roughly fifty years later, much of this large group was, or had been, in need of repair, expansion or replacement. The ripple continued, necessitating high levels of investment, only the pulses did not stop there, the war-time economy surrounding World War Two produced another pulse spurring more development. Essentially there are enough pulses coupled with the oscillations that follow to produce choppy waves whose periodicity is not as easy to discern but still hovers near the fifty-year mark.

This oversupply to undersupply oscillation, puts great strain on the economy. In public works projects alone, the under-supply brings more contractors into the business, and the over-supply kicks them back out. Many jobs are affected, hundreds to thousands are lost when one of these companies closes its doors. Moving one level away, look at the materials suppliers, in times of undersupply business is good, new companies are started, people are hired, many sales are made, but when oversupply occurs because of mismanagement in the pipeline and too many projects were started, the new projects are not ordered, and the market dries up, suppliers are forced to make drastic changes, cutting workforce, or at worst even closing doors. It is not too difficult to see that these oscillations are good on the way up in the short term, but companies grow too fast with little sight of the future, on the way down, layoffs result, orders are cut, costs rise, and companies fail. Many times the negative aspects will outweigh the positive gains when business is good. Looking at the system that supplies the parts for new infrastructure, one can see that the oscillations reach deeper than just the builders and the parts suppliers, but also to the second and third level suppliers and the banks that back them all, not to mention the companies developing the technology to make it all happen. Now look at the total spectrum of public infrastructure, not just roads, and airports, but public education, police and fire, emergency management, government infrastructure. With this in mind look also at the man power it takes to use this infrastructure, oscillations stir employment creating high demand when new projects are started, but supplying new entries into these positions has a long delay time after the pool of unemployed workers has been depleted, so the price goes up to fill the chairs, creating a employee's market, and spurring more people to be educated to serve in this position. However, when the oversupply occurs and the flow of new projects slows considerably, the need for workers falls, and with it the price, now add to that all the people that went into training for these positions who are now faced with a dried up market.

Taking the picture one step further, look now at the people who use this infrastructure. In oversupply, times are good, the student to teacher ratio drops producing better students. The response time for emergency services improves, the police have more time to pursue lesser crimes like mail theft, crimes that are important to the people, but can be overlooked because more important crimes are taking precedence. In city government, reducing the workload of plan inspectors can allow the whole system of new commercial and residential construction to proceed much quicker with fewer headaches. This is good but the oversupply reduces the flow of new infrastructure projects, and leads to undersupply, where the same people are now overworked. Educators are overwhelmed with students class sizes jump into the upper twenties and thirties. Workload increases, and students do not receive as good an education as theydid when there was ample space. The same goes for emergency services, response times increase, small cases receive less attention because the large ones demand the time. Plans take longer to be approved because the city inspectors are overworked and can spend less time showing what needs to be fixed, instead they are forced to simply say pass or fail in order to have more plans come across the desk a day.

These effects continue. The system of commerce is affected by the efficiency of infrastructure. With less congestion on the roadways, people arrive at work on time, and product is delivered quicker. When efficiency falls during times of undersupply, congestion increases and costs go up, fuel, wear and tear on the vehicles, lost time, etc. In short, resource misallocation decreases economic efficiency.

The effects are long term but simple feedback tells us that investment in infrastructure will have a significant effect on the gross domestic product. So if it makes sense analyzing the feedback, mathematically there should be a way to express this relationship. Using simple mathematical models, economist David Alan Aschauer[9] found statistical evidence linking investment to GDP. Saeed's model captures this generic relationship in greater detail. The description of Saeed's model, which was used for this project, follows below.

**The Model Description**

The following section takes an in-depth look at the structure of the model, and how it correlates to the general reality it is designed to represent. Three main building blocks are used throughout the model, these are the stock, the flow, and the converter. All three are pictured below in figure 2.1.

[9] Aschauer, D. A., *Why is infrastructure important?* In, Is There a Shortfall in Public Capital Investment:?: Proceedings of a conference held at Harwich Port, Massachusetts, June 1990, p32.2-35.2, Boston, MA: Federal Reserve Bank Boston, 1990.

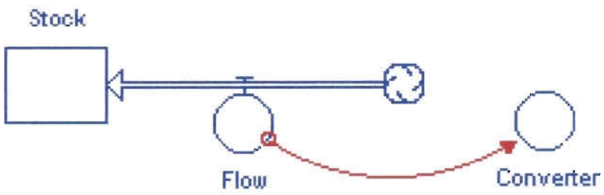


Figure 2.1: Examples of a Stock, a Flow, and a Converter.

The stock is depicted as a rectangle. Stocks are accumulators, a common analogy would be a bathtub. Stocks can vary with time or remain constant, like a savings account, or one's stress level. The next building block is the flow, which is shown in the middle of figure 2.1. A flow produces a change in the stock to which it is connected. Continuing with the bathtub analogy, the flow would be the faucet which dumps water into the bathtub at a particular rate (volume/time). Finally we have converters, this is the circle to the right in figure 2.1. Converters are used for converting and manipulating information from other stocks, flows and converters. In the bathtub example a converter could be used to turn the faucet (flow) on and off at various points in time, or to convert the rate of water flowing into the bathtub from gallons per hour to liters per minute. Information is passed between these building blocks using wires. These wires are shown in figure 2.1 as a red arc with a small circle at one end connecting the wire to the source and an arrow head at the other pointing to the destination of the information. With these simple structures in mind we can now proceed with the model discussion which follows below.

**Sector by sector description of the model**

To ease the process of construction, as well as verification, analysis, and application, the model was divided into sectors. These sectors are discussed in greater detail as follows.

**Infrastructure**

At the heart of this project is the infrastructure sector. Most of the other sectors can be summed under one description, supporting structure. At the core of the infrastructure sector is the supply chain that takes infrastructure projects from conceptualization to completion and eventually decaying to obsolescence. The basic stock flow diagram is shown below in figure 2.2.

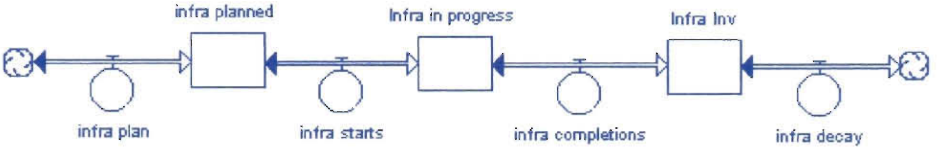


Figure 2.2: Core aging chain for the infrastructure sector.

From left to right, the process all starts with infrastructure projects in planning, which is captured with the flow, infra plan. When new infrastructure is desired the planning process starts, each of these new proposals flows in to the stock of infrastructure planned (infra planned). While the proposal spends a bit of time in this stock the details are ironed out, issues are resolved and after a while an approved plan is developed and a project is purchased, or started, which is captured with the flow infra starts. Each of these starts flows into a stock of projects in progress (infra in progress), where they spend a bit of time as they are constructed. As the projects reach completion, they are brought on line (infra completions) and join the stock of infrastructure currently in service (infra inv). The projects serve their intended purpose for a number of years, along the way they age, eventually becoming obsolete, this decay process is captured with the flow infra decay.

Delving a little deeper in to the structure of this sector we begin with how projects are planned. The structure used to capture planning appears below in figure 2.3.

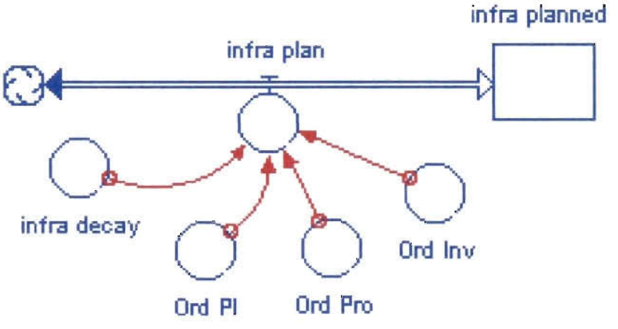


Figure 2.3: Infrastructure planning flow and the first order structure that generates the flow.

From right to left, the first converter feeding into the flow infra plan is infra decay. This captures the policy of replacing the infrastructure that decays as it wears out. Replacing the decaying infrastructure helps to keep the stock of infrastructure constant. Next we have the orders from planning (Ord Pl). These orders represent the discrepancy between the number of projects in planning and the desired number of projects in planning. In other words, there is only so much capacity to plan infrastructure projects, be it man power, computing power, or funding, so in order to maximize resources, orders are placed to keep the number of projects as close to optimal as possible. In the same way orders are generated from the desired number of projects in progress compared with the actual, this is captured using Ord Pro. Finally we receive orders from the stock of infrastructure in use (Ord Inv). The orders from infrastructure inventory compare a desired level with the actual and order a fraction of this, similar to the orders from planning and production. This order method differs in the way desired orders are captured, and will be discussed a little later on. For now we step out another level and discuss what structure is used to produce these orders.

We begin by looking at the method used to capture orders from project in planning. To ease the explanation this structure is diagramed below in figure 2.4.

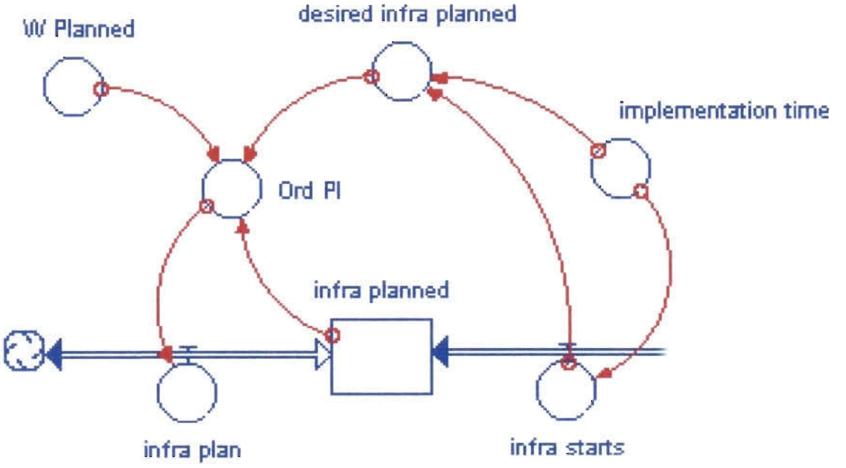


Figure 2.4: Structure capturing orders for stock of infrastructure in planning.

Starting from the right side of figure 2.4 this time, we have implementation time. This converter captures the average length of time a project takes to work through the planning process. In this case implementation time equals 5 years. From there implementation time feeds in to desired infra planned which also takes information from the flow infra starts. Desired infra planned represents the desired number of projects that are currently in the planning stages (infra planned), and thus desired infra planned is a function of the implementation time multiplied by the number of projects currently flowing out (infra starts). In the real world this means you want to keep a stock of projects in planning that is equal to the number of projects leaving multiplied by the amount of time it takes to move the average project through the process. If the outflow process is operating efficiently, this will be the most efficient number of projects to keep on hand at any given time. From there desired infra planned feeds into orders for planning (Ord Pl) which also takes input from infra planned, and the weighting fraction. The weighting fraction only allows a certain percentage of the order to proceed on, this captures the fact that in many cases, the desired as well as the actual level of projects in planning is not known. Thus this weighting factor represents how closely the system is monitored when placing new orders. Orders for planning (Ord Pl) then is equal to desired infra planned less infra planned all multiplied by the weighting fraction, W Planned. From there orders planned feeds into the planning order stream (infra plan) where they continue on down the line eventually ending up in the stock of infrastructure inventory. In the short term however, these orders from planning serve to close the gap between the desired and the actual number of projects in the planning stages. Additionally, when the stock of projects in planning is greater than the desired level, negative orders do result. These negative orders are still multiplied by the weighting fraction, but they serve to reduce the orders from infrastructure inventory and projects in progress, thus acting to further stabilize the system.

Similarly, orders from infrastructure in progress uses the same logic as the orders from planning, only the names have been changed. The structure that produces orders from the stock of infrastructure projects in progress is pictured below in figure 2.5.

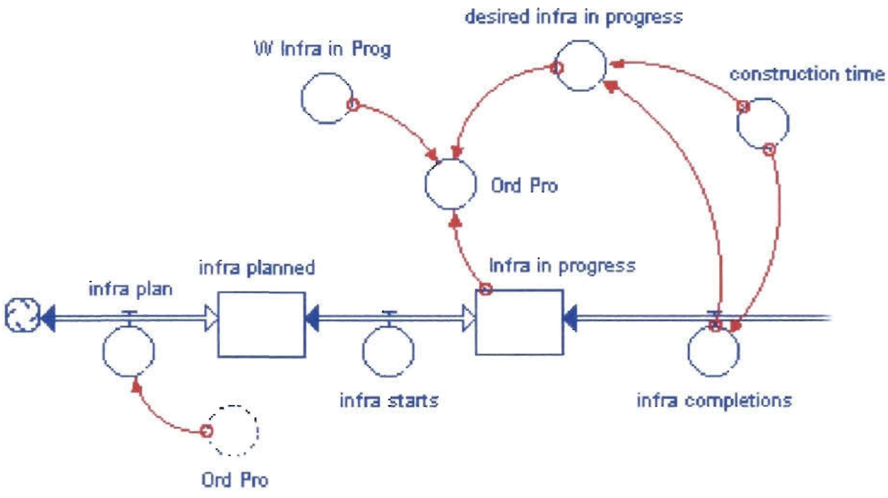


Figure 2.5: Infrastructure ordering structure from the stock of projects in progress.

**Money and Interest Rate**

The original model by Dr. Saeed contained two additional sectors one dealing with money policy and the other dealing with interest rate policy. For this project both of these sector have been disabled because they tend to add unnecessary complexity to the behavior of the economy. Thus with these two sectors turned off, the following assumptions are made; first, the interest rate is held constant throughout the life of the simulation. Second, the stock of money in the economy is managed optimally in response to changes in the economy. In other words, the total stock of money is always equal to the desired stock of money, therefore the value of money is constant or equal to 1. These simplifying assumptions make it easier to view the effect of the simulated infrastructure policy on the economy.

**Other sectors**

In the effort to conserve time and energy, an in-depth discussion of the other sectors of the model will not be provided in the body of this document. Rather, since these sectors are based on well-known macro-economic models, a brief listing of the major assumptions made will appear in the text below and the more comprehensive documentation is presented with the model equations in Appendix A.

*Aggregate Supply and Demand*

Production is a function of the technology constant multiplied by the stock of labor and the stock of capital each raised to their respective elasticity, all multiplied by the effect of infrastructure.

Sales are calculated as the sum of consumption, government spending, and capital investment, less the net imports.

Average sales is simply the sales averaged over a fixed amount of time, which in this model was 2 years.

Consumption is a function of the average sales, or the gross domestic product, multiplied by the marginal propensity to consume which is raised to the price elasticity of consumption.

*Balance of Payments*

Net imports are calculated as follows; first take the desired inventory less the actual inventory all over the average amount of time it takes to make adjustments to the inventory. Inventory undersupply would result in imports to cover the difference, and an oversupply would result in exports. Next the payments on the balance must also be subtracted from the net imports, and thus payments are calculated as the current balance divided by the average time necessary to pay the balance off, or in the case of a negative balance, to be paid back.

*Capital*

Desired capital is a function of the elasticity of capital multiplied by the desired production all over the interest rate times the general price level plus 1 over the lifetime of capital which is the depreciation cost of one unit of capital

*Employment*

Desired labor is captured as the desired production divided by the wage rate, all multiplied by the elasticity of labor, where the elasticity of labor is one minus the elasticity of capital.

*General Price Level*

The indicated general price level (GPL) is a function of the normal GPL multiplied by the effects of the inventory ratio and the value of money on GPL. When the inventory ratio (inventory over desired inventory) is high, inventory oversupply, the indicated GPL will be low, and visa versa. When the value of money is low, the indicated GPL will be high and visa versa.

*Taxation and Public Spending*

Yearly tax revenue is a fixed fraction (20%) of average sales.

Government spending is a fixed fraction of the current government balance. This fraction is stepped from 20 to 22% at year 10 to simulate a one time increase in spending.

*Wage Rate*

The indicated wage rate is a function of the normal wage rate multiplied by the effect of the unemployment rate on the wage rate. This effect simply amplifies or suppressed the normal wage rate in response to changes in the unemployment rate. When unemployment is high the indicated wage rate will be lower than normal, and visa versa.

*Chapter 3*

# PROCEDURE

## Outline

Formal System Dynamics (SD) models are developed in roughly six steps, the word roughly is used because, depending on the application and the desired product, the process can take a few additional steps. This particular project was completed in six steps, these are explained in detail below.

## Reference Mode Elicitation

In order to build a model and to avoid modeling the world to capture the dynamics of a filling bath tub, one needs to define a problem. Static problems are nice and easy to solve, but little in life is truly static. In reality change is all around us, and thus to build a dynamic model one needs to know how the problem behaves over time. This behavior over time is what system dynamicists like to call a reference mode, or the behavior over time that one refers to while constructing the model. Simply put, the reference mode is the goal, it is the behavior the modeler wants to capture and simulate. This reference mode is not so much a set of numbers over time such as the position of an automobile as it moves along a track starting from 0 and accelerating to 60 miles per hour. Rather, it is the shape of the curve, even though the numbers may be known, what is more important to the modeler is the shape of the curve, which, in the case of the automobile, would be exponential growth.

In the case of this particular model, the reference mode was a cycle in infrastructure inventory, oscillating between over supply and undersupply, finally coming to rest at equilibrium many years later. In a system without noise, this cycle will most likely be damped, however when noise is present, periodic perturbations will continue to feed the cycle so that it may seem to continue forever. A similar shape in the average sales curve was used for the second part of the reference mode, where a spike in investment would result in a dramatic increase in average sales which would move with damped oscillations about the normal level eventually returning to equilibrium.

As a source associating the model's general case with the US economy, gross domestic product (GDP) data and non-defense infrastructure investment data were assembled from multiple Economic Reports of the President, one from 1962[10] the other from 1998[11]. The two record sets were used to gather as large a time series as possible since the oscillatory trend the model replicates has a long-term time shape. The model was designed to replicate the effects of a single shock to the system, namely a one time increase in infrastructure spending and monitor the resulting effects in a noiseless environment. Thus when the noisy reality of constantly changing policies is added the system will exhibit compounded oscillations, with no true periodicity. Since the model was never intended to exactly represent a given economy but rather the general case, no effort was made to fit the model output to real data. Rather only the pattern in historical data was replicated. When we looked at US economic data, particularly the GDP stream, which spanned roughly 70 years, quite a bit of inflation had taken place as well as a number of significant events with resulting effects on the economy, thus the shapes were a bit clouded. To build a comparison, non-defense government investment data was also retrieved. Having undergone the

[10] United States President. *Economic Report of the President Transmitted to the Congress.* Washington: D.C.: Government Printing office, 1962.

[11] United States President. *Economic Report of the President Transmitted to the Congress.* Washington: D.C.: Government Printing office, 1998. (Viewed electronically via University of California, San Diego: http://ssdc.ucsd.edu/gpogate/erp98/, visited: March 98, and again on 3/13/00)

same conditions as the GDP data set, one of the easiest ways to normalize the two for comparison was to calculate non-defense government investment as a percentage of GDP over the 69 years of data. This graph appears below in figure 3.1.

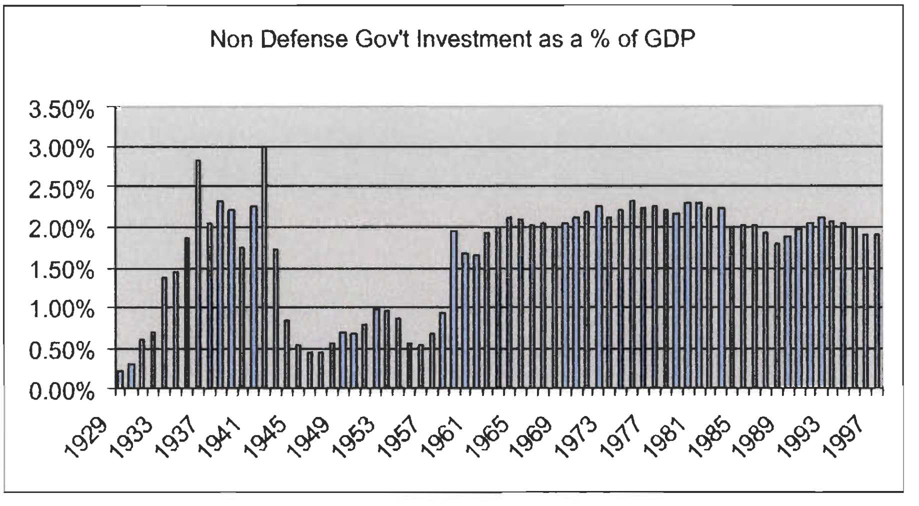


Figure 3.1: Graph of non-defense government investment in infrastructure as a percentage of GDP from 1929 to 1998.

As one can see figure 3.1 shows some of the additive oscillations that we were looking for, particularly around 1940 and 1977, but this is not a very clear picture. One note about the graph, a change in the way the data was recorded occurred between the two data sets so that a shift in base resulted around year 1959 where the sets were joined. Since we are only interested in the shape of the graph over time, the absolute values are not of great importance, thus we can work around this shift.

Because the non-defense government investment as a percentage of the GDP did not clearly show the oscillations, other views of the data had to be sought out. One of those views was non-defense government investment as a percentage of

GDP graphed with non-residential private investment as a percentage of GDP, all graphed from 1929 to 1997. This cut of the data appears below in figure 3.2.

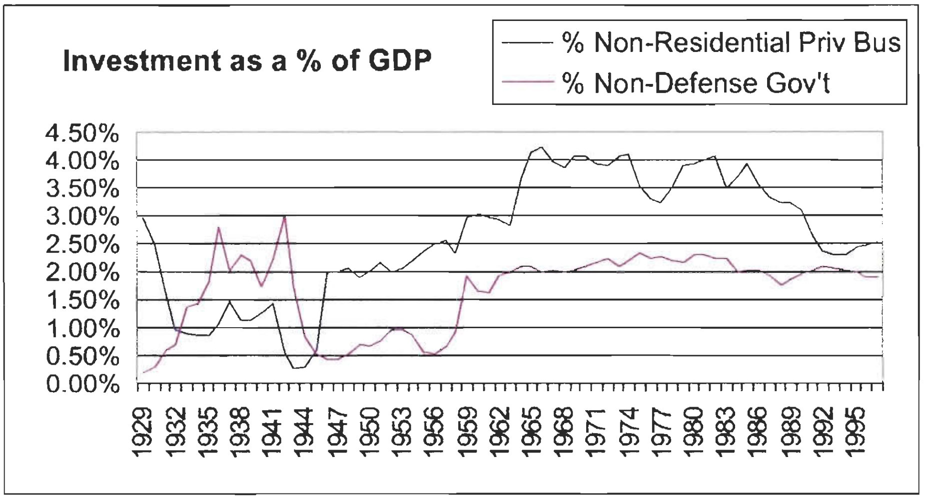


Figure 3.2: Non-defense government and non-residential private investment as a percentage of GDP

Looking at figure 3.2, the periodicity becomes a little more evident, again with peaks in government investment around 1942 and 1977, and troughs at 1947 and 1980. The shift in base at year 1959 isn't as visible here but still exists in the data.

The second view of the data took a bit more time to construct. Using a 6[th] order polynomial, the trend was removed from the non-defense government investment data which was in current dollars. The original data with the trend line is presented below in figure 3.3.

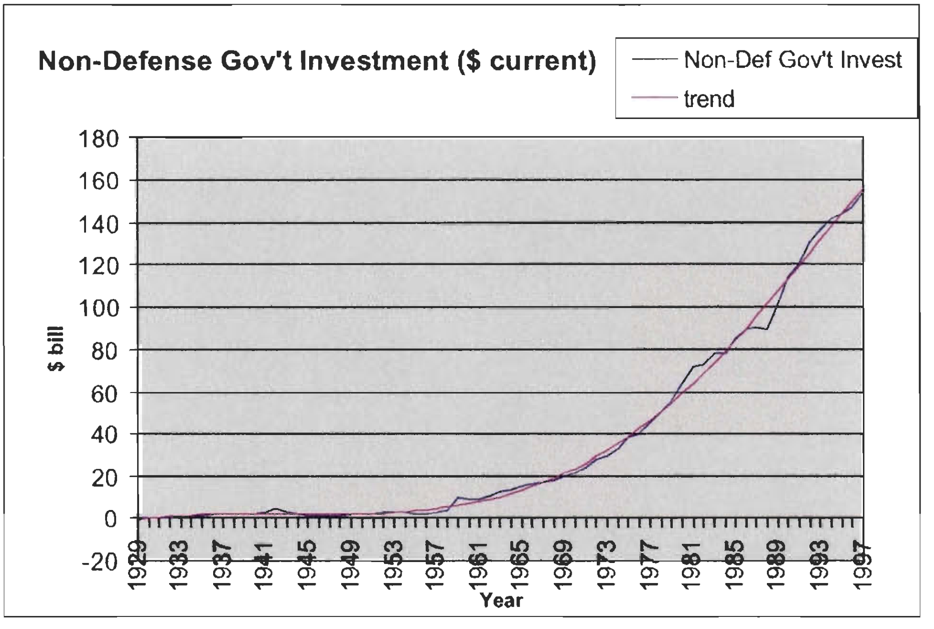


Figure 3.3 Non-defense government investment in current dollars, with the 6th order polynomial trend linc.

The equation used for this trend was calculated using Maple v4.0 and appears below:

y = -.6573649901e-8*x^6+.9186837881e-6*x^5-.4538625389e-4*x^4+.2039486638e-2*x^3-.5212697667e-1*x^2+.5932384345*x-.3828263657

The trend line was subtracted from the actual data to remove the trend. The data with the trend removed appears below in figure 3.4 and more clearly shows the oscillations in infrastructure investment.

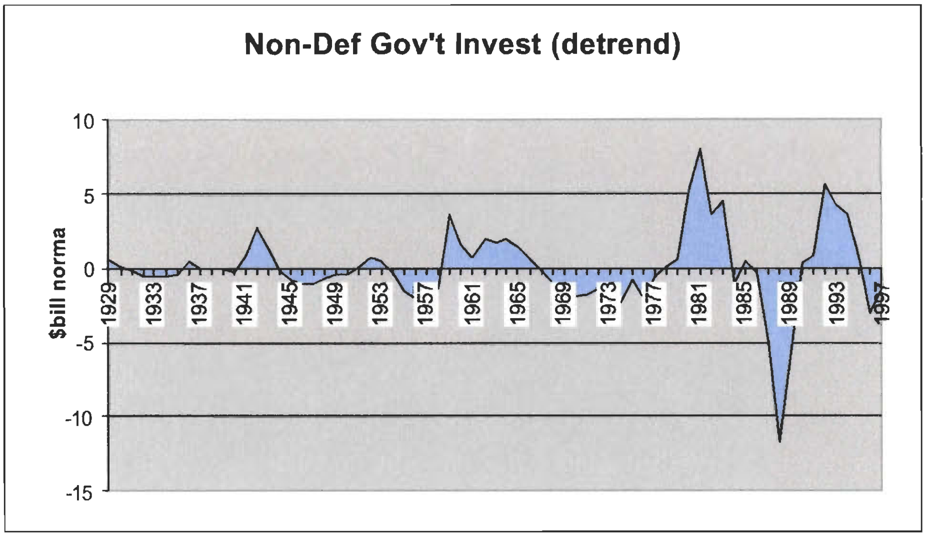


Figure 3.4: Non-defense government investment with the trend removed

Notice that clear oscillations about the normal are now visible if figure 3.4. The short periodicity is most likely the result of both the business and the Kausnet's cycles, we would posit, however, that these oscillations are also the result of over-ordering during times of infrastructure under-supply followed by under-ordering during times of over-supply.

Along the same lines, further work was done to detrend the GDP data. Two 6[th] order polynomials were used to fit the data because of the base shift at year 1959. Both equations were calculated using Maple and appear below. The first equation was used to fit the data from 1929 through 1958, the second was used to fit the data from 1959 to 1997.

Trend1: y = -.1286603945e-4*x^6 + .1058996772e-2*x^5 - .3117748301e-1*x^4 + .3535372404*x^3 + .1596768849*x^2 - 14.82853200*x + 103.3297243

Trend 2: y = .2635047609e-4*x^6 - .2631127866e-2*x^5 + .8965578646e-1*x^4 - 1.134872159*x^3 + 8.019434001*x^2 + 13.09295053*x + 501.7558473

The data and the trend lines were then merged and plotted, these appear below in figure 3.5

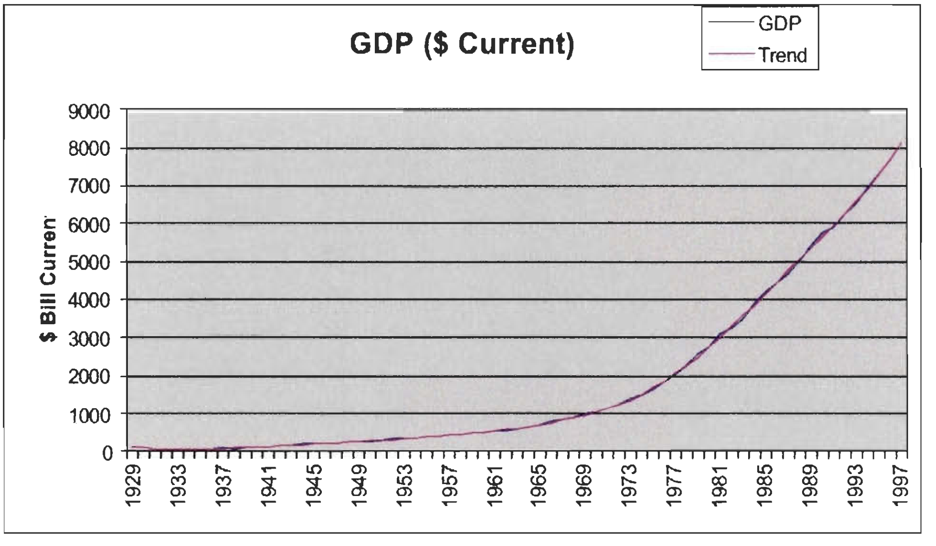


Figure 3.5: Merged GDP data in current dollars plotted with the trend line.

The trend line was subtracted from the actual data to remove the trend, this graph appears below in figure 3.6.

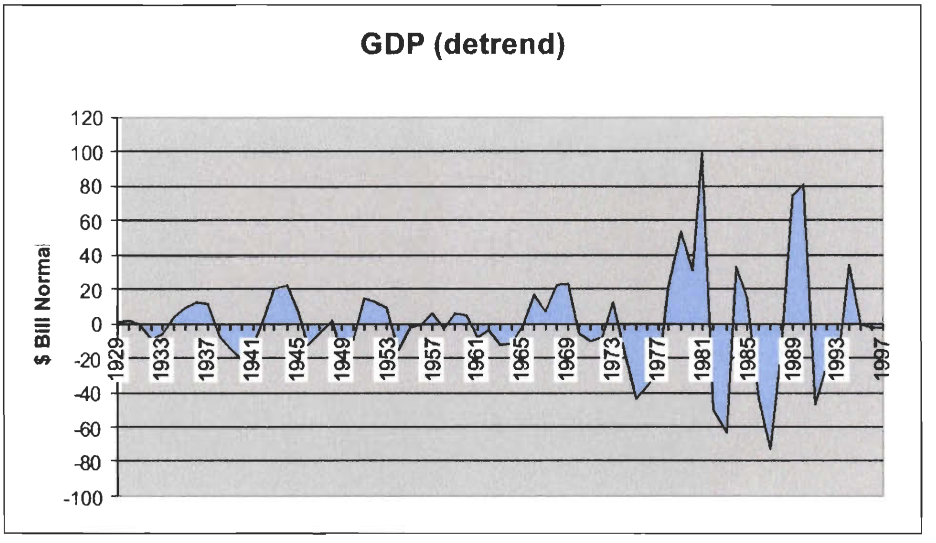


Figure 3.6: Assembled GDP data with the trend removed.

Looking at figure 3.6 we see oscillations similar to those of the normalized investment graph in figure 3.4. Similarly we would hypothesize that this behavior is not only due to the business and Kuznet's[12] cycles but also to investing in too much infrastructure when demand is high and under ordering when demand is low.

The final step was to compare the two normalized graphs: non-defense government investment and the GDP. This appears in figure 3.7.

[12] Mass, N. J., *Economic Cycles: An Analysis of Underlying Causes*. Cambridge, MA: Wright-Allen Press, 1975.

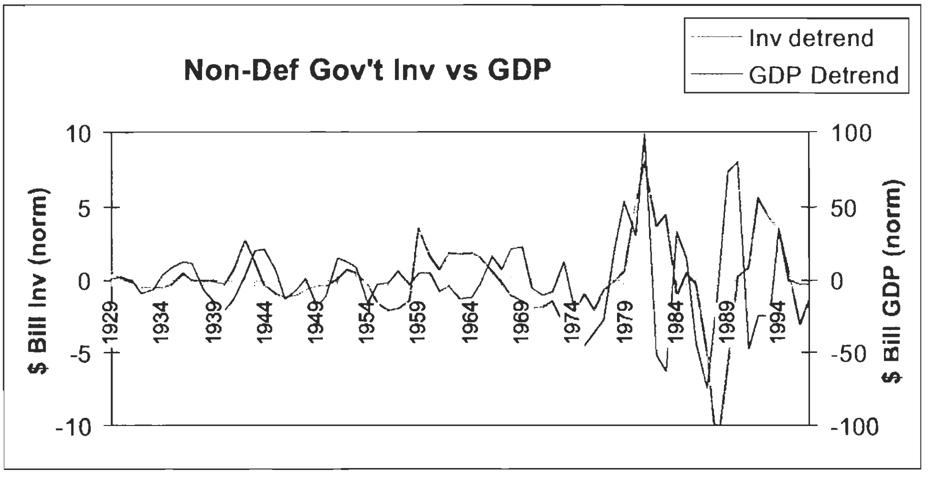


Figure 3.7: Non-defense government investment and GDP, both normalized

Upon inspecting figure 3.7 carefully, one will notice some correlation between infrastructure investment and GDP. In particular, an increase in investment in 1959 seems to spark an increase in the GDP roughly 10 year s later around 1969. The same is true with the decline in investment in 1965 and the decline in 1974. The two appear to be out slightly out of phase which by inspection would corroborate both Aschauer's research relating changes in investment to the GDP,[13] as well as the assumptions made in Saeed's model

Before moving on to the next step, one must understand the most useful characteristic of the reference mode is that it gives the model boundaries so that one does not over build a model, when a simpler one will replicate the problem shape at hand. Keeping this in mind will serve to curb the modeler from spending unneeded effort building and troubleshooting sectors that are not necessary. The temptation is always there, when building one sector the modeler

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[13] Aschauer, D. A., *Why is infrastructure important?* In, Is There a Shortfall in Public Capital Investment?: Proceedings of a conference held at Harwich Port, Massachusetts, June 1990, p32.2-35.2, Boston, MA: Federal Reserve Bank Boston, 1990.

may think of another interesting dynamic that could be incorporated, that in itself is quite all right, for modeling tends to be and explorative tool, but going down the garden path with absolute accuracy can be quite dangerous, especially when development time is at a premium. A short example would be developing a model of a checking account. A modeler starts with a stock of money, flowing in are deposits flowing out are withdrawals. Pretty simple, right? Well the question becomes; what is necessary to replicate the reference mode? If all that is needed for this particular model is a simple bank account where money is stored, this would be fine. With this in mind a trip down the garden path would be developing a checkbook register with its own balance, and capturing the 5 to 7 day delay from when a check is written to when it is withdrawn from the account. Adding in structure to capture the delay from when a check is received and deposited and when the funds become available. Although this is what happens in reality, adding this structure is not necessary. The model will still function correctly if all that is needed is a simple account. Building the additional structure will only serve to complicate the development and validation processes, wasting precious time and effort that could be applied to sectors truly needing more accurate structure.

**Dynamic Hypothesis Formulation**

After determining a reference mode, the next step in building a model is forming a dynamic hypothesis, which is simply a qualitative or causal explanation of what causes the system in question to produce the behavior captured in the reference mode. This explanation serves as a starting point for model construction by identifying the key players in the system and how they interact to cause the problematic behavior in question. As with the reference mode building a dynamic hypothesis helps to give the model boundaries, and directs the modeler to the sectors where detail is most important as well as the sectors where a simple representation of reality is all that is necessary.

With this model, the high level dynamic hypothesis was relatively simple and has been mentioned many times in the preceding sections of this paper. A demand for infrastructure occurs, prompting increased spending and proposed projects enter the mill, these projects take a while to get all the details worked out, while in the mean time the current stock of infrastructure continues to wear out prompting more demand and more new projects, eventually a some of those projects make it through the planning stages and the flow of new projects beginning construction increases. Meanwhile, the stock of infrastructure continues to decay slowly, which boost the number of orders to planning. Eventually some of the new projects in addition to the normal flow of projects begin to come on line, increasing the stock of infrastructure in use. Since there is still a demand for infrastructure more orders than normal continue to be placed, although the excess is less now that some of the additional projects that were ordered have come one line. As more and more projects are being delivered, the level of infrastructure rises, eventually reaching the normal level, only the orders keep coming. The new orders drop back to normal, but more and more projects are coming on-line pushing the stock of infrastructure to oversupply. This prompts a decrease in the number of new orders going below normal levels. The stock of infrastructure continues to rise though, because there are 15 years worth of developments in the pipeline. As time progresses, the orders are reduced even more. Finally, the flow of projects being completed begins to decline, after that it drops below normal. Since the infrastructure overstock continues, the new orders to planning are way below normal. The number of new developments being completed drops further below normal and the stock of infrastructure begins to respond dropping because the decay rate is greater than the completion rate. After a number of years the stock of infrastructure returns back to normal, and new orders return to normal levels. But the flow of project completions is still below normal so the stock of infrastructure continues to decay faster than it is replaced. New orders go above normal a little bit at first, but as the stock of infrastructure continues to fall, the orders continue to get larger. The project completion rate rises a bit but is still way below normal because all these sub normal orders are in the system from the oversupply. Soon however the completion rate rises, the stock of infrastructure responds positively, and the new orders go down a bit. The new projects are coming on line faster now as some of the larger orders make their way through the development chain. Eventually the stock of infrastructure approaches normal, but it passes normal by the orders fall below normal again a little at first, but now there are too many orders in the system. They cycle continues, over supply followed by undersupply. For a single shock these oscillations are damped for two reasons, one, only so many projects can go through planning, when there are too many, fewer orders are placed, when there are too little more orders are placed, but that desired level is not known exactly so only small adjustments are made. The same is true for the number of projects in progress. Second, only a portion of the demand for infrastructure in use is ordered every year so as to smooth these trends an allow room to correct for errors in ordering. These security measures are not enough though. Over-ordering and under-ordering still occur. Oscillations result and are quelled over time. The big problem occurs in the real world when disturbances are frequent, causing the desired level of infrastructure to change. If these changes are frequent enough, the system will never return to equilibrium, rather it will continue to oscillate with a more random periodicity.

The second reference mode concerning the behavior of average sale over time has relatively the same underpinnings in terms of the dynamic hypothesis. First off when new projects are ordered this produces an increase in government spending positively affecting the averages sales. So when the system is first disturbed by an increase in demand the new orders produce a spike in average sales. This curve then oscillates as the level of infrastructure in relation to its normal level, causes the production stream to oscillated which in turn gives rise to oscillations in the general inventory level which causes the general price level to oscillate, inducing oscillations in consumption which affects average sales causing it to exhibit the damped oscillations. These oscillations in average sales then feeds back to the desired infrastructure inventory, causing oscillations there, which produces a moving target when placing new orders for infrastructure, thus pushing the oscillations in both average sales and infrastructure inventory even further.

Additionally dynamic hypothesis formation can be aided by the construction of what are know to system dynamicists as causal loop diagrams. These diagrams help to capture graphically many of the relationships that were discussed above in the dynamic hypothesis for this model. These causal loops work rather simply, we will use the first portion of the dynamic hypothesis for this example. We begin with an increase in government spending, this eventually produces an increase in the desired level of infrastructure which when compared to the actual infrastructure inventory, results in an increase in new orders for infrastructure. With this we can now discuss the causal loop which appears in figure 3.8 below.

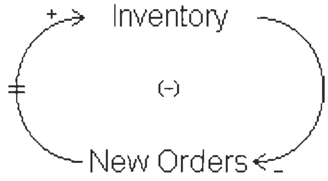


Figure 3.8: Causal loop diagram capturing the first portion of the reference mode.

The loop begins with an increase in the new orders which after a delay, produce an increase in infrastructure inventory. This is shown by the two hash marks on the arrow connecting new orders with inventory and since an increase in orders produces an increase in inventory, a plus sign is placed next to the arrowhead representing the connection's polarity. Moving on, an increase in the infrastructure inventory will produce a decrease in new orders, thus a connection is made back to the new orders this time with a minus sign at the arrowhead because new orders moves in the opposite direction compared to inventory. Finally the last step is to identify the polarity of the loop, to do this we start with an increase in new orders, which after a delay produces an increase in inventory, which produces a decrease in new orders, balancing the initial increase, therefore we call this a negative or balancing loop which is indicated by a minus sign in the center. Simulating the loop, once again we begin with an increase in new orders which after a delay produces an increase in the infrastructure inventory. When the inventory finally goes up, the new orders go down, however since there was a significant delay between when the order was placed and when it was delivered, there are still a lot of projects in the cue, and so the inventory continues to go up, until the smaller orders are delivered. When the smaller orders come on line the inventory begins to go down, moving towards the desired infrastructure level, as it does the new orders increase trying to maintain the desired level. However, there is a long delay for the increase in new orders to reach the inventory and thus the inventory continues to fall because the small orders continue to be delivered for a while. New orders increase further because inventory continues to fall. Eventually, after the delay the larger orders begin to arrive and the stock of infrastructure starts to go up. The oscillations between over-supply and under-supply continue. As one can see, this simple loop captures the first portion of the reference mode.

**Model Construction**

After the reference mode has been identified and explained with a dynamic hypothesis, model construction begins. Usually, the first section to be fleshed out is the one that is most responsible for the problem at hand. In this case the infrastructure sector would be the first on the list. From there, supporting sectors are added as prescribed by the dynamic hypothesis. Testing against the dynamic hypothesis and against reality is extremely necessary throughout the process of developing a sector. The modeler must be certain that the structure performs within the bounds of reality for the values it is designed to handle. Using this method, construction proceeds at a reasonable clip, and by testing continuously, laborious troubleshooting is avoided during sensitivity testing and model validation.

The model used for this project was originally constructed and tested by Professor Khalid Saeed, and thus the core of the development was complete when the project was initiated. The purpose of this project was to further verify the robustness of the model, and then use it for experimentation and policy testing. Therefore, an in-depth discussion of the construction of this model will not be provided in this particular paper.

**Model Validation**

Once the model has been developed, formal validation begins. Traditionally model validation refers to the statistical fit of the model output compared to the actual data. Validating system dynamic models requires a different thread. Since, as was discussed in the reference mode formulation above, we are not looking for exact numeric representations of the problem, but rather the shape of the problem or its behavior over time, numeric precision is not as necessary. One first looks at the models output: Does it replicate the reference mode? Next we must look at the structure that created this output: Does the structure reasonable replicate the processes occurring in reality. Finally parameter sensitivity testing may be in order. Sensitivity analysis pushes the model to its limits by feeding variables and controls values within the extreme logical operating range, making certain that the model continues to function within the bounds of reality. Typically during sensitivity analysis the ranges of stocks are monitored. Special attention is paid in particular to those stocks representing physical quantities that can not in reality go negative, these stocks are checked to see that they remain positive throughout each of the simulations. During model construction sensitivity testing is a vital and thus common practice before placing a newly developed sector into the model, thus much of the legwork has already been completed before the model is ready for release to policy testing.

Since the model used in this project was constructed and tested previously by a very well known modeler, Dr. Saeed, much of the critical sensitivity testing had already been preformed. Some spot checking was done while the author was acquainting himself with the model, but no formal analysis was necessary. Instead, validation through experimentation was performed, the documentation of these procedures appears below in the form of two experiments.

**Experiment 1: Equilibration Test**

*Outline / Key Variables*

- Goal: The model will exhibit flat line behavior, where the system is functioning in complete dynamic equilibrium for the entire simulation

- Sectors: All critical sectors are in active operation. The infrastructure sector is turned off for this test, an thus reports equilibrium values throughout the simulation.

- Indicators: Average Sales, and Sales will be the used to demonstrate dynamic equilibrium.

*Results*

The model ran in dynamic equilibrium with the infrastructure sector disabled. Figure 3.9 shows the equilibrium using average sales as the indicator.

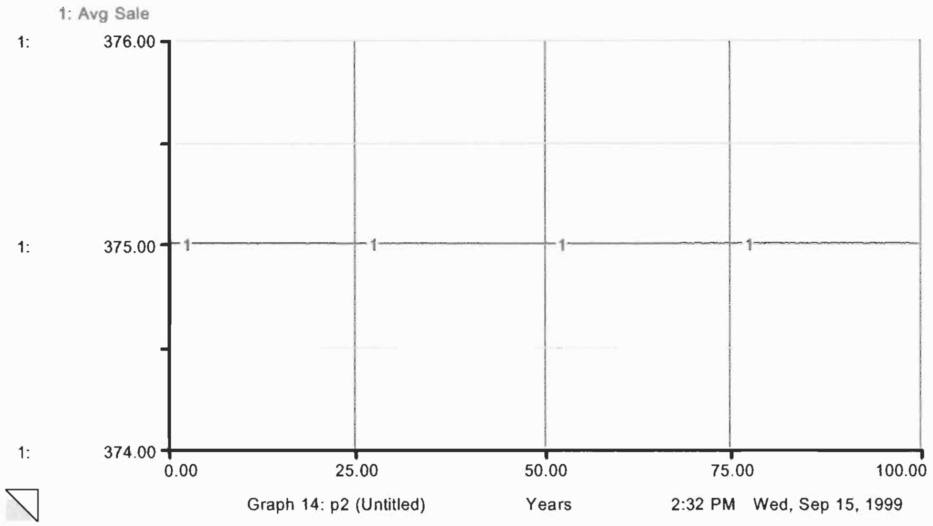


Figure 3.9: Average sales demonstrating the model operating in dynamic equilibrium.

*Conclusion*

The model has been calibrated to run in equilibrium, thus all further tests can be attributed to individual policy changes.

**Experiment #2: Infrastructure Based Cycle**

*Outline / Key Variables*

- Goal: Demonstrate cyclical destabilization due to current infrastructure investment heuristics

- Sectors: All critical sectors remain on, additionally the infrastructure sector is activated.

- Idea: With the inclusion of the infrastructure sector, the system will exhibit oscillatory behavior resulting from decisions made in the public sector. In other words, this experiment intends to show that the general policy for purchasing infrastructure leads to fluctuations in the market.

- Indicators: Comparative graphs of average sales over time and capital output ratio over time will show the cyclical fluctuations that were not present before the infrastructure sector was enabled. Additionally, a graph of infrastructure inventory will be used to give a different perspective on the oscillations that occur as a result of this policy.

*Results*

First off, running the model with the infrastructure sector and all critical sectors in operation produced the requisite dynamic equilibrium as shown in Figure 3.10

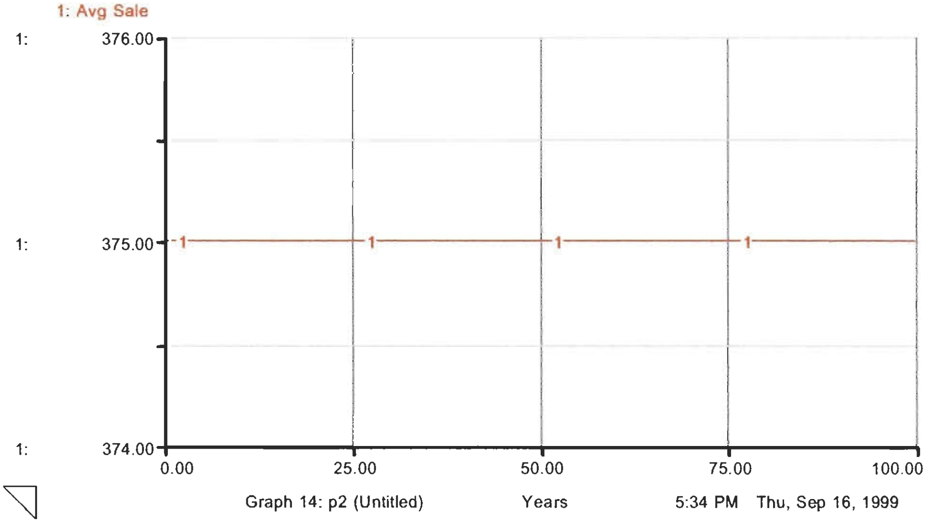


Figure 3.10: Model with infrastructure sector on, running in dynamic equilibrium.

Secondly, to demonstrate the destabilizing effect of the current infrastructure ordering policy we pulse the system slightly. For this, the fractional government budget spending was stepped up from 20% to 22% (or a 10% of the percent increase). This step occurs in year 10 of the simulation. To demonstrate that the amplified disturbance is the result of infrastructure policy, another simulation run was included in figure 3.11 below, where the infrastructure sector was disabled, meaning that infrastructure was managed perfectly during the increase in spending and the infra effect was always 1. The destabilizing effects are demonstrated below in figure 3.11.

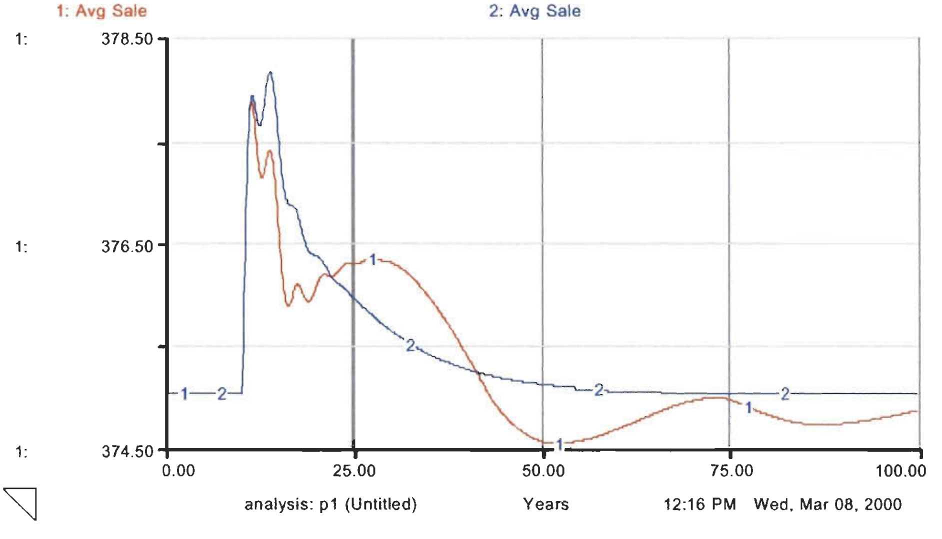


Figure 3.11: Model simulated with a step in infrastructure spending from 20% of the total budget to 22% at time = 10 years. Run 1 demonstrates the destabilizations due to current infrastructure policy. Run 2 shows the system with the infrastructure sector turned off (perfect management of infrastructure).

Comparing the first run where the infrastructure sector was operating, with the second where the sector was off, the destabilizations are easily apparent. With the common infrastructure policy in place, oscillations result from a single jump in spending.

Figure 3.12 provides a different perspective on the simulation. In this case we are looking at the current infrastructure inventory over time. Notice that the period of the first cycle is roughly 50 years, and successive cycles are damped in both periodicity and amplitude.

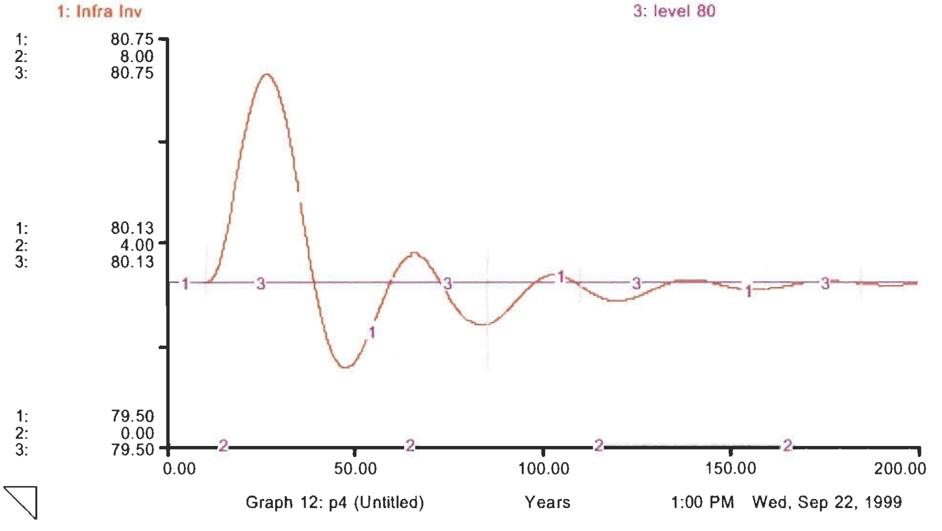


Figure 3.12: This uses the same simulation settings as figure 3.11, but instead running the model out 200 years and looking at the infrastructure inventory over time. Note the damped 50 year cycle.

The system returns to equilibrium with a single shock in a noiseless environment, however when noise is present, the model will remain in a state of dis-equilibrium exhibiting additive oscillations from each additional pulse. Randomizing the fractional government budget spending from 15% to 25% beginning at year 10 and smoothing this function with a third order smooth function and a smooth time of 2 years effectively replicates a noisy environment. This is demonstrated in figure 3.13 which compares the original single shock noiseless environment, with the multi-shock noisy environment on the basis of average sales.

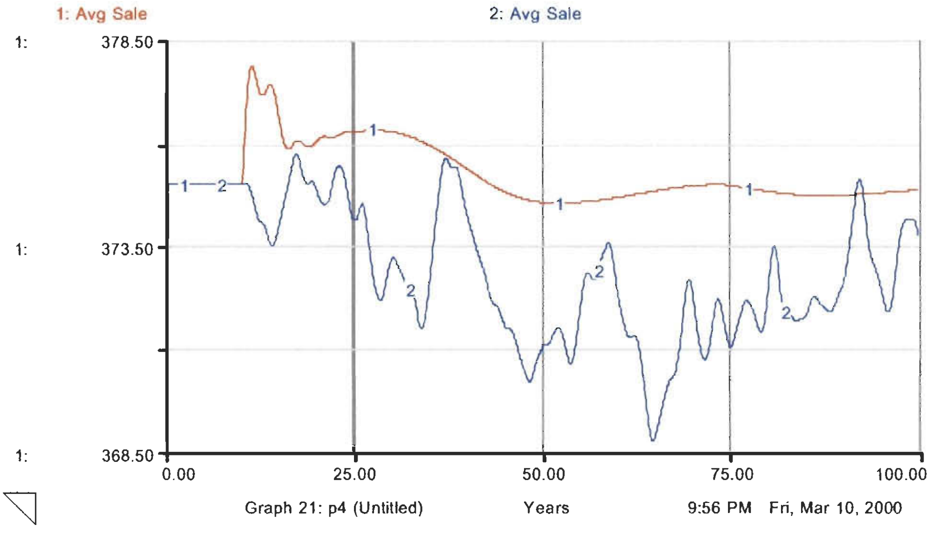


Figure 3.13: Comparative simulation looking at average sales over time. Run 1 shows the original model simulated in a single shock, noiseless environment. Run 2 demonstrates the effect of a noisy environment on the system.

Adding yet another perspective, figure 3.14 graphs the capital output ratio (Capital/Average Sales) which is a measure of capacity utilization over time. As with figure 3.11, the infrastructure sector is in operation for the first run and disabled for the second. Here again oscillations occur when the common infrastructure ordering policy is simulated.

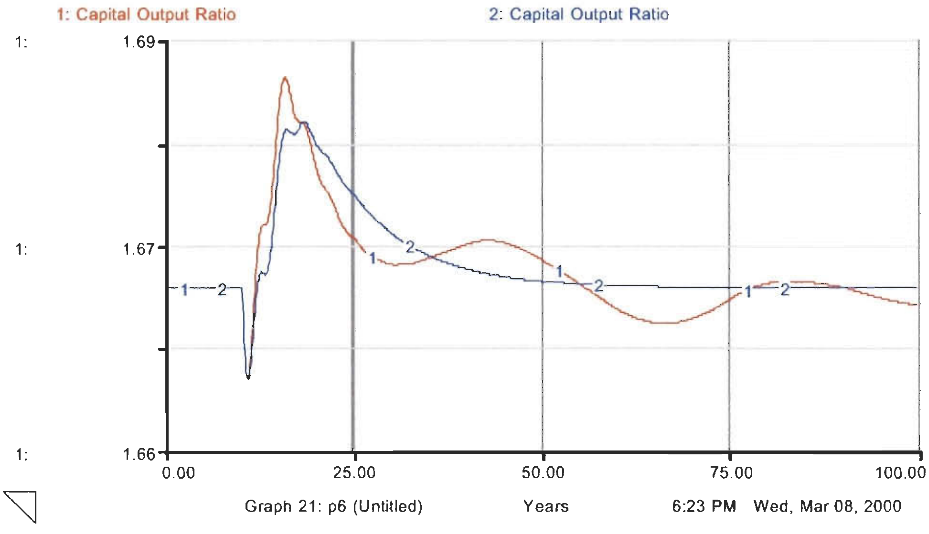


Figure 3.14: Capital output ratio, run 1 with infrastructure sector operating, run 2 without. 1

*Conclusion:*

The model demonstrates that current infrastructure investment policy amplifies disturbances in the system. In a noiseless environment the oscillations that result are damped, however when faced with noisy parameters, the oscillations will continue.

**Policy Identification / Analysis**

Once the model has been validated, policy analysis can begin. As a modeler works through the process of putting a good model together, the analysis of the problematic policy tends to follow along in a parallel manner. For as the model is constructed, the development promotes a high level of systemic understanding concerning the problem policy and how to address it, and thus a great deal of the investigation into what caused the problem and how to solve it has already been completed. Taking this knowledge further, additional sensitivity tests are done on the model to identify policy levers and the dynamics that make them effective in addressing the problem. To further expand the policy options, the feedback loops in the model are identified and those that play a particular part in generating the problematic behavior are examined at many points along each loop to see if additional structure could provide new policy levers. While all this analysis is going on, the modeler must check all policy levers against the realm of reality. A policy may be good on paper but if it cannot be executed in reality, then it is of no value and must be set aside.

**Policy 1: Reduce information delays**

Essentially the system is plagued by material delays, which are not accounted for when ordering new infrastructure. In a situation where more infrastructure is needed, orders will be placed until the stock of infrastructure equals the desired. However, because of the delay between ordering and delivery of new infrastructure, when the orders stop there will still be projects in the pipeline. As those projects come on line, they push the stock of infrastructure over its desired level, and thus we have too much infrastructure leading to zero orders in the pipeline. The no new order status continues until the infrastructure stock drops below the desired at which point orders are placed. But in this case the stock keeps falling until new projects begin to be delivered, and thus more orders a placed based on the perceived discrepancy. When these orders come on line, the stock begins to rise, until the desired level is achieved only again there are still orders in the pipeline, pushing the stock further up. These oscillations are damped because a limited amount of information about projects in the queue is returning to those ordering new infrastructure, and this is marginally factored in to the order stream. This damped oscillatory behavior is demonstrated below in figure 3.15 taken from experiment 2 above.

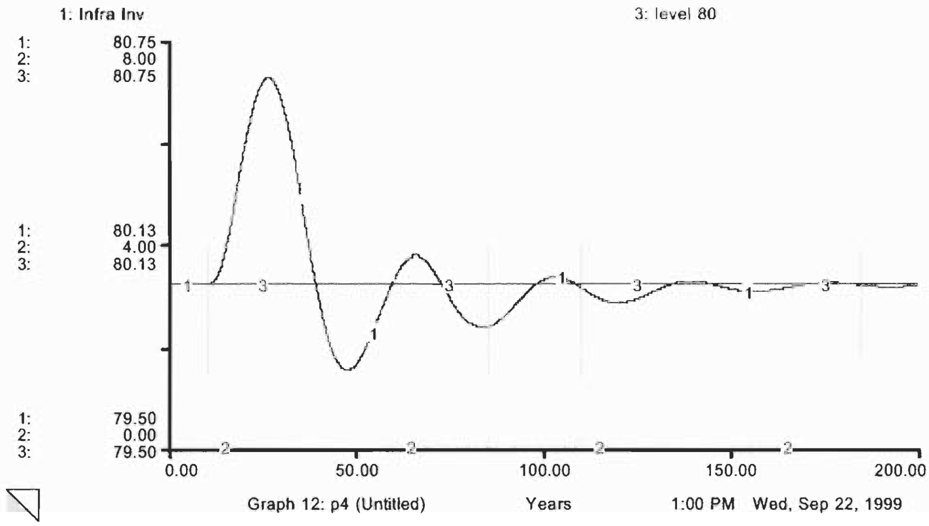


Figure 3.15: Graph of damped oscillations in infrastructure inventory over time. This is the same model run from experiment two above, with the graph appearing as figure 3.12

With this delay concept in mind, the first suggested policy will be to factor the infrastructure projects in production into the ordering function. In the real world this policy would be similar to increased monitoring of construction activities, as well as add campaigns informing the public of the progress, from initial planning to final completion. This would give greater feedback to the individuals applying the pressure for new infrastructure developments.

**Policy 2: Average demand fluctuations**

Since the desired infrastructure level is a function of average sales, which, through a long feedback loop is tied to the infrastructure inventory, oscillations in the inventory caused by delays in the order system, could serve to further exacerbate the fluctuations because the desired level of infrastructure also fluctuates. These fluctuations in the desired level of infrastructure produce an oscillating target which when coupled with the delays in order fulfillment would produce additional oscillations in the infrastructure inventory. In other words, when the infrastructure inventory moves eventually the desired level of infrastructure will also respond, depending on the delay, these motions can serve to prolong oscillations in the system. This policy attempts to reduce the impact of this feedback, by reducing the sensitivity of the desired infrastructure to fluctuations. In reality, this means that the persons responsible for making decisions take greater care in assessing the infrastructure needs of the economy, making decisions over a longer period of time and thus averaging the needs of the public. Hopefully this will reduce the load on the order stream, allowing the system to return to equilibrium much sooner.

**Conclusions**

After the policies have been tested separately and in groups, the best is chosen and then recommended. This is the final stage of model development. In addition to the recommendations, this section includes a list of the assumptions used in the model, as well as the limitations and areas suited for extension. During this phase of the project the write-up is completed, which assembles the documentation of the project. In almost all formal projects where a paper or a document is expected, writing is an integral part of the entire process from start to finish. This is done so that the modeler is not overwhelmed at the end with the mound of work that needs to be assembled and discussed to produce a well-organized report. In other settings where the client is not as interested in the process but rather the learning that resulted, documentation would be advisable but not necessary, the bulk of the write-up will have to occur near the end.

In terms of this project, the analysis and conclusions follow in the remaining chapters.

*Chapter 4*

# RESULTS

## Policy Elaboration and Testing

A reformulated infrastructure ordering policy was the goal of this project, candidate policies were identified in the previous chapter. The following will serve to further elaborate on these proposed policies, presenting them in greater detail as the results of the project.

## Policy 1: Reduce information delays

As was introduced in chapter three, this policy intends to combat the material delays in the infrastructure supply chain shown below in figure 4.1.

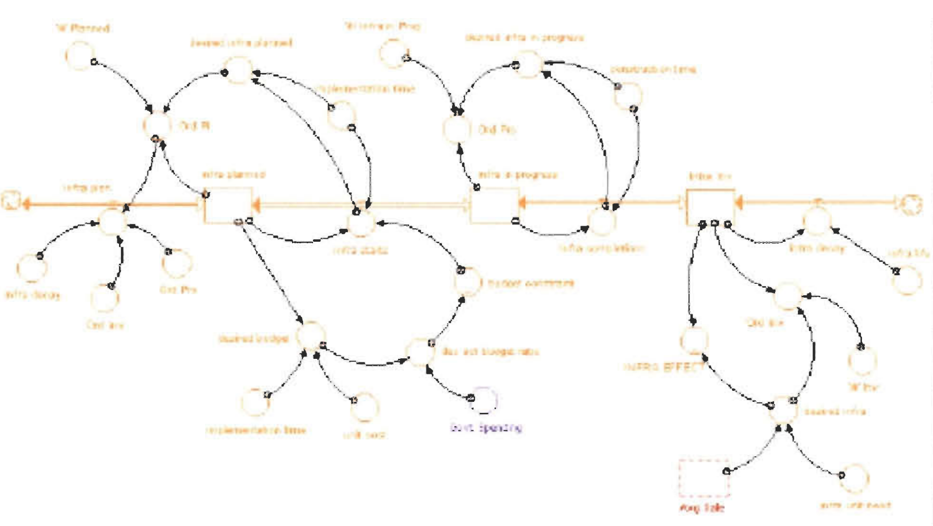


Figure 4.1: Infrastructure supply chain, capturing the entire lifespan of a project from proposal to obsolescence.

Problems occur when these material delays are not taken into account, particularly, the problem that the project addresses is the result of these material delays. In this case damped oscillations occur because orders are based on a discrepancy between the actual stock of infrastructure and the desired stock of infrastructure and the orders to fill this discrepancy take an average of fifteen years to arrive. While the orders are being processed, the discrepancy continues to grow wider and thus more new projects are planned, producing a bulge in the system in response to the growing demand. When these projects finally come on line the discrepancy is reduced, and fewer projects are planned, eventually the discrepancy is filled, orders are returned to the level necessary to replace the decaying structures, and all is well and good for the moment. The projects don't stop coming though, there are still fifteen years worth of development in the pipe. Soon the stock of infrastructure is over-filled and new orders are reduced below normal levels. This drop in orders produces a lull in the pipeline where new orders are less than the amount that is decaying for that particular year, this causes the stock of infrastructure to go down. The problem occurs when the target infrastructure is met but there are still fifteen years of below normal orders in the pipeline, and so the stock continues to fall, once again producing a bulge in the order stream that doesn't reach the stock for quite some time. This simple material delay produces oscillations in the stock of infrastructure in service as is shown below in figure 4.2

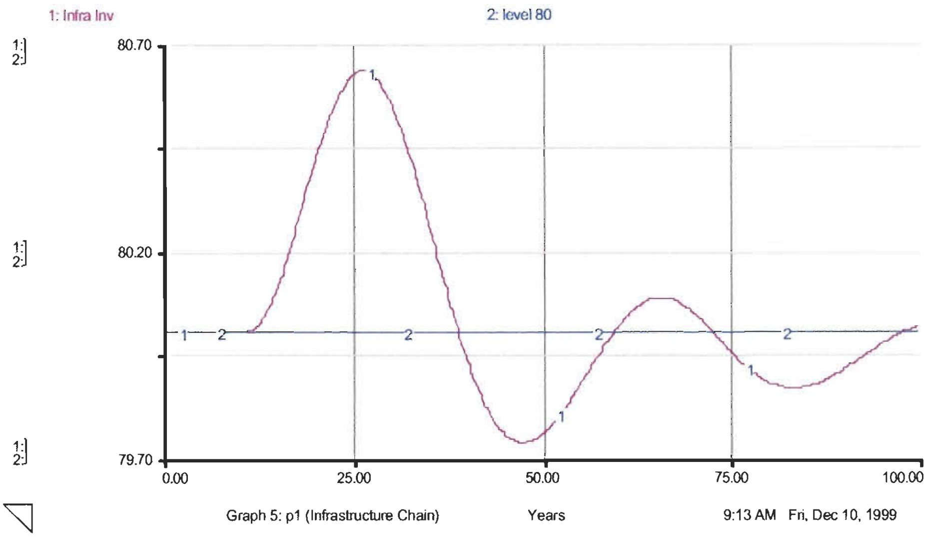


Figure 4.2: Infrastructure inventory oscillations due to material delay in placing and receiving orders for new infrastructure.

Normally, if the inventory stock was the only one used to place orders, with no mind to the chain of steps providing new infrastructure, the stock would oscillate with almost no damping, (damping depends on many factors one of which is the time of the delay). As one can see in figure 4.2 above, there is damping, this is the result of allowing the stock of projects in planning and the stock of projects in progress to influence the order stream. By calculating a desired number of projects in planning and in progress, we can now use these number compared to the stocks of projects in planning and progress and make adjustments to the order based on the discrepancies between these two numbers. The discrepancies are formulated as follows:

**Desired Infrastructure in Planning = Infrastructure starts * The Implementation Time**

Where infrastructure starts is the flow from the stock of projects in planning to the stock of projects in planning, and multiplying this with the implementation time gives a desired level for the stock at the current rate of outflow.

What does all this mean in reality though? The answer is simple. Policy makers want to keep the system functioning as normally as possible, thus when they are taking pressure to build new infrastructure on a macro scale, they determine how much is necessary to fill the discrepancy. Next they look at the number of projects in the cue and how many the would like to have in the cue, both in planning and progress, and adjust the orders accordingly so that the new orders formulation looks like this:

Infrastructure Orders = Orders for the Inventory + Orders for the Planning stock + Orders for the in Progress stock + Infrastructure decay

Where the orders for planning, progress and inventory can be negative if the particular stock exceeds the desired. Each of these orders are multiplied by a particular weighting fraction less than or equal to 1 which account for the lack of current and timely information. Simply put there is no manageable way to have perfect knowledge in the actual system which would be captured with a weight of 1. Adjusting the weight of desired orders for planning and production to ¼ produces the damped oscillatory behavior currently exhibited in reality, and was responsible for the damped oscillatory behavior in figure 4.2.

In order to test the policy of providing better information to decision makers, the weighting fractions on orders for planning and progress have to be increased. In reality this means keeping better records of projects currently under way, details that include the total stock of projects at each stage and how fast they are progressing between each stock.. Additionally keeping the public aware of the progress will reduce the complaints about the systems currently in operation and thus will reduce the pressure to order more infrastructure when the replacements are not coming on line fast enough.

As was mentioned before a weighting value of 1 equates to perfect knowledge of the system. This is certainly not attainable considering the vastness of the system, and the macro topics that it addresses. Therefore fractions of 0.6 or 0.75 would be in order. This policy was implemented in figure 4.3 below.

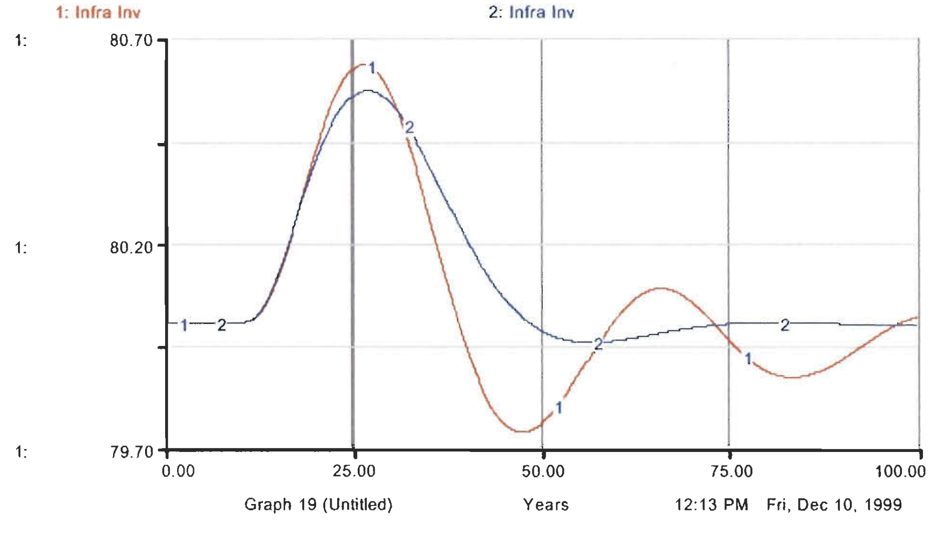


Figure 4.3: Policy #1 implemented showing further damped oscillations. Run 1 is the current formulation, run 2 shows the results with policy 1 in place.

The first run used the original values, the second used a weighting of 0.75. Notice how the additional weighting caused the system to account for orders already in the pipeline and thus the system returned to equilibrium much faster with only one marked oscillation. Figure 4.4 below compares the old policy with the new from the economic perspective, looking at average sales over time.

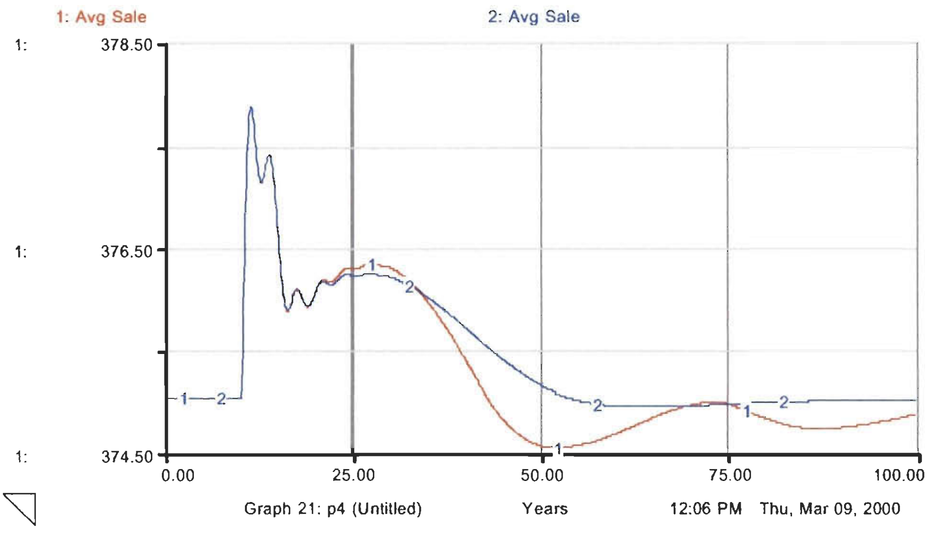


Figure 4.4: Comparative plot of average sales over time. Run 1 is the current formulation, run 2 shows the results with policy 1 in place.

Again we see that this policy serves to dampen the oscillations resulting from changes in spending. Looking at other economic indicators, figures 4.5 and 4.6 below compare the old policy with the new on the basis of the capital output ratio and production. These figures demonstrate that this policy is effective at reducing and nearly eliminating the long term oscillations that plague this system.

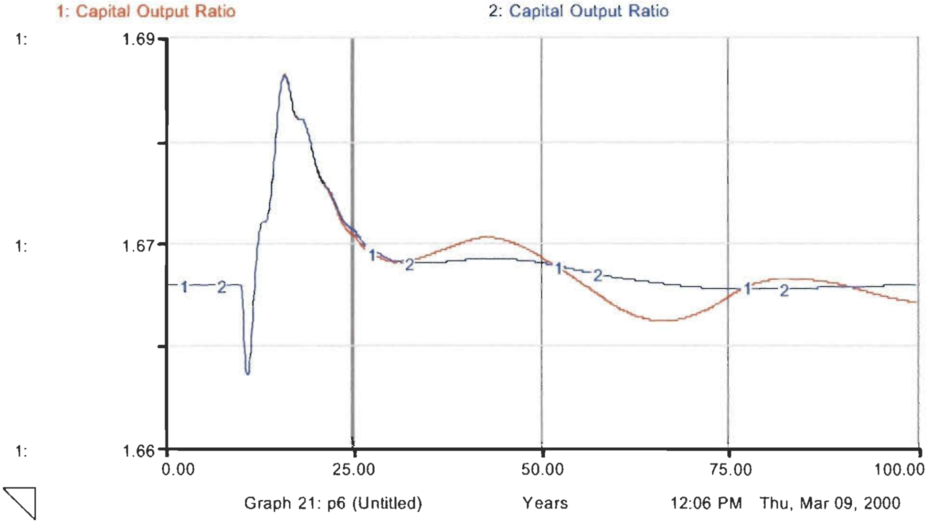


Figure 4.5: Comparative plot of the capital output ration over time. Run 1 is the current formulation, run 2 shows the results with policy 1 in place.

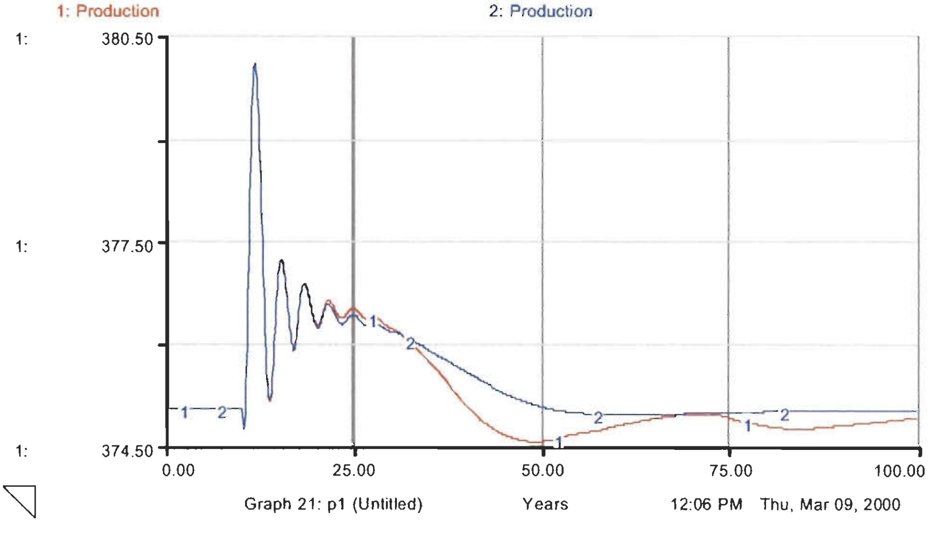


Figure 4.6: Comparative plot of production over time. Run 1 is the current formulation, run 2 shows the results with policy 1 in place

There are limitations to this policy however; the cost of additional paper work is not accounted for in how quickly the projects are brought to completion. In reality the added workload would make the project move a bit slower. If time allows this aspect will be addressed with additional runs in chapter 5. Figure 4.7 compares the effects of various degrees of accuracy in determining the desired and actual level at each of the stages in the development pipeline. The first run uses the recommendation from this policy, the fifth run uses the original method. The runs in between are divided evenly.

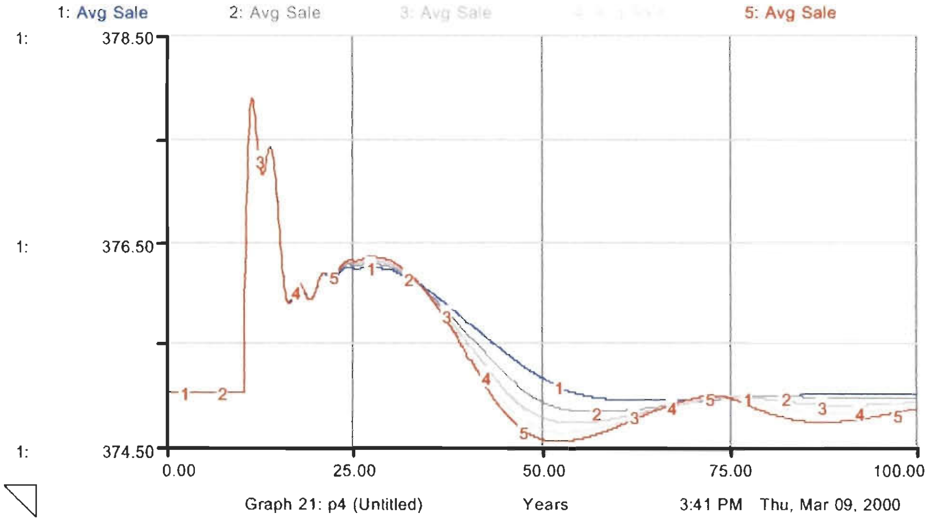


Figure 4.7: Comparative graph of average sales over time for varying degrees of accuracy when determining the desired and actual levels at each stage in the infrastructure pipeline. Run 1 uses policy 1, run 5 uses the original formulation. The other runs are divided evenly.

Notice the significant gains in stability. However there is a point to diminishing returns. Pushing for accuracy greater than that recommended by this policy will not produce enough of an effect to justify the added cost. This is demonstrated in figure 4.8 where the sensitivity analysis was extended one run further to near perfect accuracy. (For this run the weighting fraction for orders from planning and production was set to 1) Run 1 uses the recommendations from this policy, run 4 uses the original formulation, and run 5 pushes for near perfect accuracy.

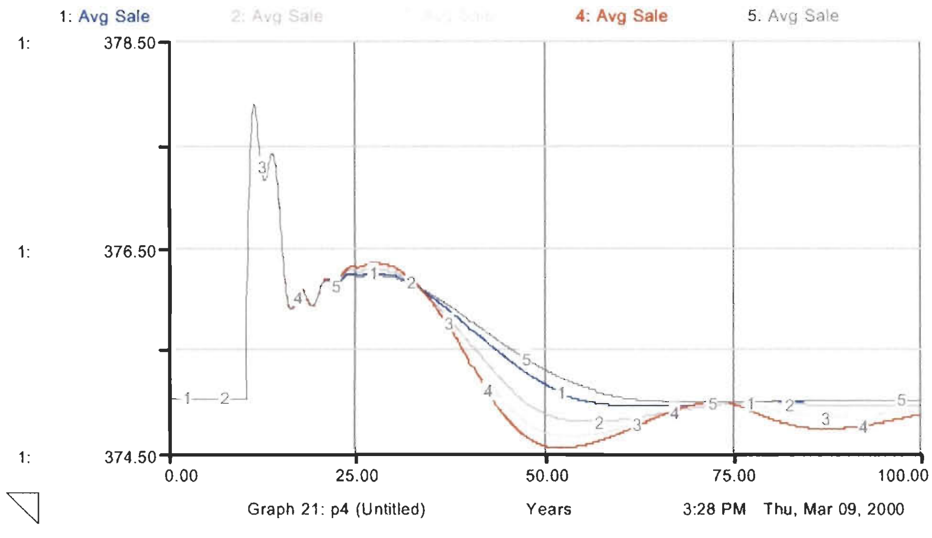


Figure 4.8: Comparative graph of average sales over time for varying degrees of accuracy when determining the desired and actual levels at each stage in the infrastructure pipeline. Run 1 uses policy 1, run 4 uses the original formulation. Run 2 and 3 are divided evenly. Run 5 simulates perfect accuracy.

A hand full of hours were spent trying to find adverse effects of this policy but not many could be found. However, when running the model without the infrastructure sector, where the infra effect returns a static 1 or perfect investment, the model performs better than with the sector on and policy 1 in place. This indicates that there is still a better policy to be found. This point is illustrated below in figure 4.9

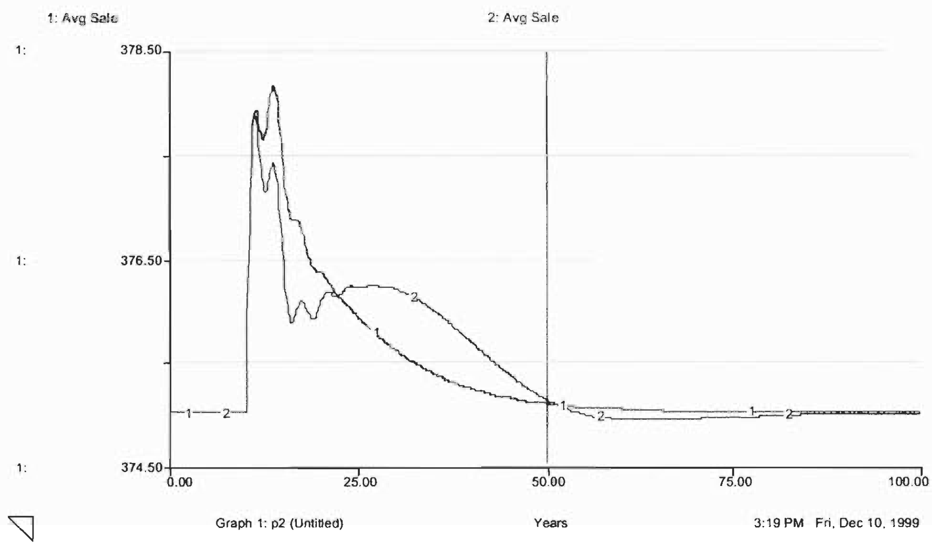


Figure 4.9: Average Sale is used as an indicator of overall economic health, where run 1 was the whole model without the infrastructure sector (the best possible infrastructure policy), and run 2 was with the infrastructure sector on and policy 1 in place.

**Policy 2: Average demand fluctuations**

As was introduced in chapter 3, this policy is designed to reduce fluctuations in the desired level of inventory. By slowing the response of desired infrastructure to changing conditions in the market, it is hypothesized that this will give the infrastructure system more time to come to equilibrium before the goal changes again in response to the oscillations of the infrastructure system returning to equilibrium. In other words, the current level of infrastructure with respect to the desired level of infrastructure feeds back through the economy to eventually affect the desired level of infrastructure. Thus fluctuations in the infrastructure inventory due to material and information delays in ordering feed back to change the desired level of infrastructure, changing the goal and prolonging the oscillatory behavior. By dampening the fluctuations in desired infrastructure we hope to reduce the fluctuations of the infrastructure system and the economy as a whole.

This policy was implemented in the following manner. The desired infrastructure was smoothed with a third order smoothing function which averaged desired infrastructure over a period of 5 years (Smooth_time). This new formulation was added to the existing one in desired infrastructure and a switch converter (Policy_2_SW) controlled which equation was used. The structure appears below in figure 4.10

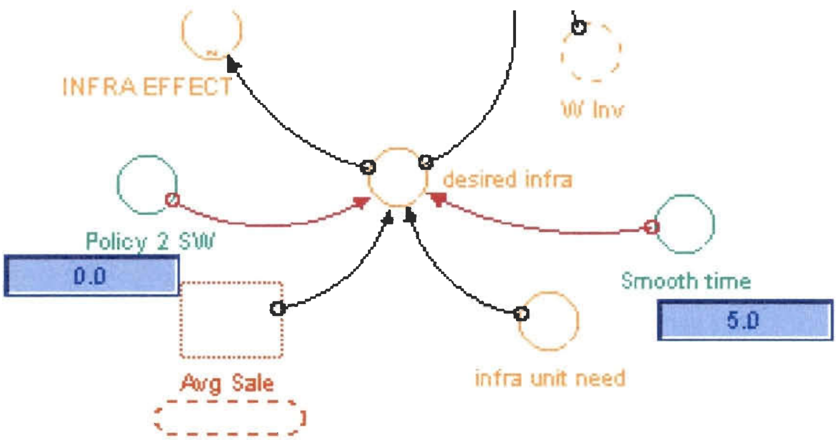


Figure 4.10: Modified desired infrastructure formulation.

The model was simulated with the original formulation and then again with the modified formulation discussed above. The results appear below in figures 4.11 through 4.15.

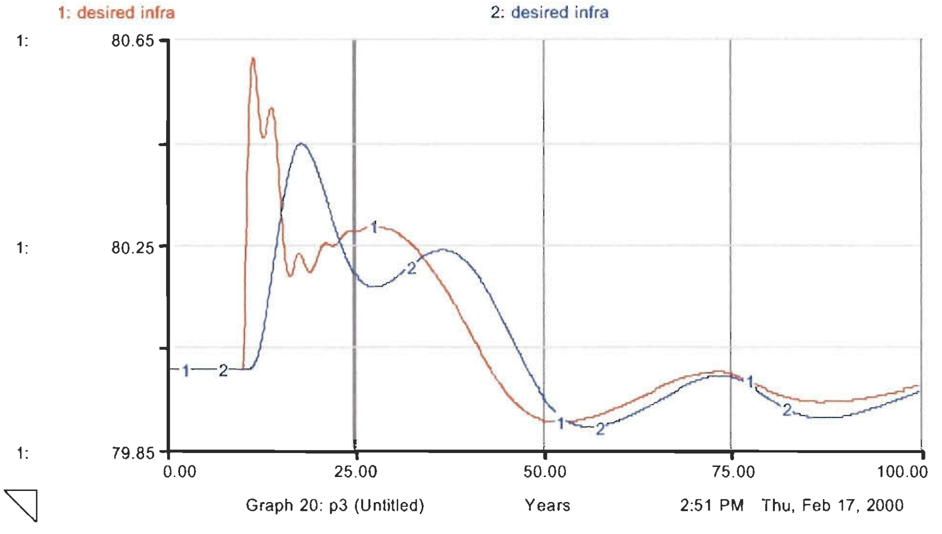


Figure 4.11: Comparative graph of desired infrastructure. Run 1 uses the original formulation, run 2 smoothes desired infrastructure over 5 years.

As one can see in figure 4.11, the second run, with a smooth function on desired infrastructure, did serve to dampen oscillations in the first 15 years or so after the shock as compared to the original formulation used in the first run. However, as the simulation continued, the two runs were essentially the same, with the second run showing a shorter periodicity and a greater amplitude as the system worked toward equilibrium.

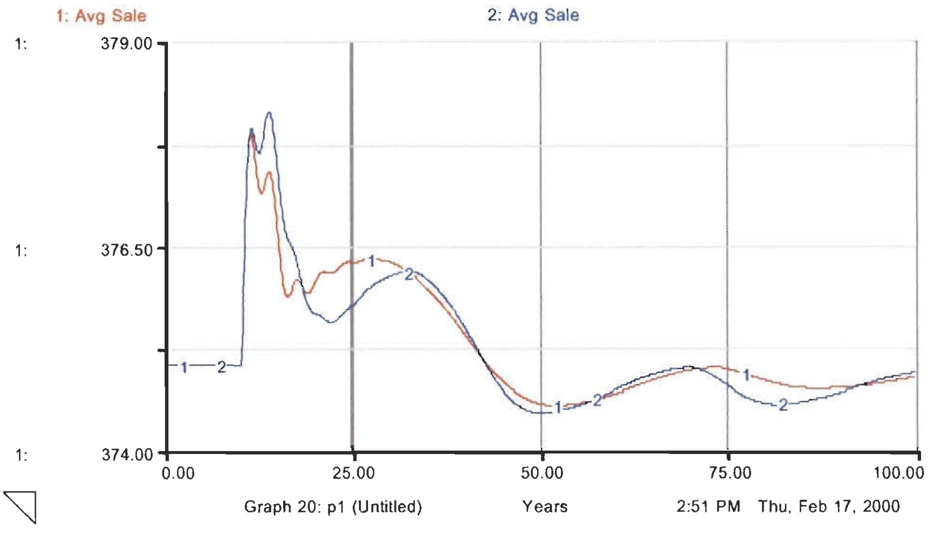


Figure 4.12: Comparative graph of average sales over time. Run 1 uses the original formulation, run 2 smoothes desired infrastructure over 5 years.

In figure 4.12 we see the effect of policy 2 on average sales. In run one the original formulation was used, in run 2 the smoothed desired infrastructure was used. Determining whether or not this is a successful policy is not as clear-cut as with the other policies. Notice that the peak in run 2 exceeds that of run 1 at roughly year 15, this is not so good. However the downturn soon after is much softer for run 2 than for run 1, this is good. After year 30 the two runs seem to be in sync, with a slight difference in the periodicity, where in run 2 the average sale seems to oscillate a bit quicker, this makes it hard to say which is better. So to summarize, in terms of average sales, dampening the oscillations in desired infrastructure serves a marginal benefit.

Continuing with the economic variables, figure 4.13 takes a look at the policy in terms of production over time. Run 1 uses the original formulation, run 2 uses this policy.

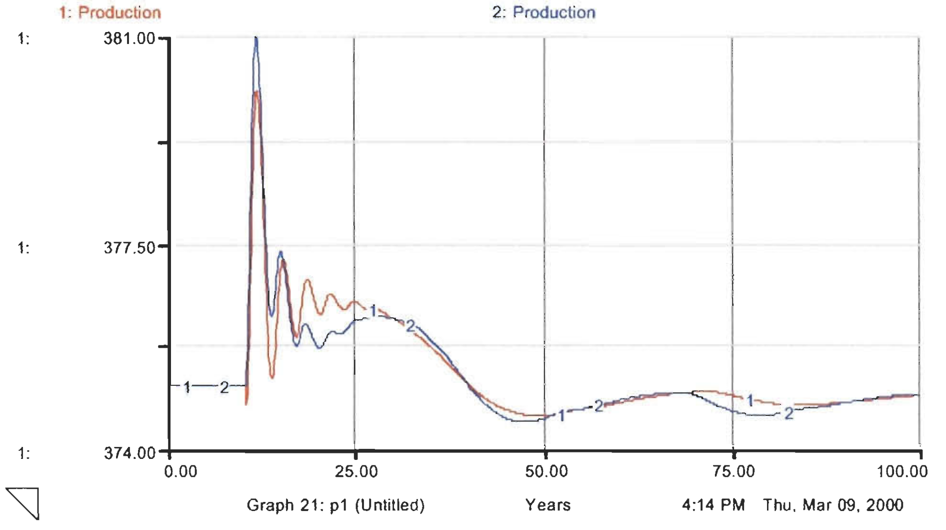


Figure 4.13: Comparative graph of production over time. Run 1 uses the original formulation, run 2 uses policy 2.

Looking at figure 4.13, notice that damping the demand does slightly reduce the oscillations between year 20 and 25, but after that there is no significant difference between the two runs. Thus, in terms of production, damping the infrastructure demand marginally reduces the short-term fluctuations, however the long-term oscillations remain relatively unaffected.

Finally in figures 4.14 and 4.15 we look at infrastructure inventory and the total orders flowing into infrastructure planning over time. These appear below.

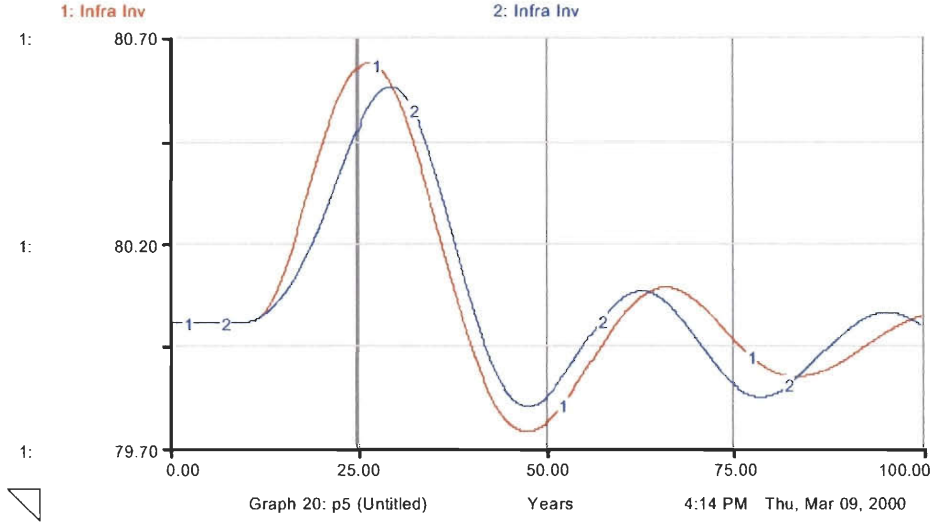


Figure 4.14: Comparative graph of infrastructure inventory over time. Run 1 uses the original formulation, run 2 smoothes desired infrastructure over 5 years.

Looking at figure 4.14 we see that initially the amplitude of the oscillations is less for the smoothed desired infrastructure of run 2 as compared to run 1, this is good. However as the simulation continues we see that in run 1 the oscillations are damped at a greater rate. Thus we see that smoothing the desired infrastructure serves to minimize the fluctuations due to problems with infrastructure ordering, however this is at the cost of the overall damping rate and thus the wave persists for a longer period of time.

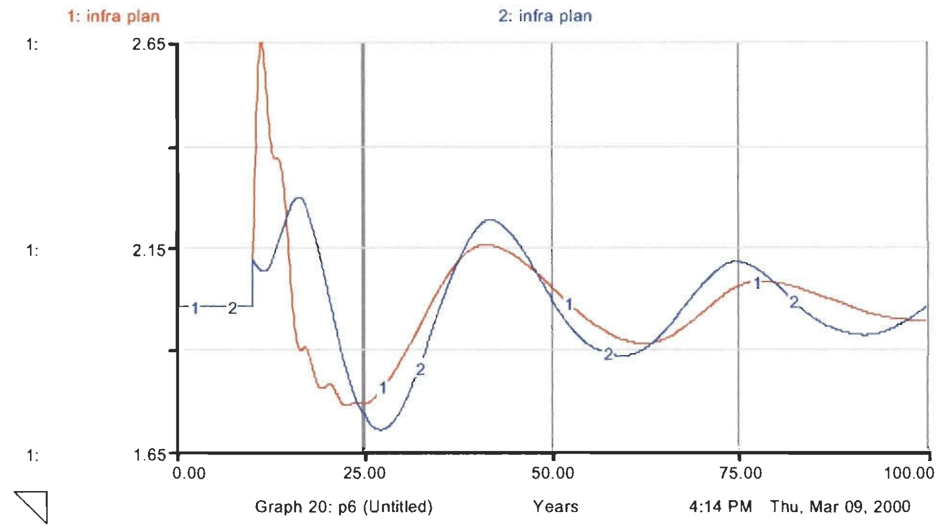


Figure 4.15: Comparative graph of total orders flowing into planning (infra plan) over time. Run 1 uses the original formulation, run 2 smoothes desired infrastructure over 5 years.

Along the same lines as infrastructure inventory in figure 4.14, total orders into planning (infra plan) in figure 4.15 shows that damping infrastructure demand reduces the amplitude of the initial spike. However, the oscillations continue for much longer, with greater amplitude than the original method shown in run 1.

In summary, smoothing the desired infrastructure reduces the magnitude of the fluctuations initially, but as time progresses the insensitivity to small changes in the demand keeps the system from returning to equilibrium. This policy serves to help the problem on the short term, but on the long term it ends up contributing to the dis-equilibrium.

*Chapter 5*

# ANALYSIS OF RESULTS

## Policy Comparison

Much of the thunder of this section has been stolen by the last chapter, therefore only a short policy comparison need be presented below.

The first policy, reducing information delays, kept better track of the current state of investments as they moved through development, attempting to maintain a desired number of projects in both stages, projects in planning, and projects in progress. By keeping better track and establishing desired levels for each stage in the line, over-ordering and under-ordering were minimized thus producing a more stable response to increases in investment.

The second policy, averaging or smoothing demand fluctuations, was designed to reduce the sensitivity of the ordering system to echoes as the economy responded to fluctuations in the stock of infrastructure in use. In the short term this policy reduced the oscillations of the system as it initially responded to a one time increase in spending, but as time progressed, the insensitivity to small changes in demand prolonged the oscillations as the system worked toward equilibrium.

The comparative graphs are presented below. Figure 5.1 looks at average sales, the variable most indicative of the overall health of the system.

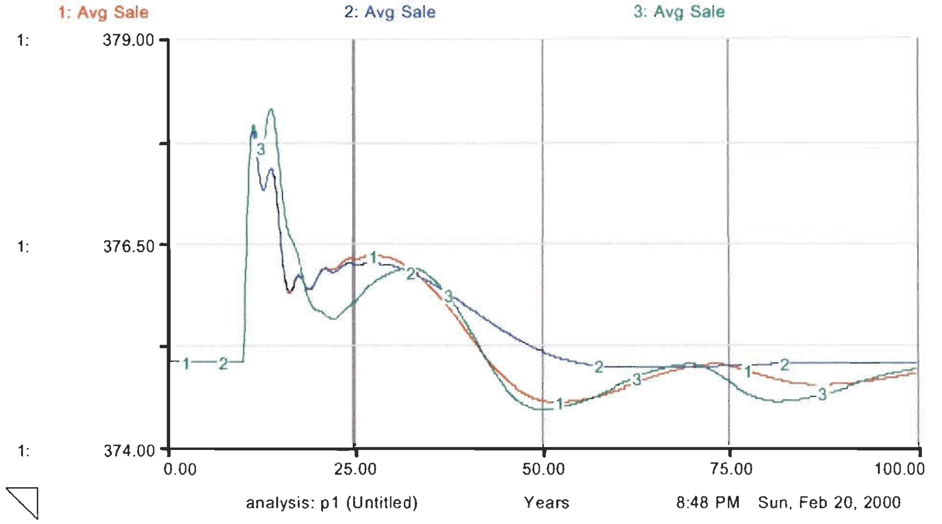


Figure 5.1: Comparative simulation using average sales as an indicator of overall economic health. Run 1 is the original model depicting the problematic oscillations. Run 2 is the model with policy 1 in place, where information delays are reduced through better project tracking. Run 3 applies policy 2, smoothing demand for infrastructure, to the problem.

In terms of average sales, clearly policy 1, at work in run number 2, provides the best solution to the problematic oscillations of the original system (run 1). Policy 2 (run 3) doesn't seem to have much of an effect on the problem from the perspective of average sales, the only change appears to be a slight increase in amplitude and periodicity, coupled with a slight decrease in damping.

Figure 5.2 below continues with the economic indicators, this time looking at the capital output ratio over time for the two policies.

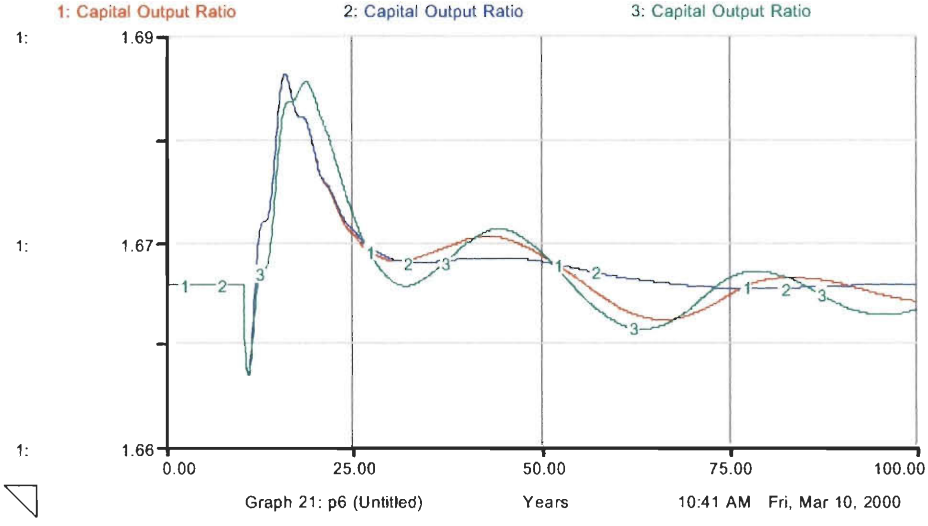


Figure 5.2: Comparative graph using the capital output ratio as an indicator of capacity utilization. Run 1 is the original model depicting the problematic oscillations. Run 2 is the model with policy 1 in place, where information delays are reduced through better project tracking. Run 3 applies policy 2, smoothing demand for infrastructure, to the problem.

In terms of the capital output ratio, which is an indicator of capacity utilization, the first policy produces the smoothest return to equilibrium over the length of the simulation. The second policy produces a positive effect, notice that capacity utilization is greater (the smaller the ratio the better the utilization) at all the troughs for the this policy. However, the second policy has a greater amplitude for the last ¾of the simulation showing that this policy keeps the infrastructure sector from returning to equilibrium as quickly as the other runs.

Figure 5.3 below, compares the two policies on the basis of infrastructure inventory over time.

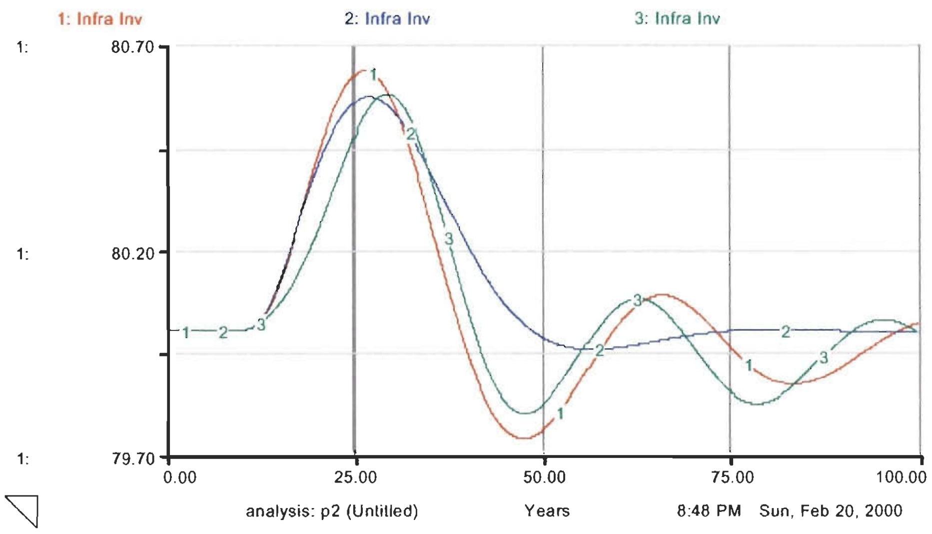


Figure 5.3: Comparative simulation looking at infrastructure inventory over time. Run 1 is the original model depicting the problematic oscillations. Run 2 is the model with policy 1 in place, where information delays are reduced through better project tracking. Run 3 applies policy 2, smoothing demand for infrastructure, to the problem.

Looking at infrastructure inventory, again policy 1 (run 2) shines out as the clear winner, minimizing over/under-ordering and allowing only one cycle before returning to relative equilibrium. Policy 2 (run 3) produces more of a positive effect on the system from this dimension, initially reducing the amplitude of the oscillations. However, again averaging the demand served to make the system less sensitive to small demand fluctuations as the system moved toward equilibrium, thus prolonging the problematic behavior.

Finally, figure 5.4 below presents the two policies side by side in a table format, identifying and explaining the model parameters, what these parameters mean in reality, and summarizing the results of tests conducted on these policies.

| Parameter | Policy in reality | Results explained in words |
|---|---|---|
| Policy 1: Adjusting the weighting function for orders from infrastructure projects in planning and progress from .25 to .75 | Better tracking of the stock of infrastructure projects in planning and in progress as well as the desired level for each of these and using this information to make orders that keep each of the stocks at their desired levels. | By ordering to maintain a desired level at each of the three positions, excessive orders during times of high demand were clipped, low orders were increased in times of over-supply-, and thus oscillations due to the infrastructure sector were minimized on all metrics both infrastructure related as well as economic. |
| Policy 2: Smoothing infrastructure demand over 5 years | Encourage decision-makers to take more time deciding the desired stock of infrastructure as indicated by the economy | Directly after the shock this policy reduced the sensitivity to fluctuations in the economy when determining the desired level of infrastructure and thus the amplitude of many variables was reduced especially the infrastructure variables. However, as the simulation progressed, the insensitivity to small changes in the economy kept the infrastructure sector from settling back down again and thus the cycles were prolonged. This produced longer oscillations in most metrics. |

Figure 5.4: Table comparing the two policies on three dimensions, the model parameter, the application to reality, and the results of the testing.

*Chapter 6*

# CONCLUSIONS AND RECOMENDATAIONS

The following chapter serves to document the recommendations that came as a result of this project. These recommendations are based on the analysis of the model from chapter three, the policy options that were further elaborated on in chapter four, and the analysis of these proposed policies conducted in chapter five. In short, chapter six serves as a summary, demonstrating that the goal of the project has been achieved

## Assumptions

The model used for this analysis is generic, and was not meant to capture the exact behavior of any actual infrastructure system, rather it was designed to emulate a problem shape that seems to affect most all nations.

## Limitations

To begin, it has often been said that there are no perfect models, just adequate ones. The same is true for this model. The model is good and accurately captures the problem within typical pressure based infrastructure ordering systems like the one currently in place in the US system of government. However, more can always be done to improve the model, in this case customizing some of the structure to better replicate that which currently plays a part in the US economic system would be of added benefit. But a warning must be issued, adding detail that does not significantly affect the output will yield very small returns on the time necessary for the development. In other words, there is a point of diminishing returns, and on an extreme scale, if one tries to model the world to capture the exact behavior of ones bathtub filling at 6:30 in the morning on Monday the third day of January in the year 2000, one will soon find that after a couple of months worth of development where the rainfall patterns in Nebraska are now being included in the model, any additional developments will not significantly affect the outcome even though these other distant systems are functioning in reality. So, in short, some customization would be in order, to analyze some of the past decisions in US infrastructure investment policy, but only to a point.

Additional experimentation was conducted where a supply chain to was added to capital formation, but for the sake of clarity those results were not incorporated into the model.

**Best Policy Package and Institutional Recommendations**

After extensive analysis, as was presented in chapters 4 and 5, policy number one was found to be the most effective in minimizing the oscillations that result from increases in infrastructure spending. That policy was aimed at reducing the information delays that plagued the infrastructure ordering system resulting in over-order in times of high demand and under-ordering during low demand, which subsequently produced damped oscillations in the stock of infrastructure in use. In order to reduce these delays, projects were tracked more carefully as they moved through development. More emphasis was placed on maintaining a desired number of projects in the two stages of the infrastructure pipeline, projects in planning, and projects in progress. Excessive orders from discrepancies in the infrastructure inventory were minimized because as the number of projects in planning exceeded the desired level, future orders were reduced in an effort to bring the number of project in planning back to the desired level. In effect this blocked the over-ordering in response to continued high demand as the projects were being constructed. The same is true when these projects finally came on line and eventually produced an infrastructure overstock. So as not to run the development pipeline dry because infrastructure orders from discrepancies in the inventory were well below normal, orders from planning were increased to maintain the desired number of projects in planning, thus balancing the order stream. This dynamic is illustrated below in figure 6.1.

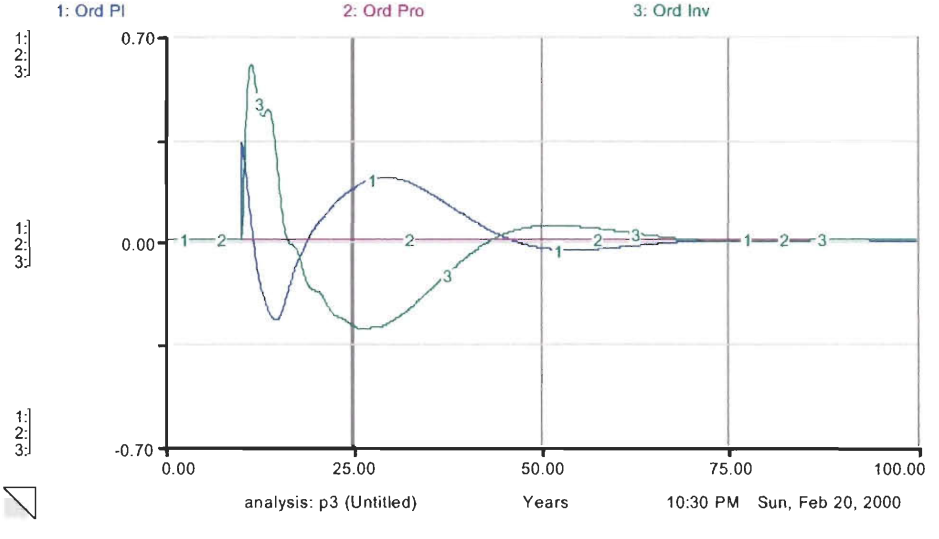


Figure 6.1: Orders from each stage in the infrastructure lifecycle, projects in planning, projects in progress, and infrastructure inventory.

Notice how excessive orders from infrastructure inventory are partially balanced by reductions in orders from infrastructure in planning and visa versa, so that the aggregate orders are much more stable than they would have been had discrepancies in inventory versus the desired inventory been used to determine the new orders. The comparative graph of average sale over time in figure 6.2 below shows the effect of this policy on the simulated economy.

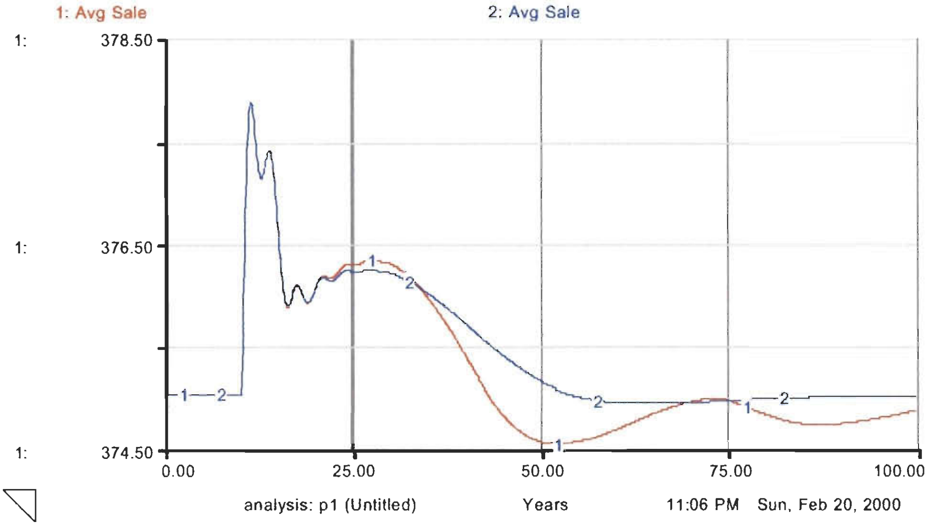


Figure 6.2: Comparative graph of average sales over time. Run 1 showing the original problematic oscillations in response to an increase in infrastructure spending. Run 2 demonstrating the effect of reducing information delays by better tracking of projects in the development pipeline.

As run 2 in figure 6.2 plainly shows, this policy dramatically minimizes the oscillations that result from one time increases in infrastructure spending, when compared to the original system simulated in run 1.

As far as institutional recommendations, this policy suggests that a department be created with the sole purpose of monitoring the infrastructure supply chain. Specifically, this department would look at the current number of projects in planning and in progress, determine what the desired levels should be and then adjust the new orders accordingly. These levels, of course, cannot be calculated exactly, this fact was reflected in the model with the weighting fractions which captured the uncertainty. The model shows, however, that even when these values are estimated, the improvements can be dramatic.

**General Conclusions**

Generalizing the learning that resulted from this project would produce one very important recommendation that spans not just infrastructure policy but public decision-making as a whole. When working with problems, we must not rely on untested assumptions and from these assumptions make policies simply because we know the problem exists. The problem at hand must be analyzed and the structure responsible must be understood before embarking on any policy aimed at modification. This method of problem solving will minimize additional unintended consequences producing fewer failed policies and increasing the efficiency of the decision-making process.

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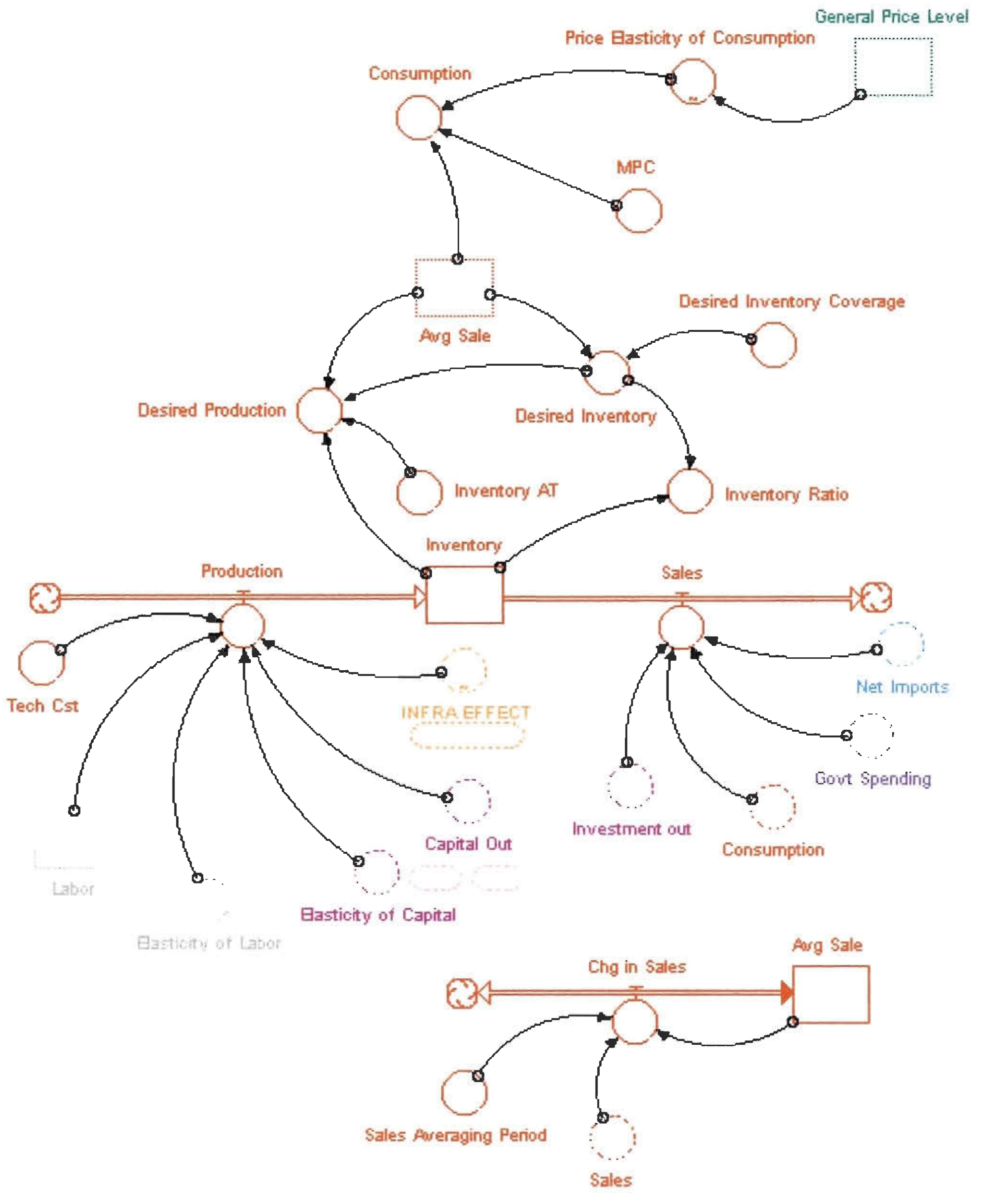
## APPENDIX A: SYSTEM DYNAMICS MODEL EQUATIONS




Aggregate Supply and Demand Sector

**Aggregate Supply and Demand**

Avg_Sale(t) = Avg_Sale(t - dt) + (- Chg_in_Sales) * dt
INIT Avg_Sale = 375

DOCUMENT: The average total sales per year. In terms of the US economy, for example, this would be equivalent to the gross national product. This stock is initialized to 375 so that the model operates in dynamic equilibrium until disturbed

OUTFLOWS:

Chg_in_Sales = ( - Sales + Avg_Sale ) / Sales_Averaging_Period

DOCUMENT: Adjustments to average sales. This is a function of the difference between the average sales and the current sales (Sales) all divided by the Sales Averaging Period.

Inventory(t) = Inventory(t - dt) + (Production - Sales) * dt
INIT Inventory = Desired_Inventory

DOCUMENT: The aggregated national inventory. This stock is initialized in equilibrium at the Desired_Inventory.

INFLOWS:

Production = Tech_Cst * ( Labor ^ Elasticity_of_Labor ) * ( Capital_Out^ Elasticity_of_Capital ) * INFRA_EFFECT

DOCUMENT: Aggregated production. This is a function of the technology constant multiplied by labor, which was corrected by the elasticity of labor, by capital (Capital_Out), which was corrected by the elasticity of capital, and finally multiplied by the effect of infrastructure on production (INFRA_EFFECT).

OUTFLOWS:

Sales = Consumption + Govt_Spending + Investment_out - Net_Imports

DOCUMENT: The aggregated sales. This is the sum of all Consumption, Government Spending, and Investments in capital (Investment_Out), less the Net Imports.

Consumption = Avg_Sale * MPC * Price_Elasticity_of_Consumption

DOCUMENT: Use of goods and services. This is a function of the average sales, multiplied by the marginal propensity to consume, thus giving the normal consumption. This normal consumption is then multiplied by the Price_Elasticity_of_Consumption to adjust for the effect of the general price level on consumption.

Desired_Inventory = Avg_Sale * Desired_Inventory_Coverage

DOCUMENT: The desired aggregated national inventory. This is a function of the average sales for that particular year multiplied by the desired number of years worth of average sales to keep in inventory at any given time (Desired_Inventory_Coverage)

Desired_Inventory_Coverage = 0.5

DOCUMENT: The desired level of inventory coverage. Or the number of years worth of units at the current average level of sales. In this case, the desired level of inventory coverage is ½of a year's worth of average sales.

Desired_Production = Avg_Sale + ( Desired_Inventory - Inventory ) / Inventory_AT

DOCUMENT: The desired level of production. This is a function of the average sales per year in the past plus any adjustments to the inventory. The inventory adjustments are calculated by taking the desired inventory less the actual inventory all divided by the time it takes to make adjustments to the inventory (Inventory_AT).

Inventory_AT = .5

DOCUMENT: Inventory adjustment time. The average amount of time necessary to make adjustments to the inventory via adjustments to the production.

Inventory_Ratio = Inventory / Desired_Inventory

DOCUMENT: The ratio of actual inventory over desired inventory. When there is an inventory oversupply the ratio will be greater than 1, and when an undersupply exists, the ratio will be less than 1

level_375 = 375

DOCUMENT: Testing variable.

level_80 = 80

DOCUMENT: Testing variable.

MPC = 237.5/375

DOCUMENT: The fraction of average sales normally due to consumption.

Net_Inv_Chg = Production - Sales

DOCUMENT: Testing variable.

Net_Prod_Pres = Desired_Production - Production

DOCUMENT: Testing variable.

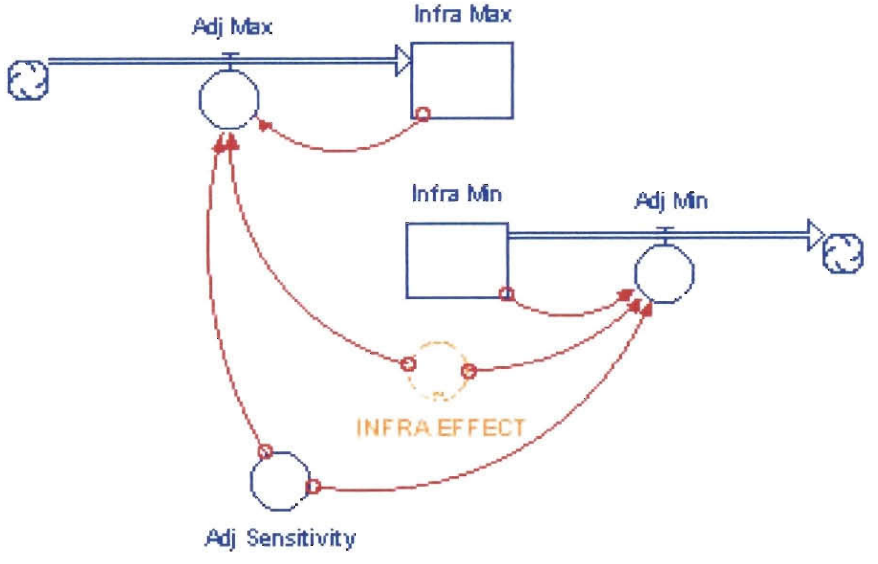
○ Pulse_time_25 = Pulse ( 1 , Step_Time ,25 )
DOCUMENT: Testing variable.

○ Sales_Averaging_Period = 2
DOCUMENT: The number of years used to calculate the average sales. In other words, Average Sales is a 2 year average of the actual sales.

○ Tech_Cst = 375 / ( EXP( 0.75 * LOGN( 0.75 * 375 / 10 ) ) * EXP( 0.25 * LOGN( 0.25 * 375 / 0.15 ) ) )

○ Zero = 0
DOCUMENT: Testing variable.

⊘ Price_Elasticity_of_Consumption = GRAPH(General_Price_Level)
(0.00, 2.00), (0.25, 1.60), (0.5, 1.32), (0.75, 1.14), (1.00, 1.00), (1.25, 0.88), (1.50, 0.79), (1.75, 0.71), (2.00, 0.66), (2.25, 0.62), (2.50, 0.6)
DOCUMENT: The effect of General Price Level (GPL) on Consumption. When GPL is less than 1, indicating under-pricing, the effect will be greater than 1, pushing consumption above normal levels. When GPL is less than 1, indicating over-pricing, the effect will be less than 1, reducing consumption below normal levels.



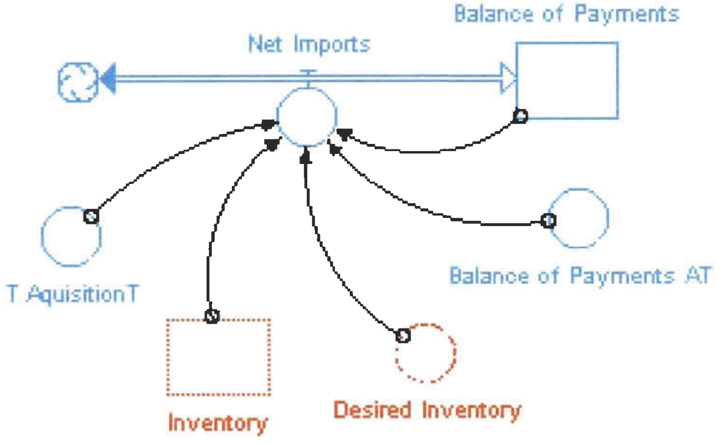

Analysis Sector

**Analysis**

Infra_Max(t) = Infra_Max(t - dt) + (Adj_Max) * dt
INIT Infra_Max = INFRA_EFFECT
INFLOWS:
Adj_Max = ( INFRA_EFFECT - Infra_Max ) * Adj_Sensitivity

Infra_Min(t) = Infra_Min(t - dt) + (- Adj_Min) * dt
INIT Infra_Min = INFRA_EFFECT
OUTFLOWS:
Adj_Min = ( Infra_Min - INFRA_EFFECT ) * Adj_Sensitivity

Adj_Sensitivity = 15




Balance of Payments Sector

**Balance of Payments**

Balance_of_Payments(t) = Balance_of_Payments(t - dt) + (Net_Imports) * dt

INIT Balance_of_Payments = 0

DOCUMENT: The current balance of payments from imports/exports. When this stock is positive, payments need to be made out, when this stock is negative, payments are due in. This stock is initialized in equilibrium at 0.

INFLOWS:

Net_Imports = ( ( Desired_Inventory - Inventory ) / T_AquisitionT ) - ( Balance_of_Payments / Balance_of_Payments_AT )

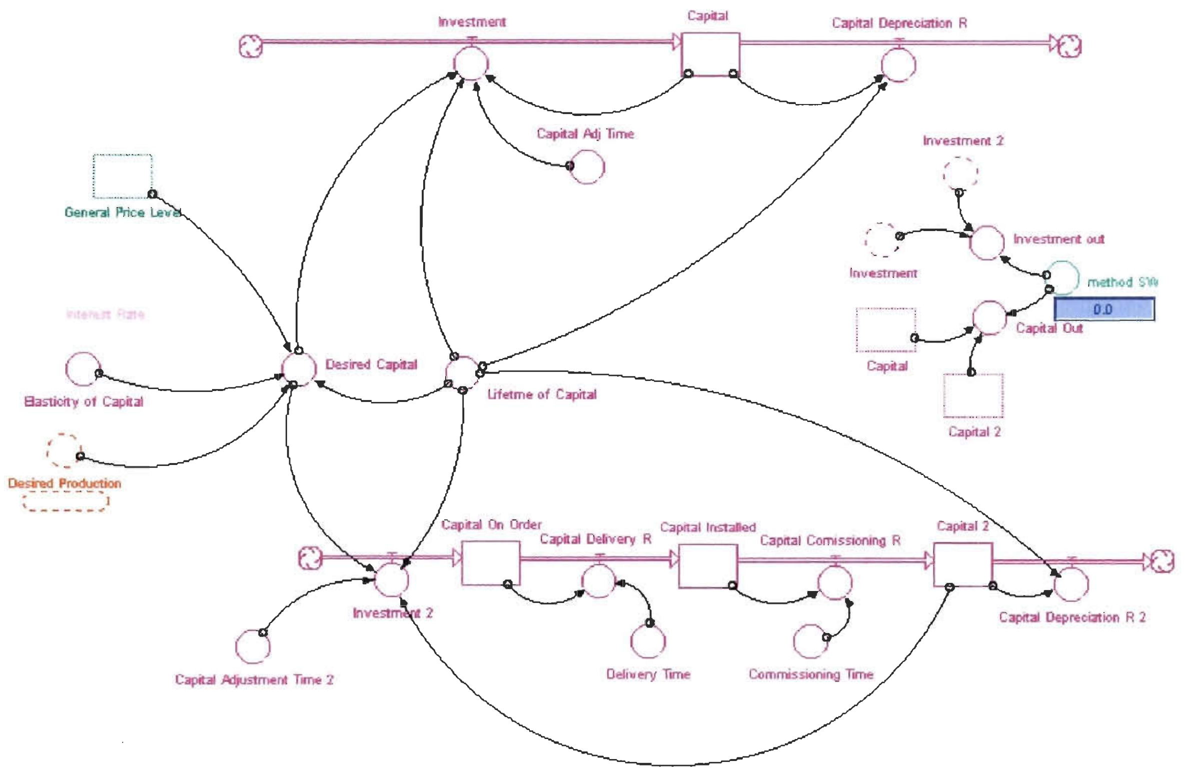
DOCUMENT: Net adjustments to the current import/export balance. Imports are a liability (we have to pay for them), exports are a negative liability (we get paid for these) thus the net imports is the imports less the exports. This does not take place instantaneously, but rather over time. First the net imports for that year are calculated by taking the desired inventory less the actual inventory all over an adjustment time. Inventory undersupply would result in imports to cover the difference, and an oversupply would result in exports. Finally the payments on the balance must also be subtracted from the net imports, and thus payments are calculated as the current balance (Balance_of_Payments) divided by the average time necessary to pay the balance off, or in the case of a negative balance, to be paid back (Balance_of_Payments_AT).

- Balance_of_Payments_AT = 2

  DOCUMENT: The time years that it takes to make adjustments to the current total of exports less imports.

- T_AquisitionT = 2

  DOCUMENT: The total aquisition time. The amount of time in years necessary to make up temporary shortages or excesses in Inventory compared to Desired Inventory, by using imports and exports.




Capital Sector

**Capital**

Capital(t) = Capital(t - dt) + (Investment - Capital_Depreciation_R) * dt

INIT Capital = Desired_Capital

DOCUMENT: The current stock of Capital. This is initialized in equilibrium at the Desired_Capital.

INFLOWS:

Investment = Capital / Lifetme_of_Capital + ( Desired_Capital - Capital ) / Capital_Adj_Time

DOCUMENT: Yearly investment in capital. This is a function of the capital depreciation of that year (Capital / Lifetime_of_Capital) plus new net investments, the Desired_Capital less the actual Capital all divided by the time it takes to make adjustments to the stock of capital (Capital Adjustment time).

OUTFLOWS:

Capital_Depreciation_R = Capital/Lifetme_of_Capital

DOCUMENT: The rate of capital depreciation per year. This is a function of the stock of capital divided by the average lifespan of capital (Lifetime_of_Capital = 10 years), thus every year 1/10 of the stock of capital is depreciated.

Capital_2(t) = Capital_2(t - dt) + (Capital_Comissioning_R - Capital_Depreciation_R_2) * dt

INIT Capital_2 = Desired_Capital

DOCUMENT: The current stock of Capital. This is initialized in equilibrium at the Desired_Capital.

INFLOWS:

Capital_Comissioning_R = Capital_Installed / Commissioning_Time

DOCUMENT: The rate at which capital investments are commissioned. This is a function of the stock of investments the have been delivered and setup (Capital_Installed) divided by the time it takes to commission these projects (Commissioning_Time).

OUTFLOWS:

Capital_Depreciation_R_2 = Capital_2 / Lifetme_of_Capital

DOCUMENT: The rate of capital depreciation per year. This is a function of the stock of capital divided by the average lifespan of capital (Lifetime_of_Capital = 10 years), thus every year 1/10 of the stock of capital is depreciated.

Capital_Installed(t) = Capital_Installed(t - dt) + (Capital_Delivery_R - Capital_Comissioning_R) * dt

INIT Capital_Installed = Desired_Capital * ( Commissioning_Time / Lifetme_of_Capital )

DOCUMENT: The stock of capital investments which have been delivered and installed. This stock is initialized in equilibrium with 4/10ths of the desired capital. Which is simply the share of investments that have been installed as compared to the total number of investments. The fraction comes from the amount of time the average investment spends being commissioned (Commissioning_Time) compared to the average lifetime of the investment from initial investment to depreciation (Lifetime_of_Capital).

INFLOWS:

Capital_Delivery_R = Capital_On_Order / Delivery_Time

DOCUMENT: The rate at which capital investments are delivered. This is a function of the stock of investments on order (Capital_On_Order) divided by the time it takes to deliver these orders (Delivery_Time).

OUTFLOWS:

Capital_Comissioning_R = Capital_Installed / Commissioning_Time

DOCUMENT: The rate at which capital investments are commissioned. This is a function of the stock of investments the have been delivered and setup (Capital_Installed) divided by the time it takes to commission these projects (Commissioning_Time).

Capital_On_Order(t) = Capital_On_Order(t - dt) + (Investment_2 - Capital_Delivery_R) * dt
INIT Capital_On_Order = Desired_Capital * ( Delivery_Time / Lifetme_of_Capital )

DOCUMENT: The stock of capital investments currently on order. This stock is initialized in equilibrium with 4/10ths of the desired capital. Which is simply the share of investments that are on order as compared to the total number of investments. The fraction comes from the amount of time the average investment spends as an order compared to the average lifetime of the investment from initial investment to depreciation.

INFLOWS:

Investment_2 = Capital_2 / Lifetme_of_Capital + ( Desired_Capital - Capital_2 ) / Capital_Adjustment_Time_2

DOCUMENT: Yearly investment in capital. This is a function of the capital depreciation of that year (Capital_2 / Lifetime_of_Capital) plus new net investments, the Desired_Capital less the actual Capital_2 all divided by the time it takes to make adjustments to the stock of capital (Capital Adjustment time_2).

OUTFLOWS:

Capital_Delivery_R = Capital_On_Order / Delivery_Time

DOCUMENT: The rate at which capital investments are delivered. This is a function of the stock of investments on order (Capital_On_Order) divided by the time it takes to deliver these orders (Delivery_Time).

Capital_Adjustment_Time_2 = 5

DOCUMENT: The average number of years necessary to make changes in the stock of capital.

Capital_Adj_Time = 5

DOCUMENT: The average number of years necessary to make changes in the stock of capital.

Capital_Out = Capital * ( 1 - method_SW ) + Capital_2 * method_SW

DOCUMENT: The stock of capital. This converter serves as the output of the sector allowing the modeler to switch between the two formulations of capital structure. When the switch (method_SW) is equal to 0 the original formulation is used (Capital), and when the switch is equal to 1 the second formulation is used (Capital_2)

Commissioning_Time = 4

DOCUMENT: The average number of years it takes for a capital investment to be commissioned after it is delivered.

Delivery_Time = 4

DOCUMENT: The average number of years it takes for a capital investment order to be delivered.

Desired_Capital = Elasticity_of_Capital * Desired_Production / ( Interest_Rate * General_Price_Level + ( 1 / Lifetme_of_Capital ) )

DOCUMENT: The desired level of capital.

Elasticity_of_Capital = .25

DOCUMENT: Elasticity of Capital

Parent: Capital

Ghost in: Aggregate Supply and Demand, Employment

Investment_out = Investment * ( 1 - method_SW ) + Investment_2 * method_SW

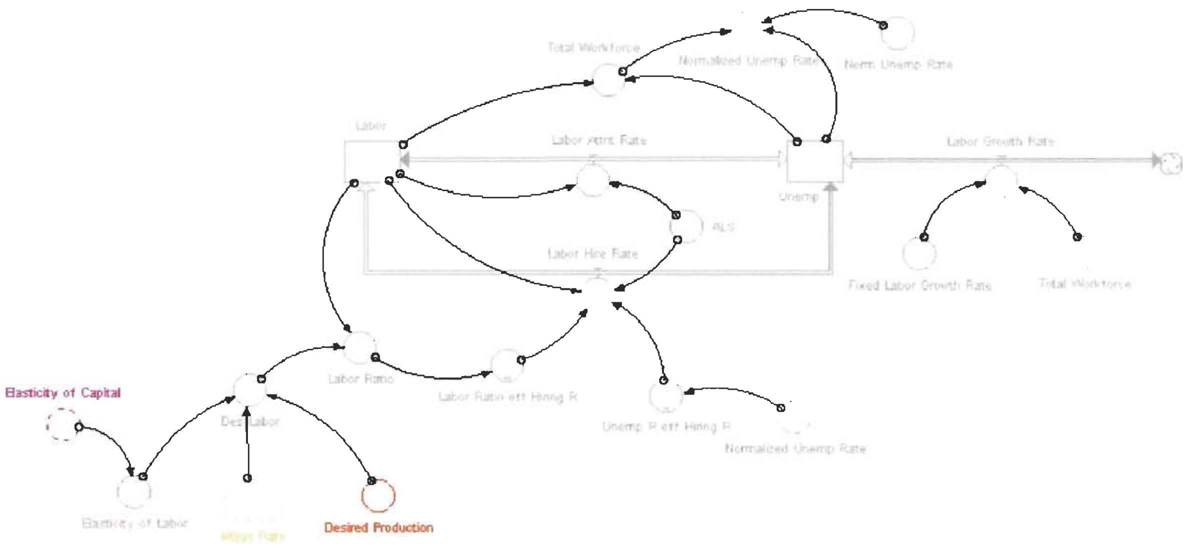
DOCUMENT: The current level of capital investment. This converter serves as the output of the sector allowing the modeler to switch between the two formulations of capital structure. When the switch (method_SW) is equal to 0 the original formulation is used (Investment), and when the switch is equal to 1 the second formulation is used (Investment_2)

Lifetme_of_Capital = 10

DOCUMENT: The average lifespan of a capital investment in years.

method_SW = 0

DOCUMENT: Switches between two formulations of capital structure. When the switch (method_SW) is equal to 0 the original formulation is used, and when the switch is equal to 1 the second formulation is used. The original formulation uses only one stock and the second formulation disaggregates the process of receiving new orders, including some new supply chain dynamics.




Employment Sector

**Employment**

☐ Labor(t) = Labor(t - dt) + (Labor_Hire_Rate - Labor_Attrit_Rate) * dt

INIT Labor = Des_Labor

DOCUMENT: The stock of people currently employed, the labor force. This is initialized at the desired level of labor (Des_Labor) thus placing the stock in equilibrium.

INFLOWS:

Labor_Hire_Rate = (Labor/ALS)*Labor_Ratio_eff_Hiring_R*Unemp_R_eff_Hiring_R

OUTFLOWS:

Labor_Attrit_Rate = (Labor/ALS)

☐ Unemp(t) = Unemp(t - dt) + (Labor_Attrit_Rate + Labor_Growth_Rate - Labor_Hire_Rate) * dt

INIT Unemp = Des_Labor * ( .2 / ( 1 - .2 ) )

DOCUMENT: The stock of people currently unemployed. This is initialized in equilibrium by taking the desired labor force (Des_Labor) and since the normal unemployment rate is set to .20, the desired labor force would be 1 minus the unemployment rate or .80 and thus to calculate the number of unemployed workers we would multiply desired labor times the unemployment rate over the employment rate, producing the number of unemployed workers.

INFLOWS:

Labor_Attrit_Rate = (Labor/ALS)

Labor_Growth_Rate = Total_Workforce * Fixed_Labor_Growth_Rate

DOCUMENT: The rate at which new labor enters the market. This is a function of the total workforce multiplied by the fixed labor growth rate (for this analysis, the fixed labor growth rate is equal to 0, capturing an employment sector where those that retire are matched by the new entrants creating a net flow of zero).

OUTFLOWS:

Labor_Hire_Rate = (Labor/ALS)*Labor_Ratio_eff_Hiring_R*Unemp_R_eff_Hiring_R

ALS = 5

Des_Labor = Elasticity_of_Labor * ( Desired_Production / Wage_Rate )

Elasticity_of_Labor = 1-Elasticity_of_Capital

DOCUMENT: The elasticity of labor. This is simply 1 minus the elasticity of capital.

Fixed_Labor_Growth_Rate = 0

DOCUMENT: The rate of labor growth as a fraction of the total workforce. For this analysis, the fixed labor growth rate is equal to 0, capturing an employment sector where those that retire are matched by the new entrants creating a net growth rate of zero.

Labor_Ratio = Des_Labor / Labor

DOCUMENT: The ratio between desired labor and the actual labor force. When the actual labor force is greater than the desired, the fraction will be less than 1. When actual is equal to the desired, the fraction will be equal to 1. As the actual falls below the desired, the fraction will be greater than 1. This fraction is used to determine the effect of labor on the hiring rate.

Normalized_Unemp_Rate = ( Unemp / Total_Workforce ) / Norm_Unemp_Rate

DOCUMENT: The normalized unemployment rate. This is fractionalized so that when the actual unemployment rate (Unemp / Total_Workforce) exceeds the normal rate (Norm_Unemp_Rate), the fraction is greater than one. When actual equals normal the system is in equilibrium and the fraction is equal to 1. As the actual falls below the normal, the fraction returns a number less than one.

Norm_Unemp_Rate = .2

DOCUMENT: The normal unemployment rate.

Total_Workforce = Labor + Unemp

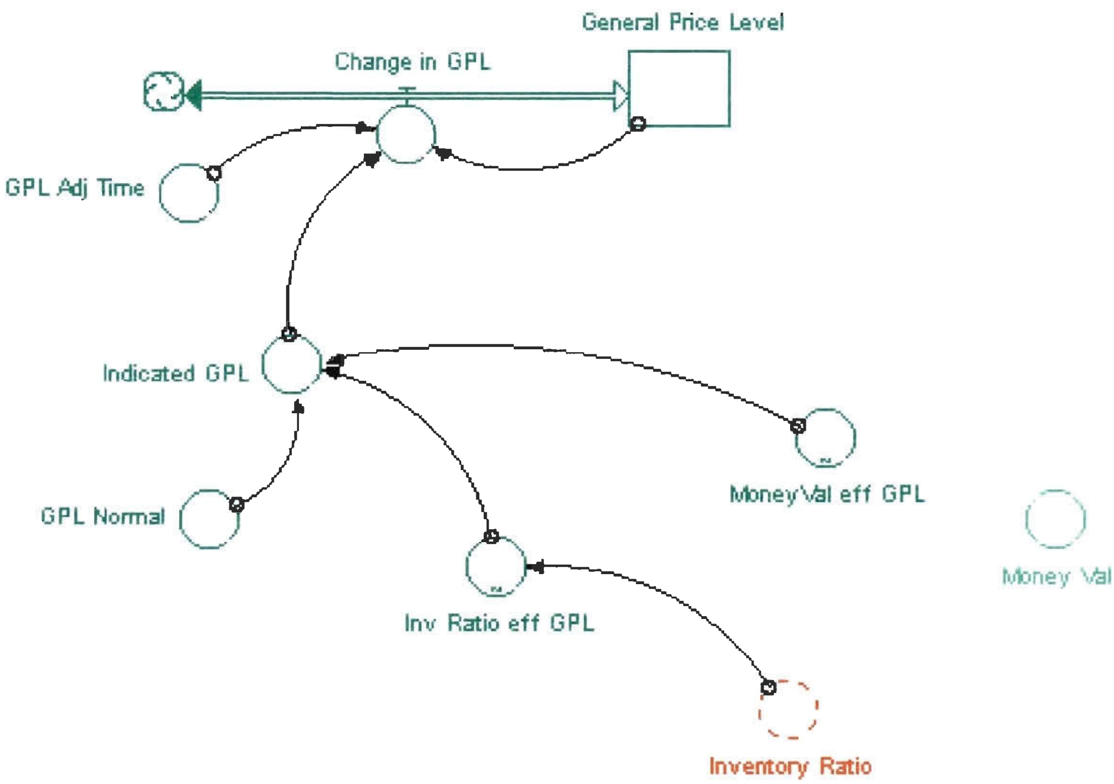
DOCUMENT: The total number of workers. This is simply the employed labor force (Labor) plus the unemployed labor force (Unemp).

Labor_Ratio_eff_Hiring_R = GRAPH(Labor_Ratio)
(0.00, 2.72e-317), (0.25, 0.04), (0.5, 0.16), (0.75, 0.46), (1.00, 1.00), (1.25, 2.02), (1.50, 2.88), (1.75, 3.40), (2.00, 3.70), (2.25, 3.88), (2.50, 4.00)

DOCUMENT: The effect of the labor ratio (desired/actual) on hiring. As the labor ratio falls below 1, indicating a labor oversupply, the effect will be to reduce the normal hiring rate. When the labor ratio is equal to 1, showing that stock of labor is at it's optimal level, the normal hiring rate will be used. As the labor ratio moves above 1, indicating a labor shortage, the normal hiring rate is increased.

Unemp_R_eff_Hiring_R = GRAPH(Normalized_Unemp_Rate)
(0.00, 3.11e-317), (0.1, 0.26), (0.2, 0.475), (0.3, 0.635), (0.4, 0.755), (0.5, 0.835), (0.6, 0.9), (0.7, 0.94), (0.8, 0.975), (0.9, 0.99), (1.00, 1.00)

DOCUMENT: The effect of unemployment on the hiring rate. As the normalized unemployment rate falls below 1, indicating that unemployment is below normal, the hiring rate would be reduced because of a smaller supply of able workers. As the normalized unemployment rate falls to 0 there will be no workers to hire and the hiring rate would thus be 0. This effect is a 0 to 1 multiplier on the indicated hiring rate, thus the hiring rate is only a fraction of what it would normally be when the unemployment rate falls below 0.




General Price Level Sector

**General Price Level**

General_Price_Level(t) = General_Price_Level(t - dt) + (Change_in_GPL) * dt
INIT General_Price_Level = GPL_Normal

DOCUMENT: General Price Level

Parent: Genral Price Level

Ghosts in: Capital, Aggregate Supply and Demand

INFLOWS:

Change_in_GPL = ( Indicated_GPL - General_Price_Level ) / GPL_Adj_Time

DOCUMENT: The change in general price level. This is a function of the indicated less the actual general price level, all over the GPL adjustment time, which makes these changes over the course of half a year.

GPL_Adj_Time = .5

DOCUMENT: The time, in years, is takes to make changes in response to a discrepancy between the indicated GPL and the actual

GPL_Normal = 1

DOCUMENT: The normal General Price Level

Indicated_GPL = GPL_Normal * Inv_Ratio_eff_GPL * MoneyVal_eff_GPL

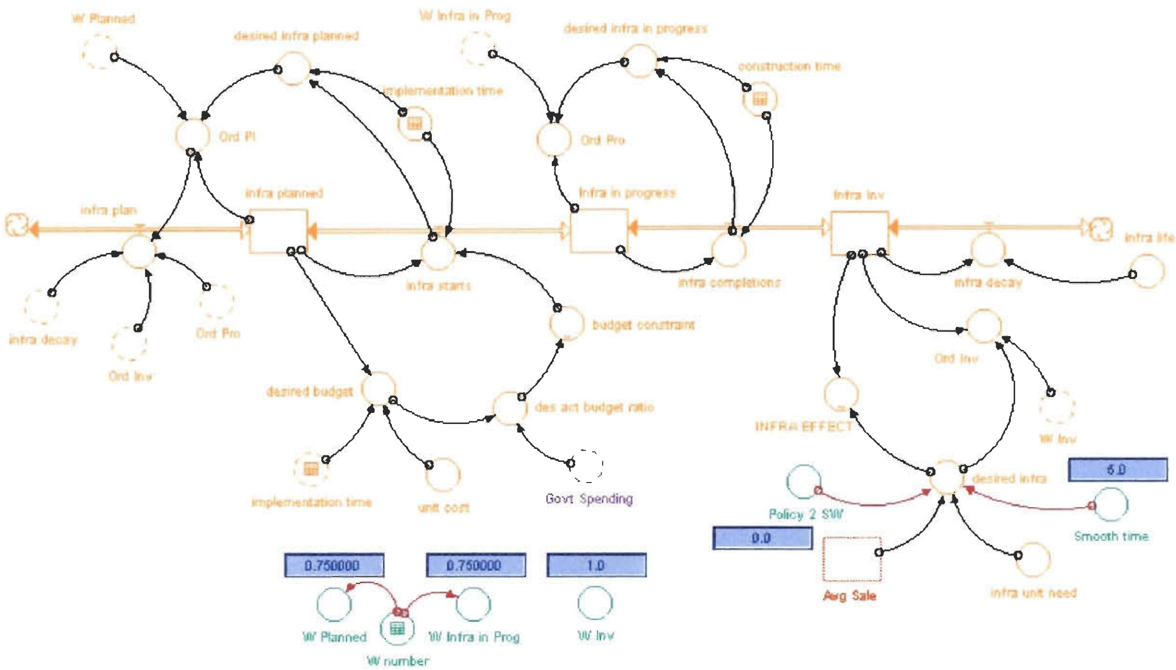
DOCUMENT: The General Price Level (GPL) indicated by the economy. This is a function of the normal GPL, multiplied by two effectors, the Effect of the Inventory Ratio (Actual Inventory over Desired Inventory), and the Effect of the value of money (desired money stock over the total money stock). These two effects either increase or decrease the Normal GPL to produce the Indicated GPL for that particular year.

Inv_Ratio_eff_GPL = GRAPH(Inventory_Ratio)
(0.00, 4.00), (0.5, 1.80), (1.00, 1.00), (1.50, 0.66), (2.00, 0.46), (2.50, 0.34), (3.00, 0.28), (3.50, 0.24), (4.00, 0.22), (4.50, 0.2), (5.00, 0.18)

DOCUMENT: The effect of the Inventory Ratio on the General Price Level (GPL). In this case when the inventory ratio falls below 1, indicating an undersupply of inventory, the effect returns a number greater than 1, pushing the general price level above normal. When the inventory ratio rises above 1, indicating an oversupply of inventory in relation to the desired, the effect will fall below 1, deflating the normal GPL.

MoneyVal_eff_GPL = GRAPH(Money_Val)
(0.00, 2.00), (0.2, 1.70), (0.4, 1.50), (0.6, 1.30), (0.8, 1.15), (1.00, 1.00), (1.20, 0.88), (1.40, 0.79), (1.60, 0.72), (1.80, 0.68), (2.00, 0.66)

DOCUMENT: The effect of the value of money (Money_Val) on the General Price Level (GPL). In the case where Money Val (Desired Money Stock over Total Money Stock) falls below 1, indicating an oversupply of money, the effect will be greater than 1, thus inflating the normal GPL. In the case where Money Val is greater than 1, indicating an undersupply of money, the effect will be less than one, deflating the normal GPL.




Infrastructure Sector

**Infrastructure**

Infra_Inv(t) = Infra_Inv(t - dt) + (infra_completions - infra_decay) * dt

INIT Infra_Inv = infra_unit_need * 375

DOCUMENT: The stock of infrastructure projects currently in the use. This stock is initialized to the amount of infrastructure needed per unit of average sale (infra_unit_need), multiplied by average sale at equilibrium (375).

INFLOWS:

infra_completions = Infra_in_progress / construction_time

DOCUMENT: The number of projects being completed every year (infra_completions) is a function of the number of projects currently in construction (Infra_in_progress) over the time necessary to construct the average project (construction_time). In other words it takes 10 years (construction_time) to bring all the projects currently under construction to completion. Thus every year 1/10 of the projects are completed and move on to serve in the stock of infrastructure in use (infra_inv).

OUTFLOWS:

infra_decay = Infra_Inv / infra_life

DOCUMENT: The rate at which infrastructure projects wear out and become obsolete. This is a function of the stock of infrastructure currently in use (Infra_Inv) divided by the average lifetime of a project (infra_life = 40 years). Thus since the average life of a project is 40 years, 1/40 of the stock of infrastructure will decay each year.

Infra_in_progress(t) = Infra_in_progress(t - dt) + (infra_starts - infra_completions) * dt

INIT Infra_in_progress = infra_decay * construction_time

DOCUMENT: The stock of infrastructure projects currently in the construction phase. This stock is initialized to 10 years worth of work (construction_time) at the current rate of infrastructure project obsolescence (infra_decay).

INFLOWS:

infra_starts = ( infra_planned / implementation_time ) * budget_constraint

DOCUMENT: The rate at which projects leave planning and enter construction (infra_starts) is a function of the number of projects currently in planning (infra_planned) over the amount of time it takes to push the average project through planning (implementation_time). Essentially this is saying that only 1/5 of the projects are completed ever year because it takes 5 years to complete the average project. This number of projects ready to enter the construction phase is then multiplied by the budget constraint. If there is enough money for all the projects (budget_constraint = 1) then all the projects that are ready will begin construction. If the there are more projects ready than the budget will allow (budget_constraing < 1) only a fraction of the projects ready for construction will move on to construction, the rest will remain in planning. If there is more money available than is necessary (budget_constraing > 1), more projects than normal will be pushed into construction to make use of the surplus.

OUTFLOWS:

infra_completions = Infra_in_progress / construction_time

DOCUMENT: The number of projects being completed every year (infra_completions) is a function of the number of projects currently in construction (Infra_in_progress) over the time necessary to construct the average project (construction_time). In other words it takes 10 years (construction_time) to bring all the projects currently under construction to completion. Thus every year 1/10 of the projects are completed and move on to serve in the stock of infrastructure in use (infra_inv).

infra_planned(t) = infra_planned(t - dt) + (infra_plan - infra_starts) * dt

INIT infra_planned = infra_decay * implementation_time

DOCUMENT: The stock of infrastructure projects currently in the planning phase. This stock is initialized to 5 years worth of work (implementation time) at the current rate of infrastructure project obsolescence (infra decay).

INFLOWS:

infra_plan = Ord_Pl + Ord_Pro + Ord_Inv + infra_decay

DOCUMENT: This flow takes orders from planning, production, current inventory and the rate of decay, summing them up to produce the number of new project orders for each individual year. These then flow into the stock of infrastructure projects in planning.

OUTFLOWS:

infra_starts = ( infra_planned / implementation_time ) * budget_constraint

DOCUMENT: The rate at which projects leave planning and enter construction (infra_starts) is a function of the number of projects currently in planning (infra_planned) over the amount of time it takes to push the average project through planning (implementation_time). Essentially this is saying that only 1/5 of the projects are completed ever year because it takes 5 years to complete the average project. This number of projects ready to enter the construction phase is then multiplied by the budget constraint. If there is enough money for all the projects (budget_constraint = 1) then all the projects that are ready will begin construction. If the there are more projects ready than the budget will allow (budget_constraing < 1) only a fraction of the projects ready for construction will move on to construction, the rest will remain in planning. If there is more money available than is necessary (budget_constraing > 1), more projects than normal will be pushed into construction to make use of the surplus.

○ construction_time = 10

DOCUMENT: The average number of years it takes to construct one project.

○ desired_budget = ( infra_planned / implementation_time ) * unit_cost

DOCUMENT: The desired budget it simply the number of projects that are leaving planning and moving on to construction (infra planned divided by the implementation time) multiplied by the cost per unit. This is the money necessary to put all the projects that are ready to enter construction completely through this phase and into service.

○ desired_infra = ( Avg_Sale * infra_unit_need ) * (1 - Policy_2_SW ) + SMTH3( ( Avg_Sale * infra_unit_need ), Smooth_time ) * Policy_2_SW

DOCUMENT: The desired level of infrastructure in use. Desired infrastructure is a function of the average level of sales (Avg_Sale) multiplied by the number of units needed for every unit of average sale (infra_unit_need). While testing Policy #2 where the desired infrastructure is smoothed over time, the equation below was expanded. On the left the original formulation is used ( Avg_Sale * infra_unit_need ) * (1 - Policy_2_SW ), this is turned on an off by the switch Policy_2_SW (where 0 is original formulation and 1 is smooth formulation). On the right appears the new formulation, SMTH3( ( Avg_Sale * infra_unit_need ), Smooth_time ) * Policy_2_SW. SMTH3 is a third order smoothing function that takes the input Avg_Sale * infra_unit_need and averages this over the averaging time (Smooth_time). This function is switched with Policy_2_SW as well (where 0 is original formulation and 1 is smooth formulation).

○ desired_infra_in_progress = infra_completions * construction_time

DOCUMENT: The desired number of projects currently in construction is a function of the number of projects being completed per year (infra_completions) multiplied by the number of years it takes to construct the average project. Keeping 10 years (construction_time) worth of projects in construction maximizes the efficiency of the process.

○ desired_infra_planned = infra_starts * implementation_time

DOCUMENT: Desired number of infrastructure projects in planning is a function of the number of infra starts multiplied by the implementation time. Essentially this means that we want to keep 5 years (the implementation time) worth of projects in the stock at the current rate of projects leaving planning and entering production (infra starts).

○ des_act_budget_ratio = min ( Govt_Spending / desired_budget , 2 )

DOCUMENT: The desired actual budget ratio is the ratio between how much money is available (Govt_Spending) and what is needed to start construction on all the projects that are ready (desired_budget). If there is more money than is necessary the ratio is above 1, if there is less then the ratio is less than one. The ratio is bounded mathematically by 0 because both government spending and the desired budget will always be positive. The ratio is bounded with a logic statement (min() ) at 2 to eliminate great excesses in the ratio where spending is much higher than desired. This is simply a flow control for the graphical function that follows so that values do not exceed the input parameters. In other words we want to limit the ratio so that when there is an excess we want to spend it to a point, but there are problems using ratios because they are not symmetrical, one runs to 0 the other to infinity centered at 1.

○ implementation_time = 5

DOCUMENT: The number of years it takes for the average project to make it's way through the planning process.

○ Infra_discrepancy = desired_infra - Infra_Inv

DOCUMENT: The difference between desired level of infrastructure in use (desired_infra) less the actual level of infrastructure in use (infra_inv). This is simply an analysis converter designed to determine when a stock is out of equilibrium and the magnitude of this discrepancy.

○ Infra_in_progress_disc = desired_infra_in_progress - Infra_in_progress

DOCUMENT: The difference between desired level of infrastructure under construction (desired_infra_ in_progress) less the actual level of infrastructure under construction (infra_in_progress). This is simply an analysis converter designed to determine when a stock is out of equilibrium and the magnitude of this discrepancy.

○ infra_life = 40

DOCUMENT: The average lifetime of a project.

○ Infra_planned_disc = desired_infra_planned - infra_planned

DOCUMENT: The difference between desired level of infrastructure in planning (desired_infra_planned) less the actual level of infrastructure in planning (infra_planned). This is simply an analysis converter designed to determine when a stock is out of equilibrium and the magnitude of this discrepancy.

○ infra_unit_need = 80/375

DOCUMENT: The number of units of infrastructure necessary for each unit of average sale.

○ Ord_Inv = ( desired_infra - Infra_Inv ) * W_Inv

DOCUMENT: Calculates the orders from the stock of infrastructure in use, by taking the desired number of projects (desired_infra) less the actual number (Infra_Inv) all multiplied by the weighting fraction (W_Inv) which captures the uncertainty and the lack of information about this system in reality.

○ Ord_Pl = ( desired_infra_planned - infra_planned ) * W_Planned

DOCUMENT: Calculates the orders from the stock of infrastructure in planning, by taking the desired number of projects less the actual number all multiplied by the weighting fraction which captures the uncertainty and the lack of information about this system in reality.

○ Ord_Pro = ( desired_infra_in_progress - Infra_in_progress ) * W_Infra_in_Prog

DOCUMENT: Calculates the orders from the stock of infrastructure in progress, by taking the desired number of projects less the actual number all multiplied by the weighting fraction which captures the uncertainty and the lack of information about this system in reality.

○ Policy_2_SW = 0

DOCUMENT: Switch used to toggle between two formulations of desired infrastructure (desired_infra). This was used to test policy #2.

0 = Original formulation

1 = Smoothed Desired Infrastructure

○ Smooth_time = 5

DOCUMENT: The number of years used to smooth desired infrastructure (desired_infra). This was used to test Policy #2.

○ unit_cost = 37.5

DOCUMENT: The average cost to take one unit or project completely through the construction phase and into service.

○ W_Infra_in_Prog = 1/W_number

DOCUMENT: Information weighting fraction ( 1 <-> 0 )

1 = full information, <1 = partial information

○ W_Inv = 1

DOCUMENT: Information weighting fraction ( 1 <-> 0 )

1 = full information, <1 = partial information

W_number = 1/.75

DOCUMENT: Inverse information weighting fraction ( 1 <-> infinity )

1 = full information, > 1 = partial information

This converter is used because it is an easier way of writing fractions, where the number is simply the inverse of the weighting fraction. In other words if a quarter of the information is used, then this converter would equal 4. 1/8 would be 8. This is much easier than writing out .125 or .25 etc.

W_Planned = 1/W_number

DOCUMENT: Information weighting fraction ( 1 <-> 0 )

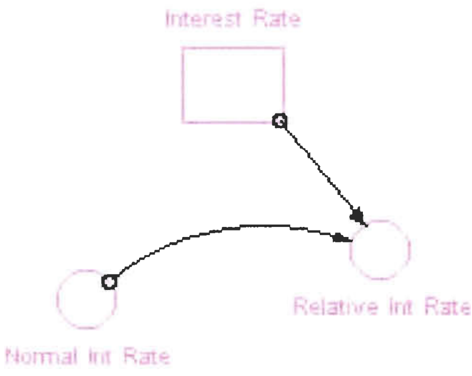
1 = full information, <1 = partial information

budget_constraint = GRAPH(des_act_budget_ratio)
(0.00, 0.00), (0.2, 0.34), (0.4, 0.57), (0.6, 0.76), (0.8, 0.89), (1.00, 1.00), (1.20, 1.09), (1.40, 1.17), (1.60, 1.23), (1.80, 1.26), (2.00, 1.28)

DOCUMENT: As the ratio of government spending to desired budget exceeds 1, the graph returns a value greater than one which is the effect on the rate at which projects leave planning and begin construction (infra starts). As the ratio falls below 1 the graph returns a value less than one, effecting the start rate. When government spending equals the desired budget the effect (budget_constraint) is equal to 1.

INFRA_EFFECT = GRAPH(Infra_Inv / desired_infra)
(0.00, 0.00), (0.2, 0.34), (0.4, 0.58), (0.6, 0.76), (0.8, 0.89), (1.00, 1.00), (1.20, 1.08), (1.40, 1.14), (1.60, 1.19), (1.80, 1.23), (2.00, 1.24)

DOCUMENT: The effect of the current level of infrastructure in relation to what is desired. This graph takes as an input the current level of infrastructure in use (Infra_Inv) divided by the desired level of infrastructure (desired_infra). When this ratio is greater than 1 the effect (infra_effect) rises above one, representing an infrastructure oversupply. When actual equals desired, the effect will be 1 which means that the infrastructure sector is in perfect equilibrium. If the actual is less than the desired the effect will be a number less than one, indicating infrastructure undersupply to the rest of the system. This is the main output of the infrastructure sector affecting production in the aggregate supply and demand sector.




Interest Rate Sector

**Interest Rate**

Interest_Rate(t) = Interest_Rate(t - dt) + (Int_Rate_Adj_Rate) * dt
INIT Interest_Rate = Normal_Int_Rate

DOCUMENT: The current interest rate. This sector is disabled throughout the simulations for this project because it further destabilizes the system when a change in spending is made. For all simulations the interest rate is constant. The interest rate is initialized in equilibrium at the normal interest rate (Normal_Int_Rate).

Normal_Int_Rate = .05

DOCUMENT: The normal interest rate. This is the standard or normal interest rate for the life of the simulation. The normal remains constant.

Relative_Int_Rate = Interest_Rate / Normal_Int_Rate

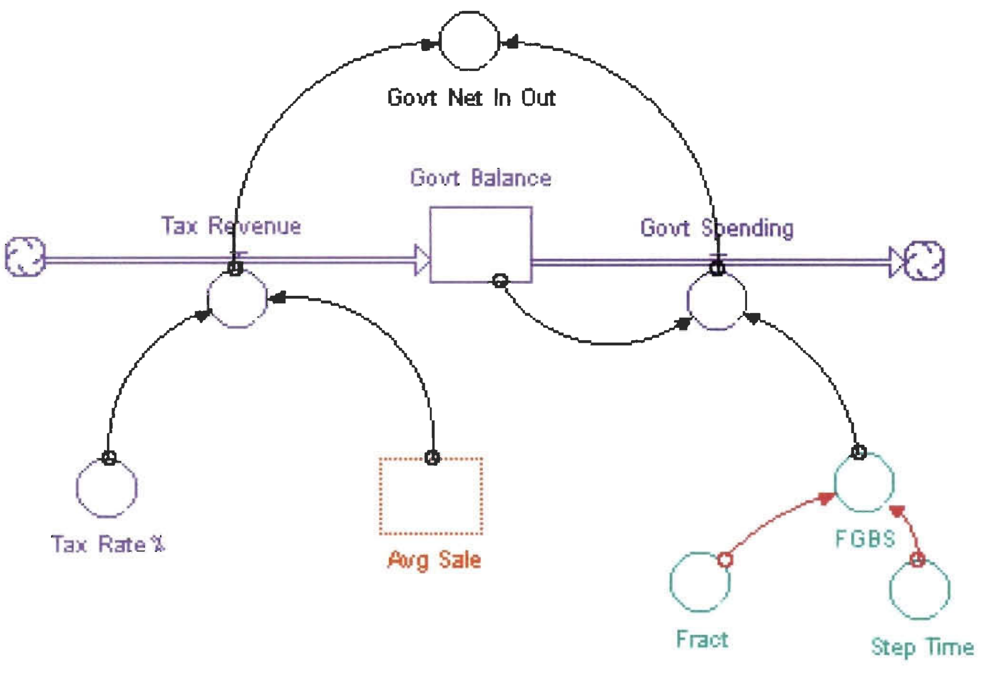
DOCUMENT: The relative interest rate, comparing the actual interest rate with the normal interest rate. This is the output for the sector. Since this sector is turned off and the stock is initialized in equilibrium, this relative interest rate returns a value of one, where the normal interest rate is equal actual interest rate.


Money Sector

**Money**

Money_Val = 1

DOCUMENT: The value of money. Normally this is a function of the desired level of money over the actual level of money. When a shortage of money occurs the ratio will be greater than 1, and when there is an excess, the ratio will be less than 1. For this project the money sector was turned off, because it can act to further destabilize the economy in response to changes in spending, thus for all tests the value of money was set to 1, meaning perfect adjustment of money policy in response to changes in the economy.




Taxation and Public Spending Sector

**Taxation and Public Spending**

Govt_Balance(t) = Govt_Balance(t - dt) + (Tax_Revenue - Govt_Spending) * dt
INIT Govt_Balance = Avg_Sale * 0.2 * 5

DOCUMENT: The amount of money currently held by the government. This is initialized to 20% of the average sale multiplied by 5 years. In other words this is 5 years wroth of tax revenue at a tax rate of 20% of the average sales per year.

INFLOWS:

Tax_Revenue = Tax_Rate% * Avg_Sale

DOCUMENT: The amount of money that the government brings in each year in the form of tax revenue. This is simply a function of the average sales for that year multiplied by the tax rate.

OUTFLOWS:

Govt_Spending = Govt_Balance * FGBS

DOCUMENT: The amount of money the government spends each year. This is a function of the amount of money currently held by the government, (in equilibrium this is equivalent to one year's average sales) multiplied by the fractional government budget spending (FGBS).

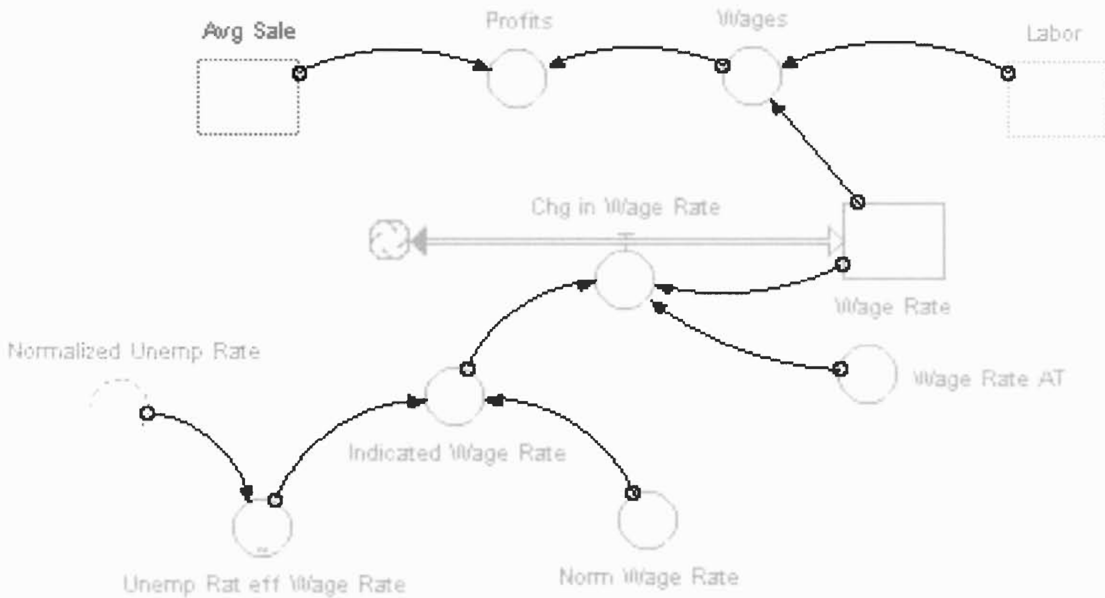
- FGBS = .2 * ( 1 + STEP ( Fract , Step_Time ) )
  DOCUMENT: The fractional government budget spending. This is the fraction of the government balance that is spent each year. This is the point where we have chosen to disturb the model from its initial equilibrium by pushing the fractional spending up by a fractional amount (Fract) at a specific point in the simulation (Step_Time). The initial fraction is 20%.

- Fract = .1
  DOCUMENT: The fractional disturbance to government spending. In this case, the fraction is set to .1 or 10%. This will shift spending up from 20% to 22%, (10% increase) kicking the model out of its initial equilibrium, and simulating the effects of a change in spending.

- Govt_Net_In_Out = Tax_Revenue - Govt_Spending
  DOCUMENT: The net flow of money into the Government. This testing converter is simply Tax Revenue less Expenses (Govt_Spending).

- Step_Time = 10
  DOCUMENT: The year when the step function will disturb the equilibrium of the model by increasing the spending toward infrastructure projects.

- Tax_Rate% = 0.2
  DOCUMENT: The percentage of average sales that are paid to the government in the form of taxes.




Wage Rate Sector

**Wage Rate**

Wage_Rate(t) = Wage_Rate(t - dt) + (Chg_in_Wage_Rate) * dt
INIT Wage_Rate = Norm_Wage_Rate

DOCUMENT: The average wage per worker per year. This is initialized at the normal wage rate setting the stock in equilibrium.

INFLOWS:

Chg_in_Wage_Rate = ( Indicated_Wage_Rate - Wage_Rate ) / Wage_Rate_AT

DOCUMENT: Net adjustments to the wage rate. This is a function of the indicated wage rate less the actual wage rate all divided by the wage rate adjustment time in years (Wage_Rate_AT).

Indicated_Wage_Rate = Norm_Wage_Rate * Unemp_Rat_eff_Wage_Rate

DOCUMENT: The target or indicate wage rate. This is a function of the normal wage rate multiplied by the effect of the unemployment rate on the wage rate. This effect simply amplifies or suppressed the normal wage rate in response to changes in the unemployment rate.

Norm_Wage_Rate = 10
DOCUMENT: The normal amount paid per worker per year.

Profits = Avg_Sale - Wages
DOCUMENT: The amount of money left from the sales (average_sales) after the costs (Wages) have been taken out.

Wages = Wage_Rate*Labor
DOCUMENT: The total cost of labor per year. This is simply the stock of labor multiplied by the cost per year per worker.

Wage_Rate_AT = 2
DOCUMENT: The rate in years, at which wages change.

Unemp_Rat_eff_Wage_Rate = GRAPH(Normalized_Unemp_Rate)
(0.00, 2.50), (0.5, 1.52), (1.00, 1.00), (1.50, 0.688), (2.00, 0.537), (2.50, 0.438), (3.00, 0.375), (3.50, 0.338), (4.00, 0.325), (4.50, 0.325), (5.00, 0.325)
DOCUMENT: The effect of unemployment on the wage rate. This is a multiplied effect, meaning that the normal wage rate will be multiplied by this effect to produce the indicated wage rate. As the normalized unemployment rate rises above 1, indicating an oversupply of workers, the effect on the wage rate falls below 1. When the normalized unemployment rate equals 1 the effect will equal 1. When the normalized unemployment rate falls below 1, indicating an undersupply of workers, the effect rises above 1, boosting the indicated wage rate.