Analysis of Household Water Filtration in China: A System Dynamics Model

by

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Abstract

As the economy has been growing fast in China, Chinese people have more income and then a higher standard of living. In the case of household water treatment, more and more urban residents in China use bottled water or water filtration systems instead of tap water because people have started to worry about polluted tap water. According to a survey from China Water Supply Services Promotion Alliance in 2014, 59% of urban residents drinking water is from tap water (after being boiled), and 41% from bottled water and water filtration systems. 41% of participants prefer bottled water as the first choice over water filtration systems.

The comparative advantages and disadvantages of home water filtration systems and bottled water are analyzed using comparative analysis. The reasons why the home water filtration industry has grown slowly in urban China even though it is less expensive and has environmental benefits are analyzed using a system dynamics model. The model focuses on the physical system of home water filtration industry. The study shows that order delivery delay and service time are key factors to the adoption rate of home water filtration system. However, initial cost becomes a limiting factor to the growth of the market of home water filtration systems. The study proposes the according market policy, demand policy, and supply policy to improve the current situation.

Acknowledgements

With a deep sense of gratitude, I wish to express my sincere thanks to my advisor, Professor Khalid Saeed, for his stimulating suggestions and immense help in planning and executing the study in time. His profound professional knowledge and timely wit guided the study to come along. His valuable instructions and suggestions during the course of work are greatly acknowledged.

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Introduction

As the economy has been growing fast in China, Chinese people have more income and then a higher standard of living. In the case of household water treatment, more and more urban residents in China use bottled water or filtered water instead of tap water because people have started to worry about polluted tap water. In early 2013, 7,500 rotten pig carcasses were found floating in the Huangpu River. The event aroused mass media and people's attention, as the river supplies 80% of tap water to Shanghai, one of the biggest cities in China. Although the authorities have guaranteed the quality of the city's drinking water, residents have remained concerned about water safety and many of them have stopped drinking tap water and are buying bottled water or installing home water filtration systems instead. Between bottled water and home water filtration systems, customers have preferred bottled water as the first choice over home water filtration systems. Are there some obvious advantages of bottled water over home water filtration systems? My curiosity about this question brings me to write this paper.

This paper analyzes why home water filtration systems in China have grown slowly when they have a number of advantages over bottled water and explores strategies for governing authorities and companies to increase the adoption of home water filtration systems. The analysis is accomplished through system dynamics modeling, thoroughly explaining the feedback loops behind models and effectively testing the impacts on various variables.

Detailed Problem Description

According to a survey from China Water Supply Services Promotion Alliance in 2014, 59% of urban residents' drinking water is from tap water (after being boiled), and 41% from bottled water and home water filtration systems. One report (Wen 2011) estimated that 3–5% of the Chinese urban population used household water filters. If this 4% prevalence estimate for household water filtration is applied to the total mainland Chinese urban population of 749.16 million in 2014, this suggests a population of 29.97 million filtering their water and a population of 277.19 million using bottled water. Why people buy a lot of bottled water products instead of using water filtration systems. Are there some obvious advantages of bottled water over water filtration system? I have done some comparative analysis between bottled water and water filtration systems. Table 1 checks the advantages of bottled water and water filtration systems in each catalog.

Table 1 Comparative Analysis Between Bottled Water and Home Water Filtration Systems

	Bottled Water	Home Water Filtration Systems
Convenience	√	
Affordability		√
Eco-friendliness		√
Health and safety		
Maintenance	√	

Water filtration systems seem to have some weaknesses and limitations. First, the water filtration service industry is not very mature in China, which may cause issues of maintenance of home filtration systems. Home filtration systems need regular maintenance. That means if you're not replacing or cleaning the filter as recommended, you may be doing more harm than good. Second, people tend to go to stores or online stores to buy bottled water instead of waiting for calling, scheduling, and installing home filtration systems, although filtered water will be available on tap after installation, whenever you need it for drinking or cooking. Third, consumers are still worried about the quality and safety of water filtered through home filtration systems. On the one hand, they are concerned whether filter systems are able to filter water or not. Not all filters are created the same. The quality of filtered water is largely influenced by the type of water filter systems consumers decide to install. Some filters only remove sediments and chlorine, others will also remove certain bacteria and heavy metals. Therefore, consumers need to know what their tap water contains and choose a filter accordingly.

However, bottled water is not perfect in every way. First, bottled water is less affordable than filtered water. The selling price of home water filtration system is at least 2000 Chinese yuan per unit and the replacement cost is around 500 Chinese yuan per year. If you want to buy a home water filtration system with average quality, the cost would be between 2000 Chinese yuan and 5000 Chinese yuan. Compared to home water filtration systems, the annual spending of bottled water would be at least 760 Chinese yuan, assuming an average person drinks 2 litres/day and if all the water drunk came from bottled water. Thus for a typical family (3 members), the cost of drinking water would at least 2280 Chinese yuan per year. However, if you purchase premium bottled water, whose quality can be compared with water filtered by a home water filtration system with average quality, the cost could be 5-10 times more. Second, bottled water is not environmental friendly. The bottled water industry uses a lot of plastics. According to the Pacific Institute (2007), producing one tonne of bottled water would require about 28.8 kg of plastics, mostly Polyethylene terephthalate (PET). And most of these plastics are not recycled. As little as 23% of all plastics was recycled in 2013, according to National Development and Reform Commission (NDRC) statistics (NDRC 2014). In China, there is a common misconception that plastic bottles are not wasted because scavengers collect them and sell them for money. However, this is not always true. Bottles are still flowing to landfills or incineration plants. In fact, according to NDRC's statistics (NDRC 2014), China's recycling rate has been decreasing over the last five years, most likely due to the falling oil price, which reduces the incentive to recycle plastic waste. Moreover, bottled water increases energy consumption. The Pacific Institute's study (Pacific Institute 2007) estimated that, for every bottle of water produced, twice as much extra water is used in the production process. This means, producing 1 litre of bottled water, requires in total 3 litres of water. Third, bottled water is not totally healthy and safe either, some bottled water products failing to meet regular quality checks by the government. In 2012 quality checks in Hunan Province showed that 60% of sampled bottled water products failed to pass national standards, and similar tests in Henan Province reported 37.5%. Generally, consumers tend to trust big brand names, but this too doesn't necessarily mean better quality. Robust, Wahaha, C'estbon and Nestlé (all renowned brands in China) have all been previously featured in the 'blacklist' of nonquality compliant products. In September 2014 in Beijing, C'estbon's bottled water was found to contain bacteria 1,450 times the allowed limit and Wahaha's product was found to contain over 8 times the limit. (Beijing Daily 2014) This is not to mention the boom of bottled water in China has resulted in the emergence of 'fake water'. 'Fake water' refers to bottled water produced by unauthorized or unregulated companies that source water from illegal wells or use tap water without proper treatment. 'Fake water' often poses health risks, as the water is not sufficiently treated. Furthermore, those illegal bottlers tend to use poor quality recycled plastic containers which may not meet the grade of food and safety standards. Drinking water from such containers could pose health risks.

The comparative analysis shows both home water filtration systems and bottled water have some disadvantages. However, according to market research reports (2017), the compound annual growth rate of the home water filtration market and the bottled water market is respectively 5.0% and 10.9% from 2014 to 2017. In the meantime, many industry research reports predict bottled water has a higher growth rate than home water filtration system. The compound annual growth rate of home water filtration market and bottled water market is expected respectively to be 2.3% and 9.2% from 2017 to 2021. This brings my research question: Why has the use of home water filtration systems grown slowly even though they are less expensive and have environmental benefits? This paper will focus on the physical system of home water filtration industry, including delivery, production control, service, service capacity as well as their effects on attractiveness and adoption. This paper applies a system dynamics model to analyze why the home water filtration industry has grown slowly in China and explores strategies to improve the situation.

This paper will not include price in the model. The reason is that "managers' actions are motivated by their own delivery delay conditions more than by price, which by default is assumed as given—a reasonable assumption for a price-taking firm dealing with the short run. (Forrester 2013; Saeed 2014b)" Sterman (1985) also claimed that the effects of price, liquidity and marginal costs and revenues are subsumed in industry's decision structure, although they are not critical to its unique explanations of the complex economic history of free market economies. (Saeed 2014b)

Literature Review

Self-limiting Corporate Systems

Many researchers study self-limiting corporate systems (Whitestone 1983; Paich & Sterman, 1993; Sterman, 2000; Sterman, Henderson, Beinhocker, & Newman, 2007). One of the most popular cases is People Express Airlines (Whitestone 1983). People Express went from a startup in 1981 to the fifth-largest US airline and annual revenues in excess of $1 billion by 1986. They launched a series of "new management" policies, such as universal employee ownership, work teams, and job rotation. These policies' goal was to increase fleet capacity and the number of passengers. Two key factors to improve passenger capacity were service quality and service capacity. However, when integrating service quality into management strategies, the number of passengers of People's Express still declined. The reason is that although better service quality brings more passengers, better service quality also means smaller service capacity because more services will be provided to one passenger. Therefore, in the long term the policy of improving service quality could not increase the number of passengers of People's Express. In the first nine months of 1986 the firm lost $245 million, and, in September 1986, the firm was purchased by Texas Air for only $125 million.

Researchers (Paich & Sterman, 1993; Sterman, 2000; Sterman, Henderson, Beinhocker, & Newman, 2007) have found that boom and bust (B&B) dynamics are common among firms in a large range of different industries. Durable consumer electronics (e.g. televisions, VCR's, calculators, etc.), telecommunications, medical equipment, chemicals, real estate, pulp and paper, agricultural commodities, natural resources, toys and games, tennis equipment, bicycles, semiconductors and running shoes, are examples of industries where boom and bust dynamics have occurred. B&B dynamics means aggressive capacity expansion occurs in the boom period when demand typically outstrips supply. Aggressive capacity expansion strategies in the boom phase ultimately result in excess capacity turning the boom into bust (Bakken, Gould, & Kim, 1992; Moxnes, 1998; Paich & Sterman, 1993; Sterman, 1989a, 1989b; Sterman, 2000). The fundamental problem is that in many cases capacity adjustments cannot be made quickly enough to match demand. Time delays associated with expanding or reducing capacity require firms to forecast demand and make strategic decisions to initiate capacity changes far in advance. This combination of rational decision-making and capacity adjustment delays gives rise to B&B dynamics (Sterman et al., 2007).

One of the well-known B&B cases is Atari in home video games and the subsequent repeated B&B of Worlds of Wonder in toys. Worlds of Wonder (WoW) was an American toy company founded in 1985 by former Atari employees including Donald Kingsborough, the former president of Atari. WoW achieved one of the fastest two-year growth spurts of any major US manufacturing start-up. The company's talking bear, Teddy Ruxpin, and Lazer Tag, a gun game, were among the toy industry's biggest hits during 1985 and 1986. The high-tech, high-priced toys were selling so fast and quickly went out of stock. However, sales of Teddy Ruxpin and Lazer Tag began to collapse in 1987 turning the boom to bust. By the end of 1987, WoW filed for bankruptcy protection. Many of WoW's senior managers had also been part of Atari's senior management, but they failed to learn from the previous experiences, and repeated their mistakes a few short years later at WoW.

Application of System Dynamics in Operational Management

John Sterman developed the People Express Management Flight Simulator (Sterman 1988). The system dynamics model integrates the operations, human resources, organizational structure, and philosophy of People Express with the structure of the US air-travel market and competitive environment of the early 1980s. In addition to "hard" variables such as fleet size, flight schedule, aircraft capacity and a full set of financial reports, the model includes a variety of "soft" variables including hiring and training lags; the effects of overtime, fatigue, and stock price changes on morale, productivity, and employee turnover; and the effects of service quality on reputation and customer demand. Following standard marketing models, demand is driven by both advertising and word of mouth. Potential customers respond to the flight schedule and availability of service, fares, service quality, and "service scope" (the range of services offered).

System dynamics modeling also can explain B&B dynamics very well. The boom cycle increases for a period during which word of mouth and other factors increase demand. And while the cycle can be maintained for some period through enhanced marketing, eventually the discard rate will outpace the adoption rate, and the product will be replaced by competition and die. John Sterman in his paper "Booms, Busts, and Beer: Understanding the Dynamics of Supply Chains" (Sterman 2015) demonstrated that supply chains are fundamental to a wide range of systems and many exhibit persistent instability and oscillation. Management policies are designed to keep the stocks at their target levels, compensating for usage or loss and for unanticipated disturbances in the environment. Often there are important delays between the initiation of a control action and the result, creating a supply line of unfilled orders. He developed a generic model of the stock management structure and showed how it can be customized to various situations. A range of factors, from information availability to individual incentives, contribute to the failure to account for time delays and the supply line.

Industrial Dynamics has contributed a lot to operational management using system dynamics modeling. I cannot list all contributions here and only give one great example: Forrester (2013) gave a stock-and-flow map translating his perspective on the way a firm operates in the market. Managers working with limited information try to adjust the number of machines, inventory and workforce to be able to clear their backlog of orders.

Methodology

System dynamic modeling is useful for addressing the dynamics of change in any system that contains quantities varying over time and describing feedback, the transmission, and receipt of information. The system dynamic approach consists of six steps (see Table 2).

Table 2 Process of System Dynamic Approach

Conceptual	1. Problem Definition	Refinement
	2. System Conceptualization	
	3. Model Representation	
Technical	4. Model Behavior	
	5. Model Evaluation	
	6. Policy Analysis & Model Use	Application

This paper uses system dynamic approach to analyze the system behavior of household water filtration in urban China. Household water filtration systems contain quantities, which vary over time, such as adoption, delivery, production control, service, service capacity, etc. These elements in household water filtration systems can be described and analyzed within a closed system of feedback loops, which is demonstrated in the following model section.

Model

Reference Mode

The first step to build a system dynamics model is to build a reference mode. Based on the current market share of home water filtration system and bottled water in urban China and the compound annual growth rates of both household water treatment systems (see Detailed Problem Description), by 2021, the market share of home water filtration system will be 6.87% and the market share of bottled water will be 93.13%. Urban population growth rate is set as 0.012. I assumed that each household has three people.

Table 3 Home Water Filtration Systems and Bottled Water Market Share Projection

	Home Water Filtration Customers (million people)	Home Water Filtration Market Share (%)	Bottled Water Customers (million people)	Bottled Water Market Share (%)
2014	29.97	9.76	277.19	90.24
2015	31.78	9.29	310.48	90.71
2016	33.71	8.84	347.76	91.16
2017	35.75	8.41	389.53	91.59
2018	37.91	7.99	436.30	92.01
2019	40.20	7.60	488.70	92.40
2020	42.63	7.23	547.39	92.77
2021	45.21	6.87	613.12	93.13

Therefore, the reference mode of market share of home water filtration systems is as Figure 1 shows. The market share is declining from 9.76% to 6.87% and the number of adopters is rising from 9.9 to 15.1 (Million Households).

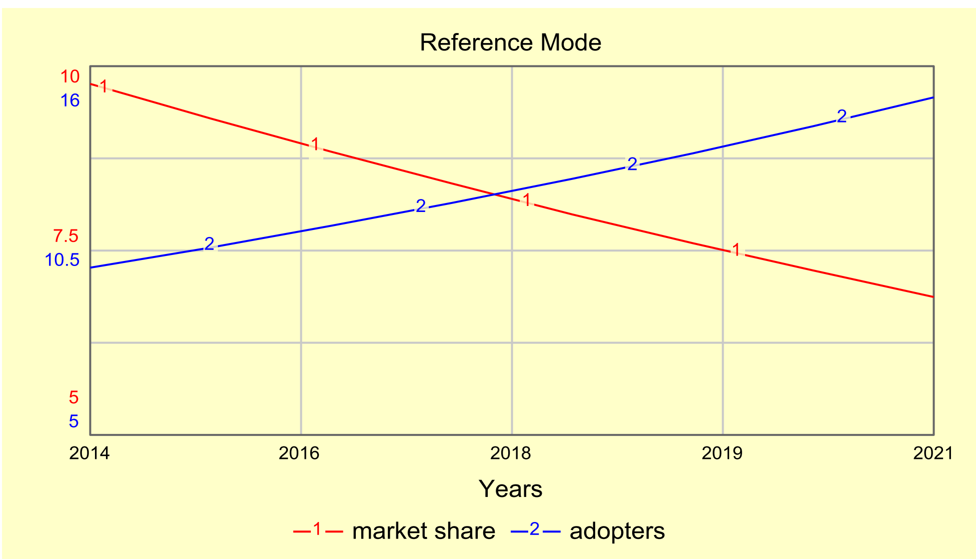

Figure 1 Reference Mode

Dynamic Hypothesis

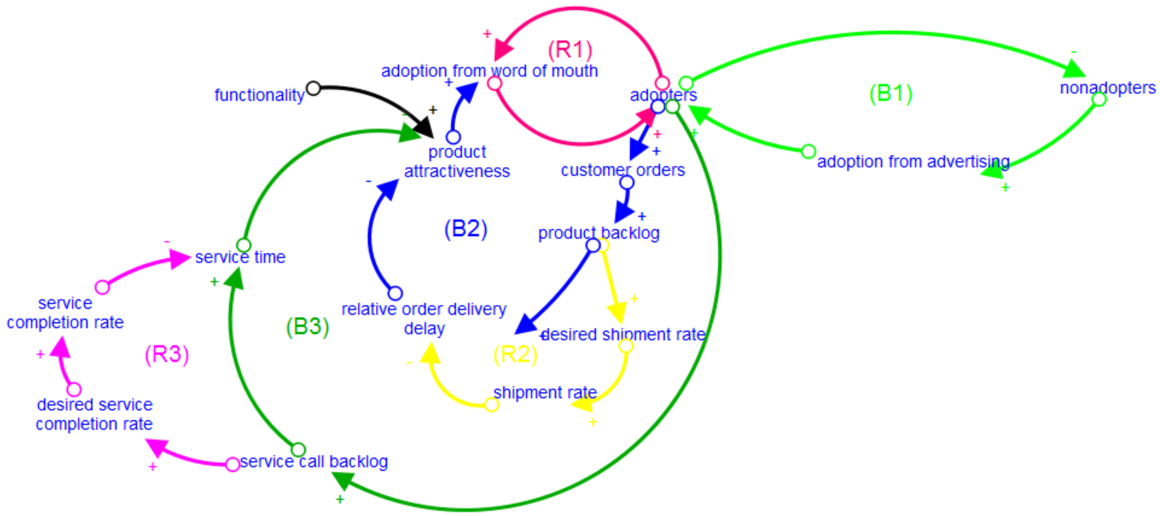

Figure 2 Dynamic Hypothesis

There are 3 reinforcing feedback loops and 3 balancing feedback loops in this model. (see Figure 2)

R1: More adopters bring more adoption from word of mouth. More adoption from word of mouth also increases the number of adopters.

R2: More adopters mean more customer orders, increasing product backlog. More product backlog increases desired shipment rate and then shipment rate. More shipment rate means less order delivery delay, increasing product attractiveness. Higher product attractiveness has positive effects on adoption from word of mouth and thus the number of adopters.

R3: More adopters mean more service call backlog, which makes the desired service completion rate go up, increasing service completion rate. More service completion rate means less service time. Less service time makes product more attractive. Higher product attractiveness has positive effects on adoption from word of mouth and thus the number of adopters.

B1: More nonadopters mean more adoption from advertising. More adoption from advertising brings more adopters, which reduces the number of nonadopters.

B2: More adopters mean more customer orders, increasing product backlog. More product backlog lowers order delivery delay, which decreases product attractiveness. Lower product attractiveness has negative effects on adoption from word of mouth and thus the number of adopters.

B3: More adopters increase service call backlog, which means more service time. More service time makes product less attractive. Lower product attractiveness has negative effects on adoption from word of mouth and thus the number of adopters.

Functionality is an external factor that impacts product attractiveness. Functionality includes the quality of water filtered through home water filtration system as well as what elements (such as sediments, chlorine, bacteria, and heavy metals, etc.) can be removed. More functionality means higher product attractiveness.

Model Description

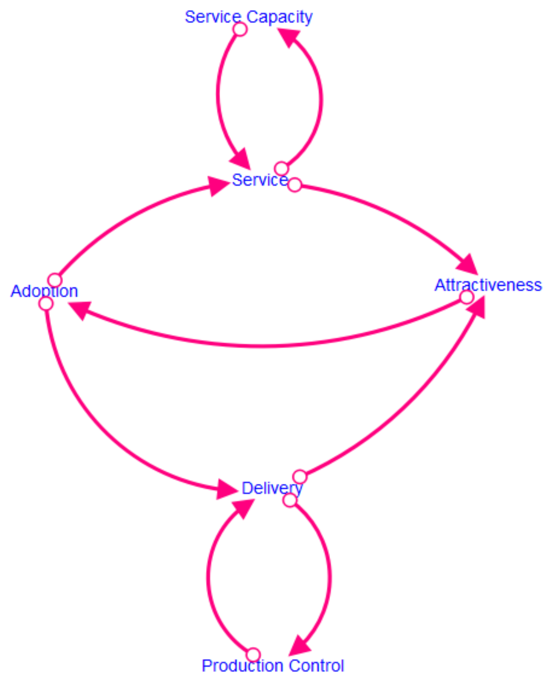

Figure 3 Sector Map

The next step was to translate dynamic hypothesis into a system dynamics model that was built for simulation. The model consists of six sectors—adoption, attractiveness, delivery, production control, service, and service capacity. The model is shown in Appendix A. Figure 3 shows the relationships among different sectors according to the dynamic hypothesis. Delivery Sector and Service Sector both serve as an intermediary between Adoption Sector and Attractiveness Sector. Their roles are to translate customers' demand into product and service supply and their performances determine product attractiveness, which promotes or deters customers' demand. Production Control Sector determines how to meet the demand of delivery. Service Sector and Service Capacity Sector interact with each other to adjust supply and meet the demand of service. The following part explains the structure of each sector.

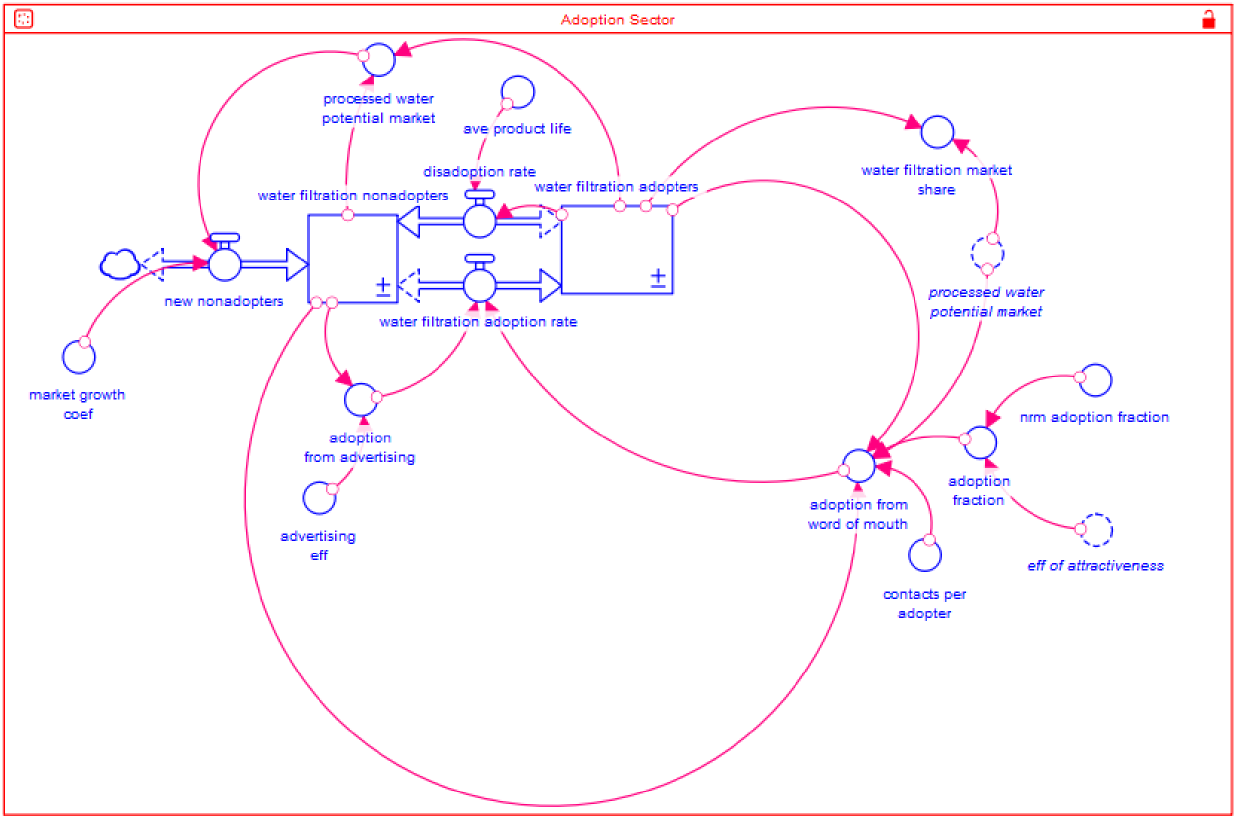

Figure 4 Adoption Sector

In the adoption sector (see Figure 4), there are two stocks—water filtration adopters and water filtration nonadopters. Water filtration adopters are households who hear about water filtration systems through word of mouth and advertising and purchase water filtration systems. Water filtration nonadopters are households who never hear or have not heard about water filtration systems lately. The initial value of water filtration adopters is 10 million households (29.97 divided by 3; I assume one household has three people). The initial value of water filtration nonadopters is 92 million households (277.19 divided by 3). Water filtration adopters and water filtration nonadopters consist of the processed water potential market. Adoption from word of mouth and adoption from advertising together drive water filtration adoption. The average life of water filtration systems is 10-15 years so I set the average product life at 12.5 years. After 12.5 years, disadoption rate equals water filtration adopters divided by 12.5. Market growth coefficient, which drives new nonadopters, is 0. 12 because I assumed that urban population growth rate is 0.012 and I calculated the growth rate of household (I assumed that each household has three people). Attractiveness has effects on adoption from word of mouth because customers tell their neighbors when they find a product attractive. Part of this sector was translated from the Bass Model, which was first published in Management Science in 1969 by Frank Bass, into the stocks, flows and feedback loops. The Bass Model expresses a dynamic hypothesis for growth—nonadopters (potential adopters) become adopters through word-of-mouth. (Bass 1969)

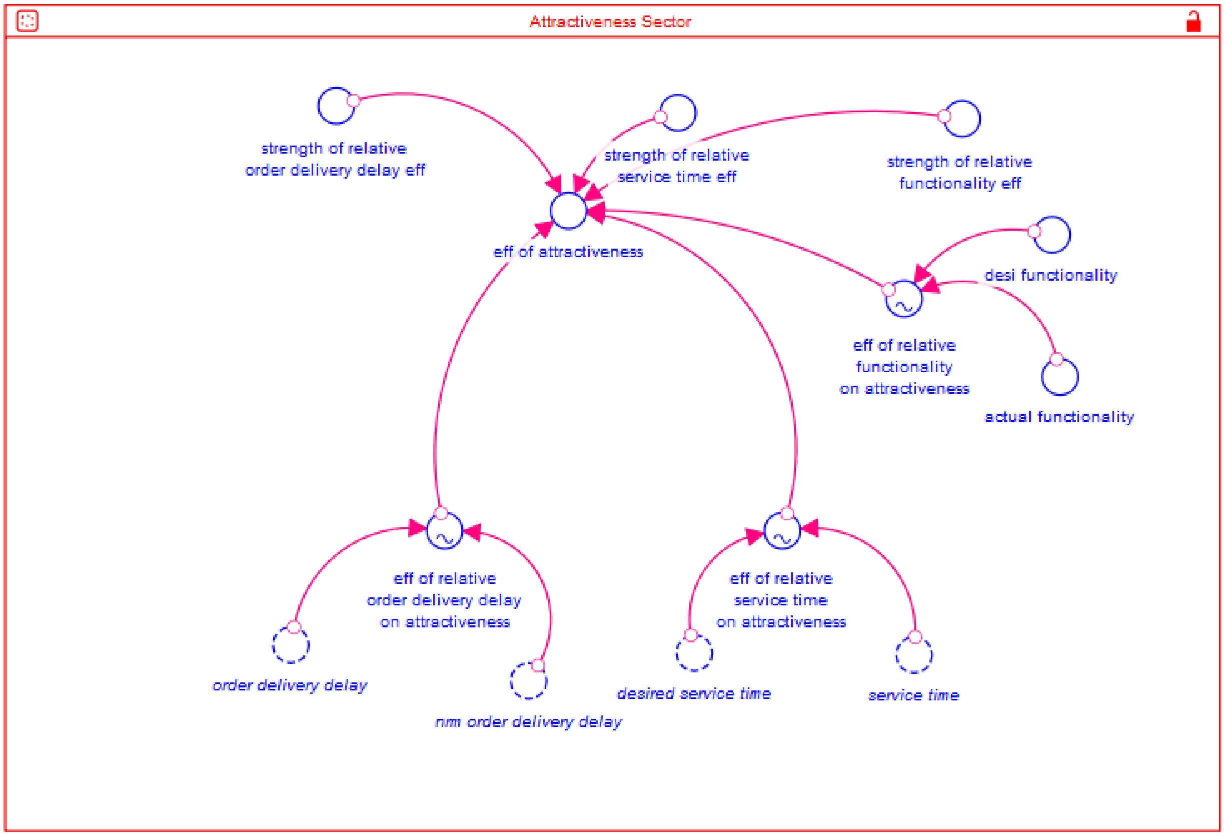

Figure 5 Attractiveness Sector

In the attractiveness sector (see Figure 5), effect of attractiveness is the product of normal effect of attractiveness, effect of relative order delivery delay on attractiveness and its strength, effect of relative service time on attractiveness and its strength, and effect of relative functionality on attractiveness and its strength.

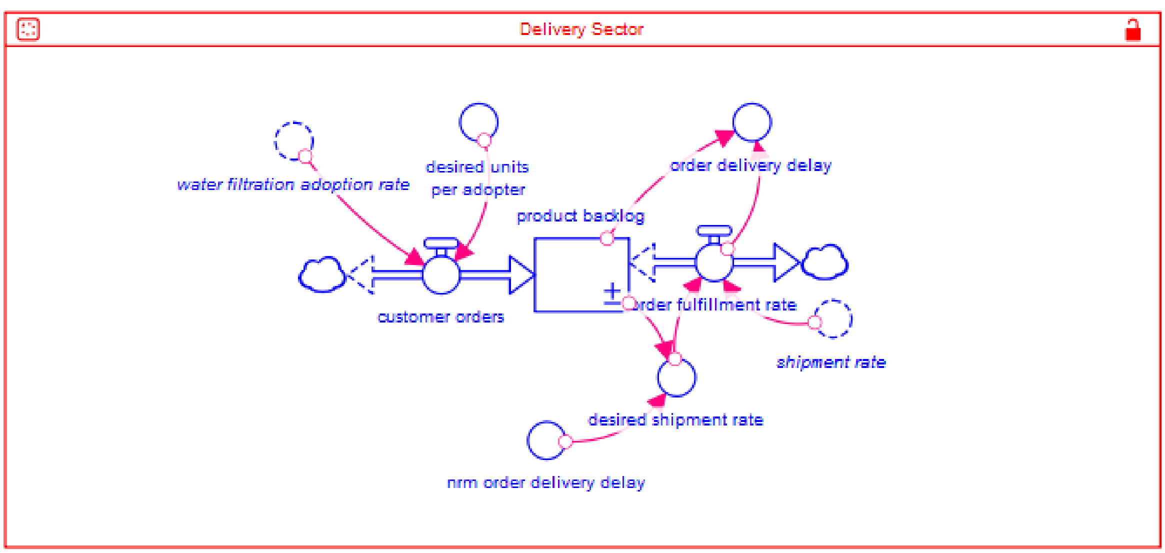

Figure 6 Delivery Sector

In the delivery sector (see Figure 6), there is one stock—product backlog, whose inflow is customer orders and outflow is order fulfillment rate. Adoption rate and desired units per adopter determine customer orders. Order fulfillment rate depends on minimum value between shipment rate and desired shipment rate. Order deliver delay equals product backlog divided by order fulfillment rate.

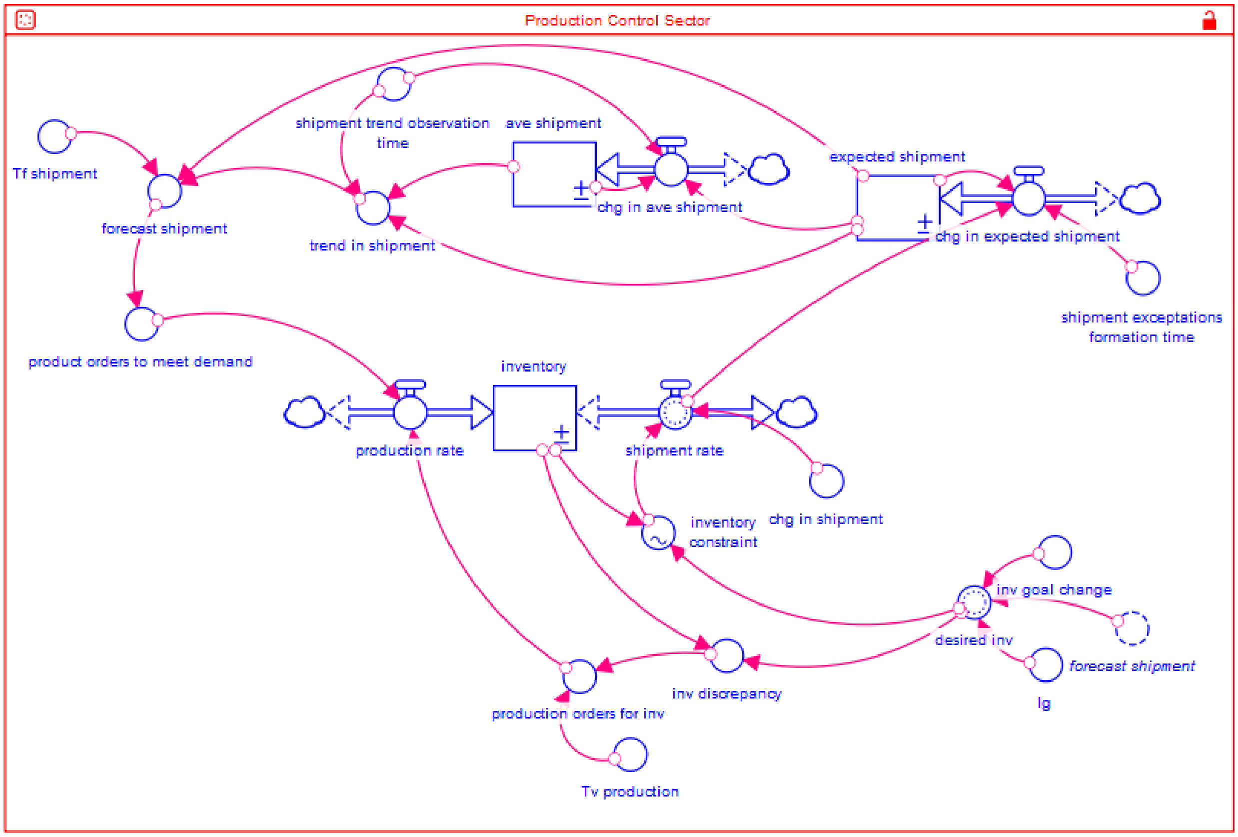

Figure 7 Production Control Sector

In the production control sector (see Figure 7), there are three stocks—inventory, average shipment, and expected shipment. Production orders are based on inventory discrepancy and a forecast of shipments. This sector refers to the case "Production orders based on demand and instantaneous inventory discrepancy" discussed in "Can trend forecasting improve stability in supply chains? A response to Forrester's challenge in Appendix L of Industrial Dynamics" (Saeed 2014a).

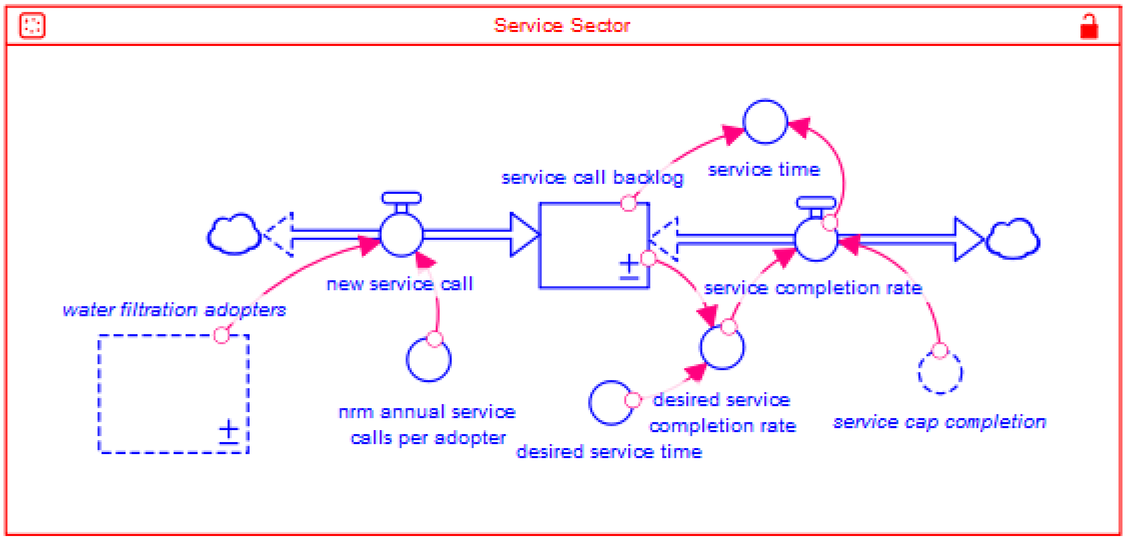

Figure 8 Service Sector

In the service sector (see Figure 8), there is one stock—service call backlog. Water filtration adopters and normal service calls per adopter determine new service call. Service time equals service call backlog divided by service completion rate. Service completion rate depends on minimal value between service capacity completion and desired service completion rate.

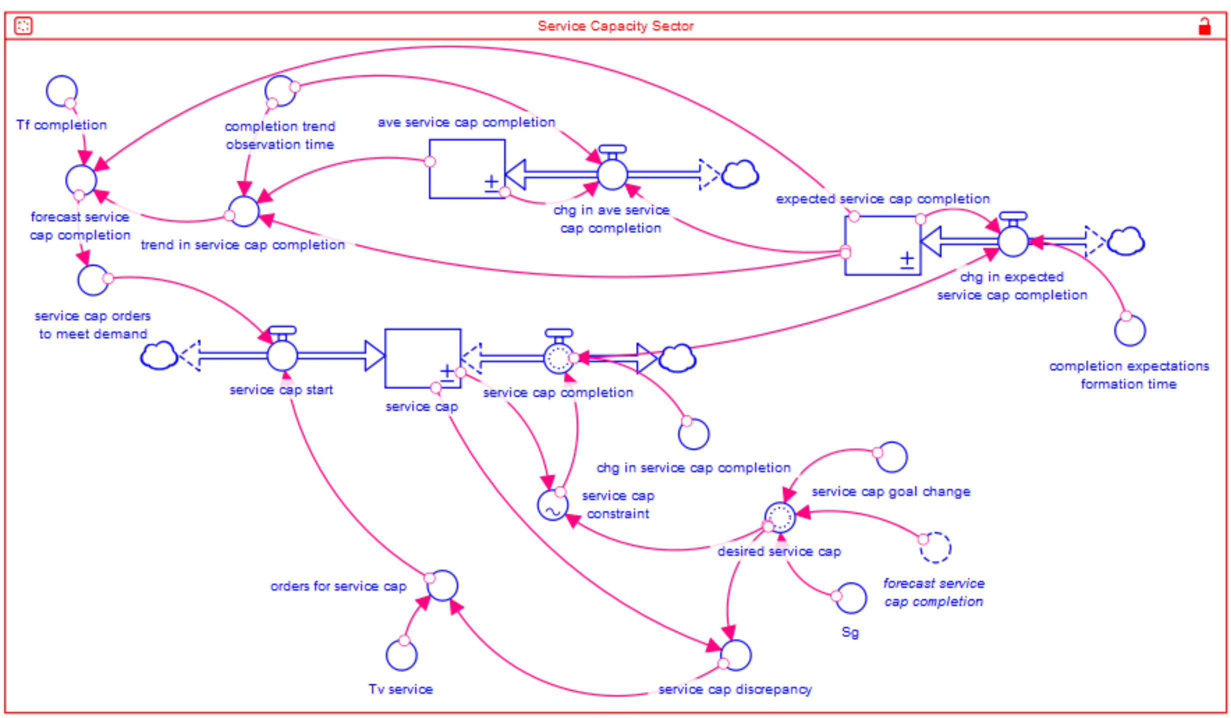

Figure 9 Service Capacity Sector

In the service capacity sector (see Figure 9), there are three stocks—service capacity, average service capacity completion, and expected service capacity completion. Orders for service capacity are based on service capacity discrepancy and a forecast of service capacity completion. This sector also refers to the people express case discussed in "Endogenous limits and bottlenecks: Improving Anticipation and Response in VHA Homeless Programs Operations: A strategic thinking exercise based on a simplified model of people express case" (Saeed et al., 2015).

There are five graphical functions used in the model, including effect of relative order delivery delay on attractiveness, effect of relative service time on attractiveness, effect of relative functionality on attractiveness, inventory constraint, and service capacity constraint.

Effect of relative order delivery delay on attractiveness depends on order delivery delay and normal order delivery delay. As the increase in order delivery delay, effect of relative order delivery delay on attractiveness declines.

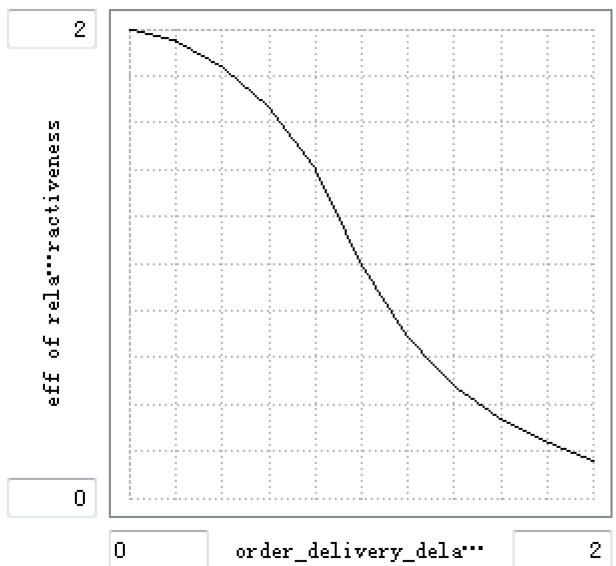

Figure 10 Graphical Function—Effect of Relative Order Delivery Delay on Attractiveness

Effect of relative service time on attractiveness depends on service time and desired service time. As service time increases, effect of relative service time on attractiveness declines.

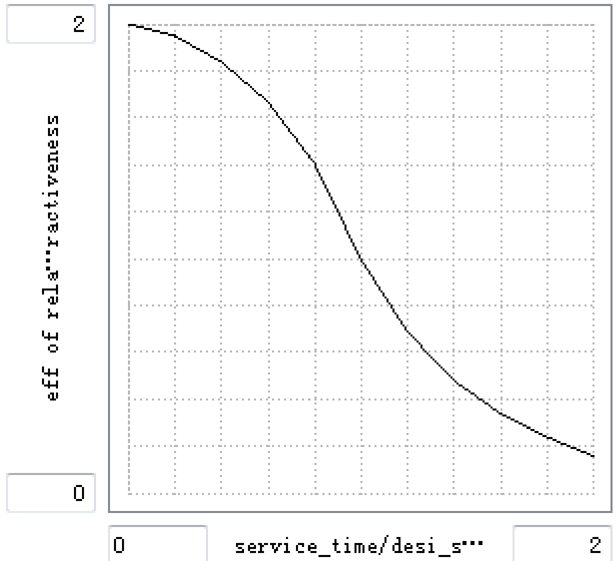

Figure 11 Graphical Function—Effect of Relative Service Time on Attractiveness

Effect of relative functionality on attractiveness depends on actual functionality and desired functionality. As actual functionality increases, effect of relative functionality on attractiveness goes up.

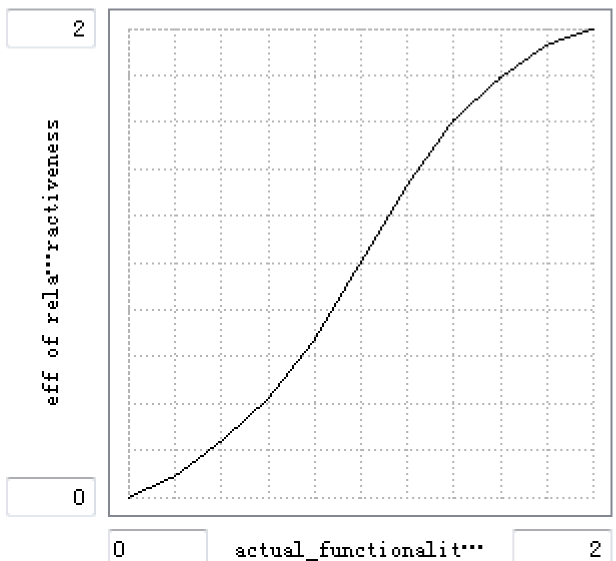

Figure 12 Graphical Function—Effect of Relative Functionality on Attractiveness

Inventory constraint depends on inventory and desired inventory. As inventory increases, inventory constraint is raised.

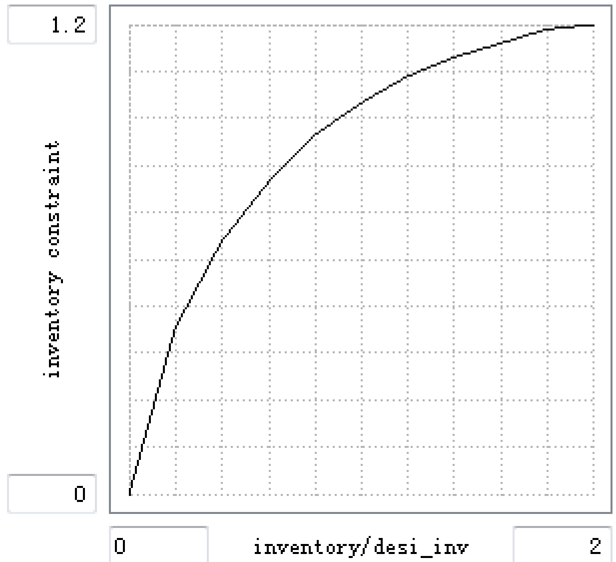

Figure 13 Graphical Function—Inventory Constraint

Service capacity constraint depends on service capacity and desired service capacity. As service capacity increases, service capacity constraint is raised.

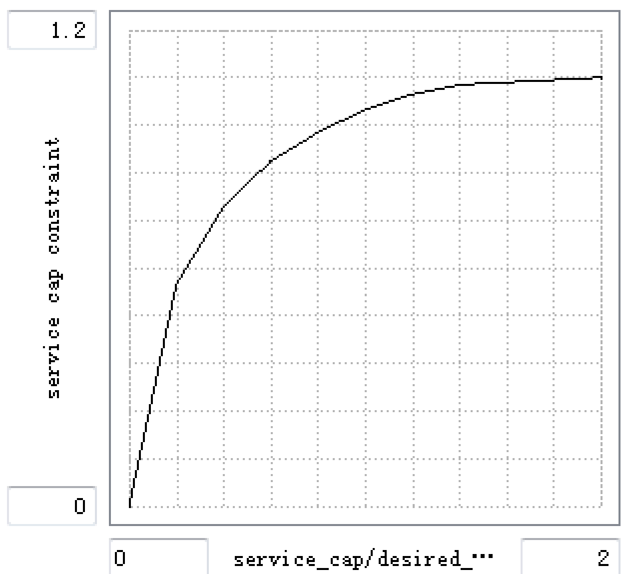

Figure 14 Graphical Function—Service Capacity Constraint

Base Case Behavior

The model was established to run between 2014 and 2021. In the market sector, the home filtration market share declined from 9.76% to 6.63% and the number of adopters rose from 9.9 to 15.6 (Million Households), which match with the reference mode.

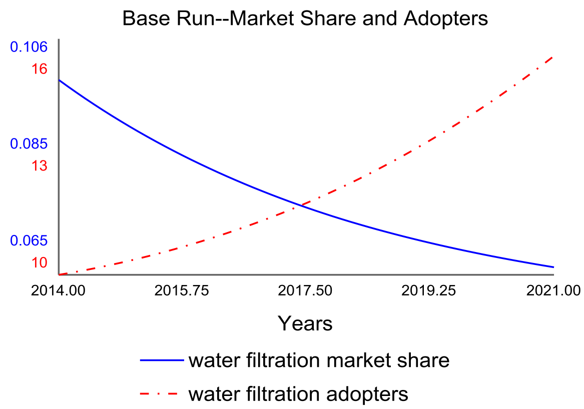

Figure 15 Base Case—Market Share and Adopters

I also compared the actual data (including projection) and model output. (see Figure 16, Figure 17, and Table 4) Data needed to run the model include the initial value of water filtration nonadopters, water filtration adopters, and the urban population growth (the market growth coefficient). Table 4 shows the projection result and model output by 2021.

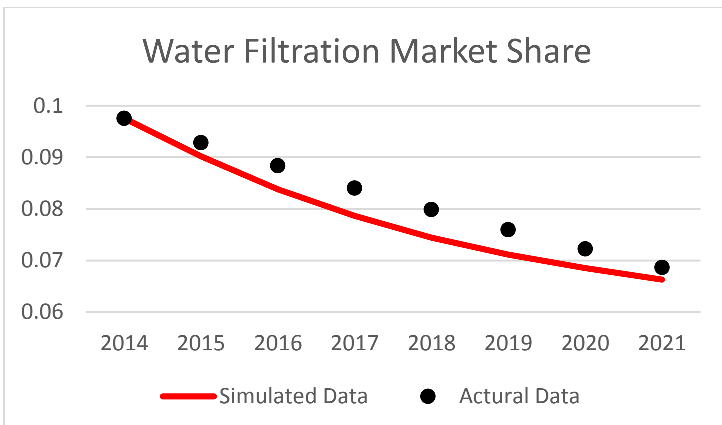

Figure 16 Comparison of Actual Data and Simulated Data--Market Share

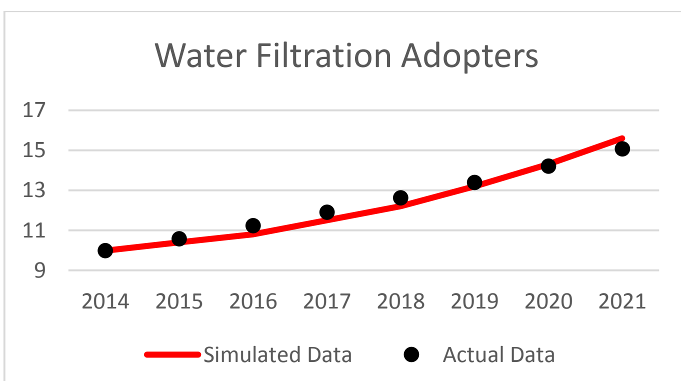

Figure 17 Comparison of Actual Data and Simulated Data—Adopters

Table 4 Comparison of Actual Result and Model Output

	Projection	Simulated Base Run
Water Filtration Market Share (%)	6.87	6.63
Water Filtration Adopters (Million Households)	15.1	15.6
Water Filtration Nonadopters (Million Households)	204.4	219.0

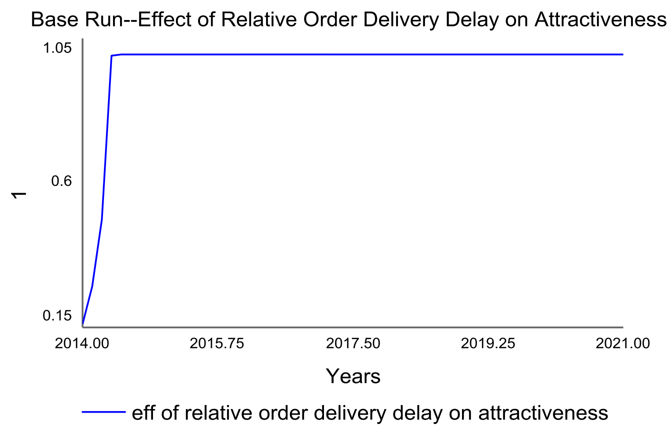

Figure 18 Base Case--Effect of Relative Order Delivery Delay on Attractiveness

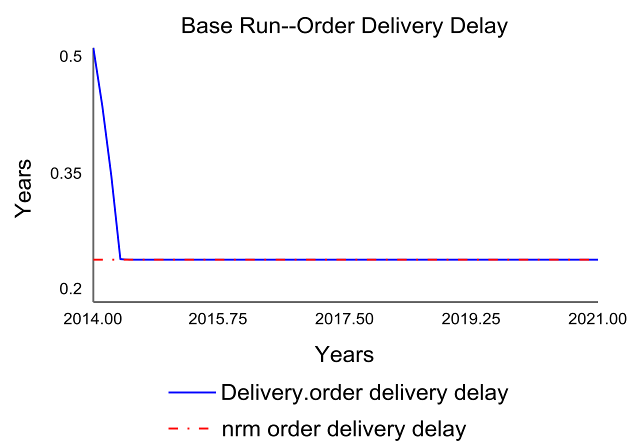

Figure 19 Base Case—Order Delivery Delay

From Figure 18 and Figure 19, we can see that when order delivery delay declines, the effect of order delivery delay on attractiveness goes up.

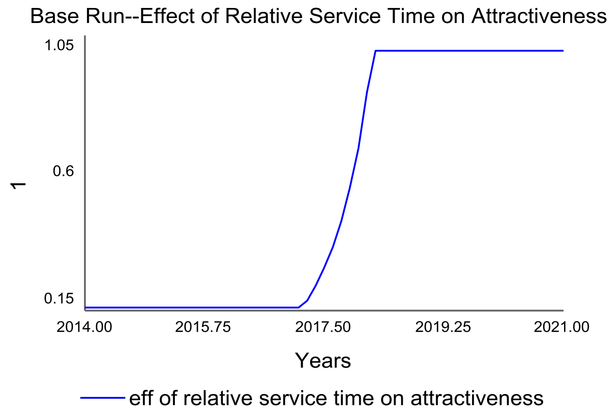

Figure 20 Base Case--Effect of Relative Service Time on Attractiveness

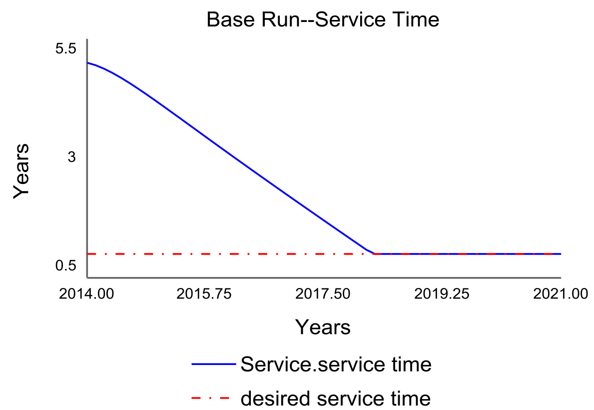

Figure 21 Base Case—Service Time

From Figure 20 and Figure 21, we can see that when service time goes down, the effect of service time on attractiveness goes up. Home water filtration systems need to have a maintenance service once a year. Service time in the current scenario takes longer than one year.

From the base run, we can see that order delivery delay and service time are some of the reasons that cause a low adoption rate of home water filtration systems. However, order delivery delay and service time are not limiting factors in the current scenario because order delivery delay and service time get close to the desired goals by the end of the current scenario.

Discussion

Since order delivery delay and service time are not limiting factors in the current scenario, what has caused the low market share of home water filtration systems in urban China? Though the overall cost of home water filtration systems is lower than the cost of bottled water, the initial cost of water filtration systems is much more expensive than bottled water. Is the initial cost a limiting factor of customers not to choose water filtration systems?

Home water filtration systems customers' analysis report (2016) investigated 287 families in 10 major urban areas in China. The report collected the data of budget for home water filtration systems in different families. (see Table 5) 67% of low income families have less than 2000 Yuan of budgets for home water filtration systems, which makes them not choose the systems because the average initial cost of water filtration systems is between 2000 Yuan and 5000 Yuan. According to National Bureau of Statistics of the People's Republic of China (2014), low income families account for 35.5% of all families in urban China. Therefore, home water filtration systems lose around 24% of market share because many low income families are not willing to spend money on the high initial cost.

Table 5 Budget for Home Water Filtration Systems in Different Families

Unit (Yuan)	<2000	2000-5000	5000-10000	>10000
High income family	0.03	0.06	0.60	0.31
Low income family	0.67	0.28	0.05	0.00

Except low income families, there are around 20% of urban residents renting apartments instead of owning apartments. (Cui 2018) Their landlords are normally not willing to pay a high initial cost to install a home water filtration system. These landlords often do not belong to low income families because they have their own property, making them have a high annual income. I assumed three people share an apartment. Therefore, home water filtration systems lose about 20% of market share because of limited purchase from landlords.

Sensitivity Analysis

Through a sensitivity test, I found that the following parameters were sensitive to market share and adoption rate; they were contacts per adopter, normal adoption fraction, advertising effect, and average product life. These parameters were sensitive because as the increase or decline of their values, the values of market share and adoption rate would accordingly change. The increase or decline of the values of insensitive parameters cannot change the values of market share and adoption rate. The performance of sensitivity test is shown as Table 6. The explanation of the sensitivity test to each parameter is as following.

Contacts Per Adopter

The base (first) run value of contacts per adopter is 0.04 (Households/Household/Year). In the second run, the value of contacts per adopter is adjusted to 0.6; in the third run, the value of contacts per adopter is adjusted to 0.01. From Table 6, we can see contacts per adopter are sensitive to market share and adoption rate. As contacts per adopter increases, adoption from word of mouth grows, which increases adoption rate and thus market share.

Normal Adoption Fraction

The base (first) run value of normal adoption fraction is 0.04 (Unitless). In the second run, the value of normal adoption fraction is adjusted to 0.6; in the third run, the value of normal adoption fraction is adjusted to 0.01. From Table 6, we can see normal adoption fraction is sensitive to market share and adoption rate. As normal adoption fraction increases, adoption fraction goes up and then adoption from word of mouth grows, which increases adoption rate and thus market share.

Advertising Effect

The base (first) run value of advertising effect is 0.012 (1/Year). In the second run, the value of advertising effect is adjusted to 0.02; in the third run, the value of advertising effect is adjusted to 0.006. From Table 6, we can see advertising effect is sensitive to market share and adoption rate. As advertising effect increases, adoption from advertising grows, which increases adoption rate and thus market share.

Market Growth Coefficient

The base (first) run value of market growth coefficient is 0.12 (1/Year). In the second run, the value of market growth coefficient is adjusted to 0.15; in the third run, the value of market growth coefficient is adjusted to 0.09. From Table 6, we can see for the larger value run, adoption rate goes up, while market share goes down; for the smaller value run, adoption rate goes down, while market share goes up. However, we cannot easily change the population growth rate, so, I will not consider market growth coefficient as a sensitive parameter.

Average Product Life

The base (first) run value of average product life is 12.5 (Years). In the second run, the value of average product life is adjusted to 15; in the third run, the value of average product life is adjusted to 8. From Table 6, we can see for market share, as average product life increases, market share grows; as average product life decreases, market share declines because shorter product life makes more adopters become nonadopters, decreasing market share. Average product life is sensitive to market share.

Normal Order Delivery Delay

The base (first) run value of normal order delivery delay is 0.25 (Years). In the second run, the value of normal order delivery delay is adjusted to 0.05; in the third run, the value is adjusted to 2. From Table 6, we can see normal order delivery is insensitive to market share and adoption rate.

Desired Service Time

The base (first) run value of desired service time is 1 (Years). In the second run, the value of desired service time is adjusted to 0.5; in the third run, the value is adjusted to 2. From Table 6, we can see desired service time is insensitive to market share and adoption rate.

Actual Functionality

The base (first) run value of actual functionality is 1 (Unitless). In the second run, the value of actual functionality is adjusted to 2; in the third run, the value is adjusted to 0.5. From Table 6, we can see actual functionality is insensitive to market share and adoption rate.

Desired Functionality

The base (first) run value of desired functionality is 1 (Unitless). In the second run, the value of desired functionality is adjusted to 2; in the third run, the value is adjusted to 0.5. From Table 6, we can see desired functionality is insensitive to market share and adoption rate.

Strength of Relative Order Delivery Delay Effect

The base (first) run value of strength of relative order delivery delay effect is 1 (Unitless). In the second run, the value of strength of relative order delivery delay effect is adjusted to 2; in the third run, the value is adjusted to 0.5. From Table 6, we can see strength of relative order delivery delay effect is insensitive to market share and adoption rate.

Strength of relative service time effect and strength of relative functionality effect have the similar performances as strength of relative order delivery delay effect. They are both insensitive to market share and adoption rate.

Time to Change Production Orders for Inventory

The base (first) run value of time to change production orders for inventory is 2 (Years). In the second run, the value of time to change production orders for inventory is adjusted to 1; in the third run, the value is adjusted to 3. From Table 6, we can see time to change production orders for inventory is insensitive to market share and adoption rate.

Shipment Trend Observation Time

The base (first) run value of shipment trend observation time is 3 (Years). In the second run, the value of shipment trend observation time is adjusted to 2; in the third run, the value is adjusted to 4. From Table 6, we can see shipment trend observation time is insensitive to market share and adoption rate.

Shipment Expectations Formation Time

The base (first) run value of shipment expectations formation time is 1 (Years). In the second run, the value of shipment expectations formation time is adjusted to 0.5; in the third run, the value is adjusted to 2. From Table 6, we can see shipment expectations formation time is insensitive to market share and adoption rate.

Inventory Goal

The base (first) run value of inventory goal is 2000 (Million Widgets). In the second run, the value of inventory goal is adjusted to 1500; in the third run, the value is adjusted to 2500. From Table 6, we can see inventory goal is insensitive to market share and adoption rate.

Inventory Goal Change

The base (first) run value of inventory goal change is 1 (Years). In the second run, the value of inventory goal is adjusted to 0; in the third run, the value is adjusted to 2. From Table 6, we can see inventory goal change is insensitive to market share and adoption rate.

Desired Units Per Adopter

The base (first) run value of desired units per adopter is 1 (Widgets/Household). In the second run, the value of desired units per adopter is adjusted to 2; in the third run, the value is adjusted to 0.5. From Figure Table 6, we can see desired units per adopter is insensitive to adoption rate and market share.

Time to Change Orders for Service Capacity

The base (first) run value of time to change orders for service capacity is 1 (Years). In the second run, the value of time to change orders for service capacity is adjusted to 0.5; in the third run, the value is adjusted to 2. From Table 6, we can see time to change orders for service capacity is insensitive to market share and adoption rate.

Completion Trend Observation Time

The base (first) run value of completion trend observation time is 3 (Years). In the second run, the value of completion trend observation time is adjusted to 2; in the third run, the value is adjusted to 4. From Table 6, we can see completion trend observation time is insensitive to market share and adoption rate.

Completion Expectations Formation Time

The base (first) run value of completion expectations formation time is 1 (Years). In the second run, the value of completion expectations formation time is adjusted to 0.5; in the third run, the value is adjusted to 2. From Table 6, we can see completion expectations formation time is insensitive to market share and adoption rate.

Service Capacity Goal

The base (first) run value of service capacity goal is 2000 (Calls). In the second run, the value of service capacity goal is adjusted to 1500; in the third run, the value is adjusted to 2500. From Table 6, we can see service capacity goal is insensitive to market share and adoption rate.

Service Capacity Goal Change

The base (first) run value of service capacity goal change is 1 (Years). In the second run, the value of service capacity goal change is adjusted to 0; in the third run, the value is adjusted to 2. From Table 6, we can see service capacity goal change is insensitive to market share and adoption rate.

The runs of normal annual service calls per adopter are similar to those of desired units per adopter, which is insensitive to adoption rate and market share.

Table 6 Sensitivity Test

Parameters		Order delivery delay (Years)	Service time (Years)	Effect of relative order delivery delay on attractiveness (Unitless)	Effect of relative service time on attractiveness (Unitless)	Adoption rate (Million Households/Year)	Market Share (Unitless)
Base Run		0.25	1	1	1	2.65	0.067
Contacts per adopter (0.04)	0.6	0.25	1	1	1	2.99	0.074
	0.01	0.25	1	1	1	2.64	0.066
Normal adoption fraction (0.04)	0.6	0.25	1	1	1	2.99	0.074
	0.01	0.25	1	1	1	2.64	0.066
Advertising effect (0.012)	0.02	0.25	1	1	1	4.29	0.093
	0.006	0.25	1	1	1	1.36	0.046
Market growth coef (0.12)	0.15	0.25	1	1	1	3.29	0.059
	0.09	0.25	1	1	1	2.14	0.076
Average product life (12.5)	15	0.25	1	1	1	2.64	0.070
	8	0.25	1	1	1	2.68	0.055
Normal order delivery delay (0.25)	2	0.25	1	1.92	1	2.64	0.067
	0.05	0.25	1	0.16	1	2.68	0.067
Actual functionality (1)	2	0.25	1	1	1	2.68	0.067
	0.5	0.25	1	1	1	2.64	0.066
Desired functionality (1)	2	0.25	1	1	1	2.64	0.067
	0.5	0.25	1	1	1	2.68	0.067
Strength of relative order delivery delay on attractiveness (1)	2	0.25	1	1	1	2.68	0.067
	0.5	0.25	1	1	1	2.64	0.066
Strength of relative service time on attractiveness (1)	2	0.25	1	1	1	2.68	0.067
	0.5	0.25	1	1	1	2.64	0.066
Strength of relative functionality on attractiveness (1)	2	0.25	1	1	1	2.68	0.067
	0.5	0.25	1	1	1	2.64	0.066

Tv Production (2)	3	0.25	1	1	1	2.65	0.067
	1	0.25	1	1	1	2.65	0.066
Shipment Trend Observation Time (3)	4	0.25	1	1	1	2.65	0.067
	2	0.25	1	1	1	2.65	0.066
Shipment Expectations Formation Time (1)	2	0.25	1	1	1	2.65	0.067
	0.5	0.25	1	1	1	2.65	0.066
Inventory Goal (2000)	2500	0.25	1	1	1	2.65	0.067
	1500	0.25	1	1	1	2.65	0.066
Inventory Goal Change (1)	2	0.25	1	1	1	2.65	0.067
	0	0.25	1	1	1	2.65	0.066
Desired units per adopter (1)	2	0.25	1	1	1	2.65	0.067
	0.5	0.25	1	1	1	2.65	0.066
Tv Service(1)	2	0.25	1	1	1	2.65	0.067
	0.5	0.25	1	1	1	2.65	0.066
Completion Trend Observation Time(3)	4	0.25	1	1	1	2.65	0.067
	2	0.25	1	1	1	2.65	0.066
Completion Expectations Formation Time (1)	2	0.25	1	1	1	2.65	0.067
	0.5	0.25	1	1	1	2.65	0.066
Service Capacity Goal (2000)	2500	0.25	1	1	1	2.65	0.066
	1500	0.25	1	1	1	2.65	0.066
Service Capacity Goal Change (1)	2	0.25	1	1	1	2.65	0.067
	0	0.25	1	1	1	2.65	0.066
Desired service time (1)	2	0.25	1	1	1.76	2.64	0.067
	0.5	0.25	1	1	0.16	2.67	0.066
Normal annual service calls per adopter (1)	2	0.25	1	1	1	2.65	0.066
	0.5	0.25	1	1	1	2.65	0.066

Policy Analysis

Based on the above analysis, some parameters in the market sector are sensitive to market share and adoption rate, however, any single parameter cannot bring big changes to market share and adoption rate. Therefore, it is worth discussing the possibility of multiple policies and decision rules adopted by companies and governing authorities.

Experiment #1—Contacts Per Adopter

I ran contacts per adopter from 0.04 (Households/Household/Year) to 0.4. From Figure 22 and Figure 23, we can see as contacts per adopter increases, market share and adoption rate grow. Increasing contact per adopter can be achieved by companies incentivizing customers to tell their neighbors about the benefits of water filtration system, such as a program of giving gift cards if customers refer home filtration to a certain number of neighbors. This also indicates that customers' experiences of water filtration system are important. If they feel the product quality, delivery, and service are satisfied, there are more chances they will recommend friends or neighbors to use the product.

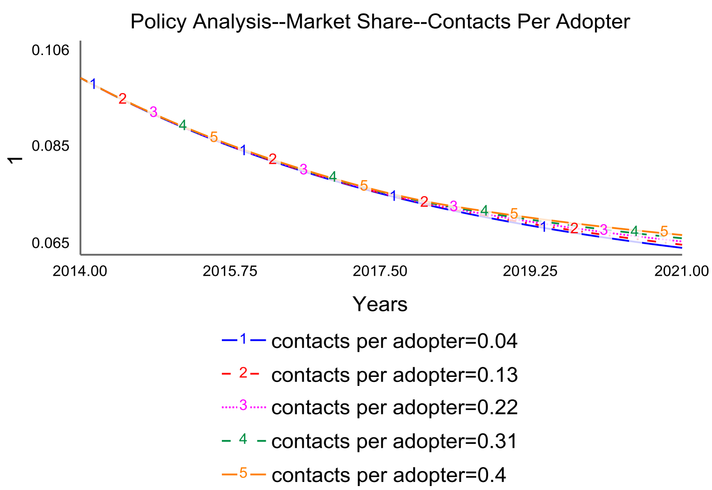

Figure 22 Policy Analysis--Market Share--Contacts Per Adopter

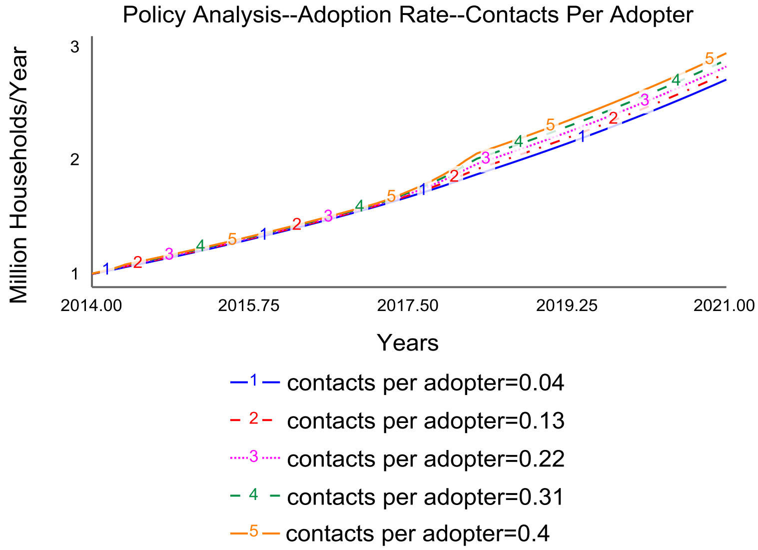

Figure 23 Policy Analysis--Adoption Rate--Contacts Per Adopter

Experiment #2—Normal Adoption Fraction

I ran normal adoption fraction from 0.04 (Unitless) to 0.4. From Figure 24 and Figure 25, we can see as normal adoption fraction increases, market share and adoption rate grow. The policy effect of increasing normal adoption fraction is as the same as that of increasing contacts per adopter. Increasing normal adoption fraction can be achieved by governing authorities providing a subsidy for customers' purchases of water filtration system, especially for low income families and landlord supporting programs. This policy incentivizes demand by subsidizing customers.

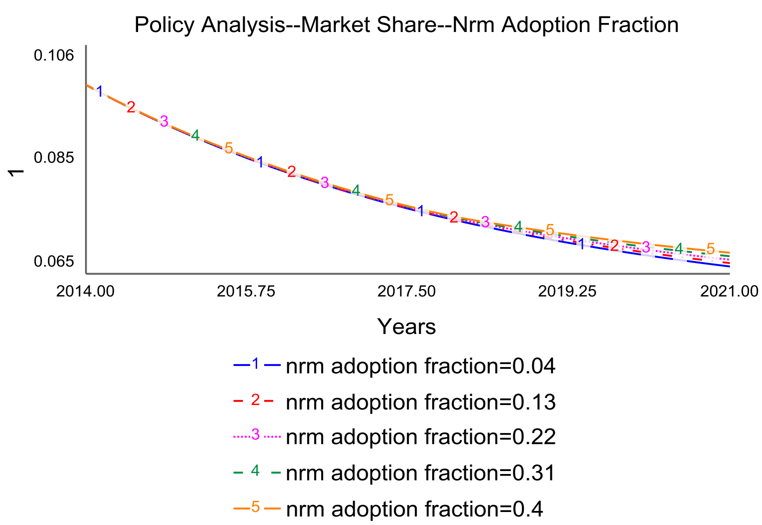

Figure 24 Policy Analysis--Market Share--Normal Adoption Fraction

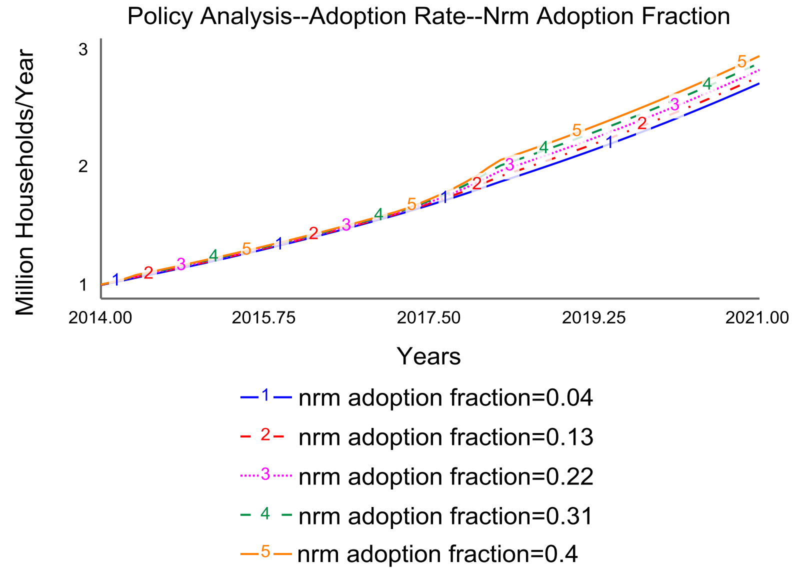

Figure 25 Policy Analysis--Adoption Rate--Normal Adoption Fraction

Experiment #3—Advertising Effect

I ran advertising effect from 0.012 (1/Year) to 0.02. From Figure 26 and Figure 27, we can see it is apparent that an increase in advertising effect will boost market share and adoption rate. As advertising effect goes up to 0.02, market share will grow. Increasing advertising effect can be achieved by companies increasing the investment in advertisement and positively advertising social benefits of water filtration systems such as less pollution and more recyclable benefits. However, the investment in advertisement may be limited due to companies' initial capital, so, the policy should combine with other market strategies such as increasing contacts per adopter.

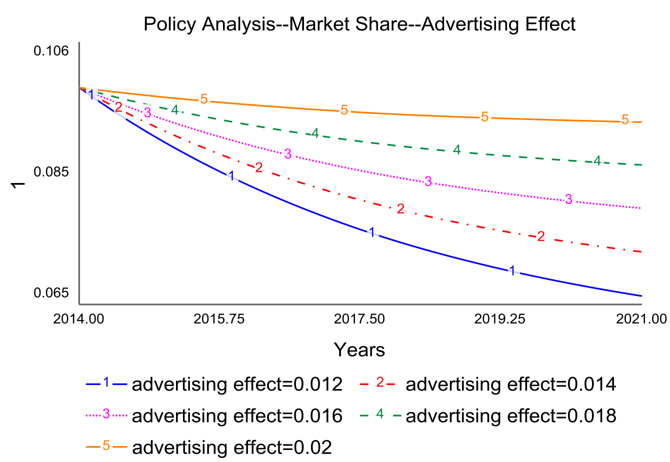

Figure 26 Policy Analysis--Market Share--Advertising Effect

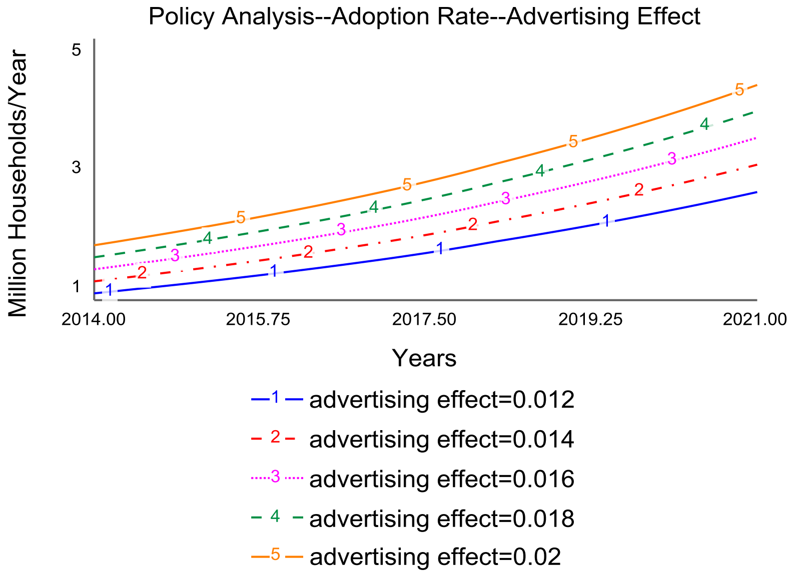

Figure 27 Policy Analysis--Adoption Rate--Advertising Effect

Among the above three parameters, normal adoption fraction along with the effect of attractiveness drive adoption fraction, which along with contacts per adopter drive adoption from word of mouth. The advertising effect drives adoption from advertising. Adoption from word of mouth and adoption from advertising together drive water filtration adoption rate. Although the advertising effect has a big influence on market share, it cannot eliminate the barrier of the high initial cost of home water filtration systems. On the one hand, the initial capital of companies may be limited to be used in advertising, on the other hand, we are not sure about the advertising effect to the specific subjects such as low income families and landlords. Moreover, in real life, word of mouth often plays an important role in expanding market because product attractiveness brought by user experience determines whether customers purchase a product or not. Therefore, I suggest that companies should combine multiple policies such as initial cost subsidy, customers' incentives as well as advertising.

Experiment #4—Average Product Life

I ran average product life from 12.5 (Years) to 20. From Figure 28 and 29, we can see as average product life increases, market share grows and adoption rate stays similar to the base run. The reason behind this is longer product life makes fewer adopters become nonadopters, increasing market share. Average product life does not impact a lot on adoption rate. Increasing average product life can be achieved by companies focusing on product quality and producing more durable products. This policy is meaningful to the inventory and capacity management. Long product life can be helpful in adjusting the inventory and guiding companies how to add capacity. It may avoid excessive stock caused by short product life. However, this policy needs to combine with other policies to achieve a significant policy effect.

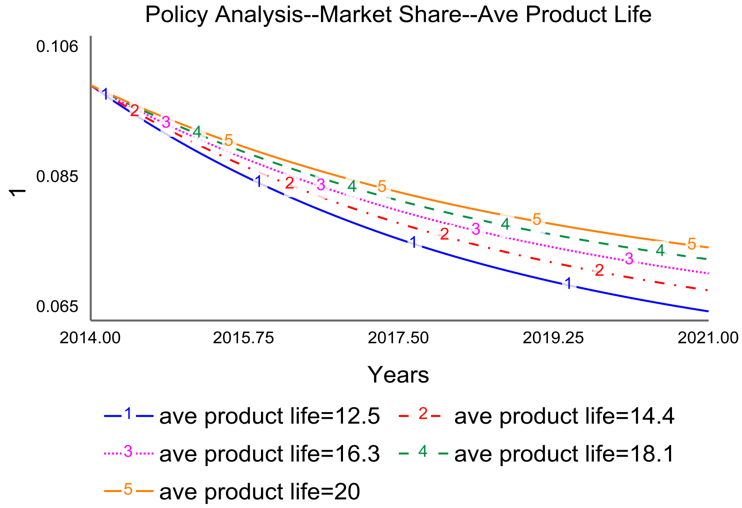

Figure 28 Policy Analysis--Market Share--Average Product Life

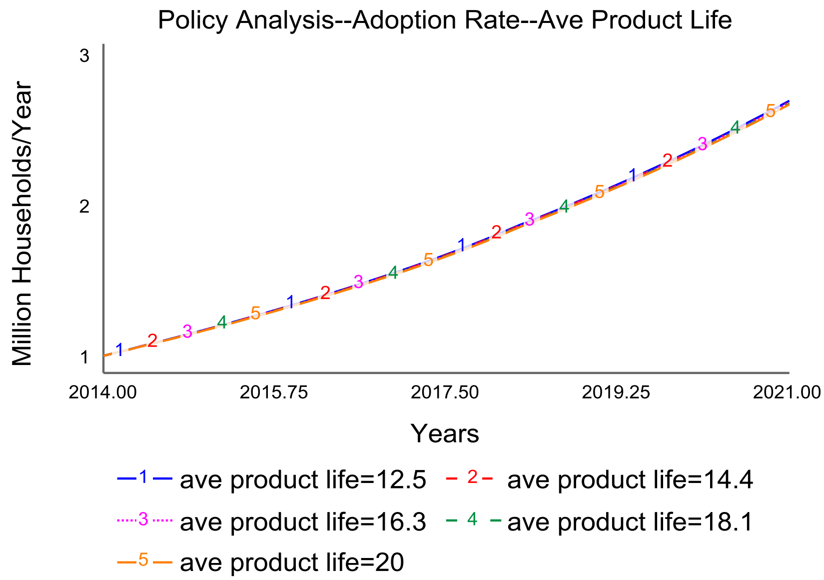

Figure 29 Policy Analysis--Adoption Rate--Average Product Life

Experiment #5—Supply and Demand Policy

If combining supply policy (increasing average product life) and demand policy (increasing normal adoption fraction), from Figure 30 and Figure 31, we can see they have relatively big policy effects on market share, even though the market share of home water filtration systems is still declining.

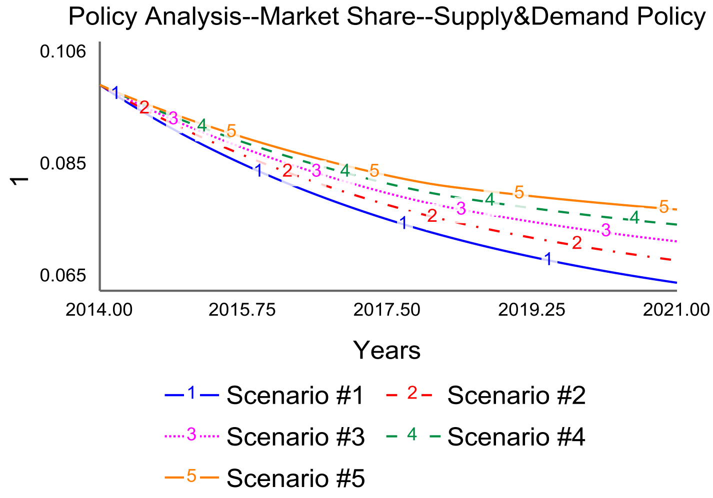

Figure 30 Policy Analysis--Market Share—Supply & Demand Policy

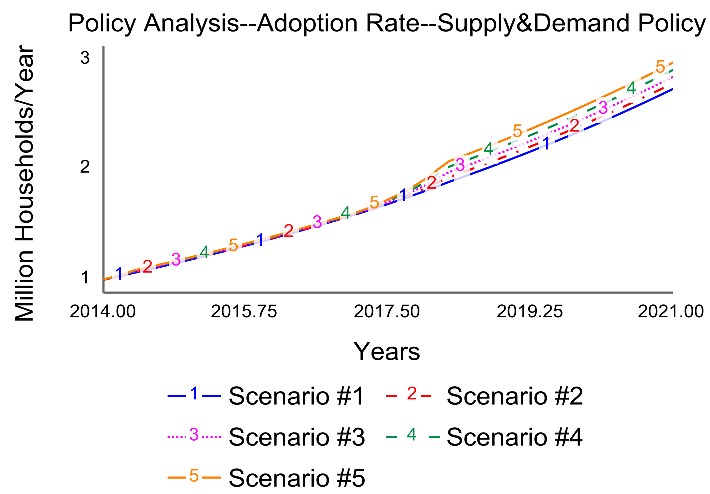

Figure 31 Policy Analysis--Adoption Rate—Supply & Demand Policy

Experiment #6—Supply and Market Policy

If combining supply policy and market policy (increasing contacts per adopter and increasing advertising effect), from Figure 32 and Figure 33, it is evident from the results of this experiment that this policy combination will totally change the story of home water filtration systems in urban China.

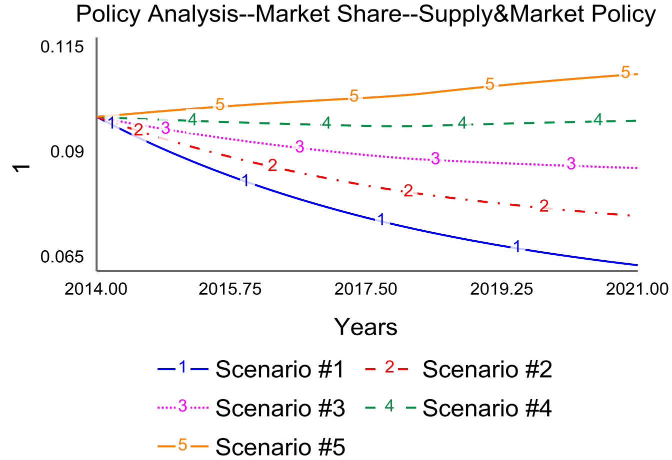

Figure 32 Policy Analysis--Market Share—Supply & Market Policy

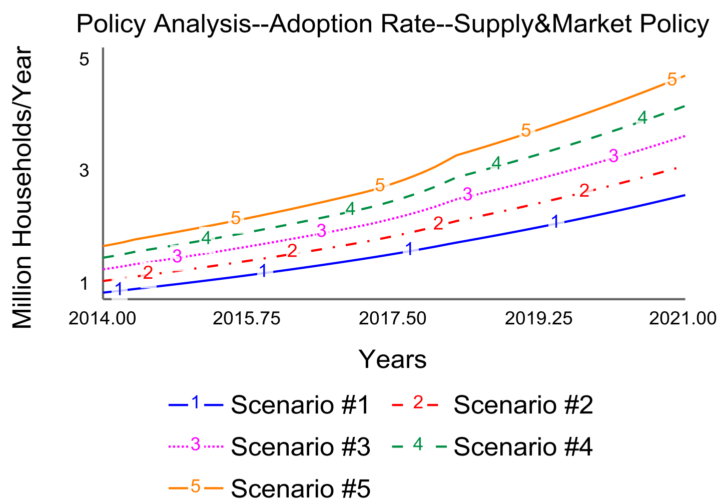

Figure 33 Policy Analysis--Adoption Rate—Supply & Market Policy

Experiment #7—Integrated Policies

If combining supply policy, demand policy, and market policy, from Figure 34 and Figure 35, we can see the effects of combining three policies are the strongest among all the policy tests. In the fifth scenario, when average product life equals 20, normal adoption fraction equals 0.4, contacts per adopter equals 0.4, and advertising effect equals 0.02, the market share climbs to 14.91% by 2021.

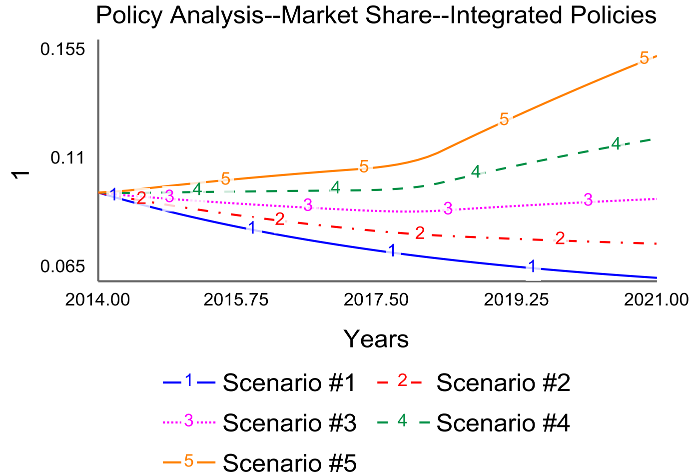

Figure 34 Policy Analysis--Market Share—Integrated Policies

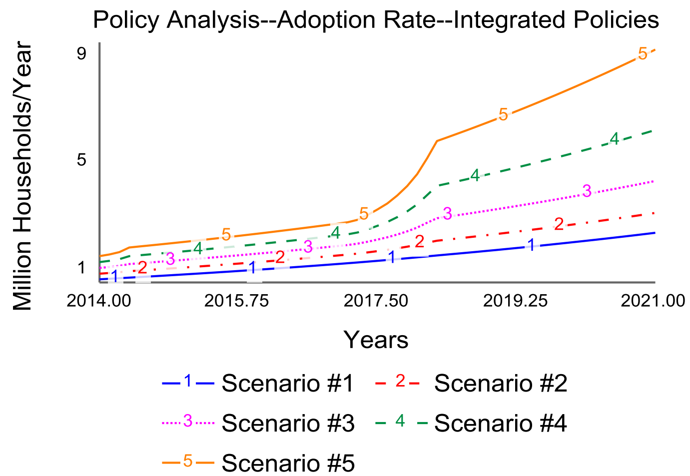

Figure 35 Policy Analysis--Adoption Rate—Integrated Policies

We need to notice the market cannot grow without any limitations. There should be some limitations on future growth that comes from within the model as saturation occurs. This may be a market size with a graphical function that constrains future growth, such as a graph below. In this way, the growth of new nonadopters will be limited.

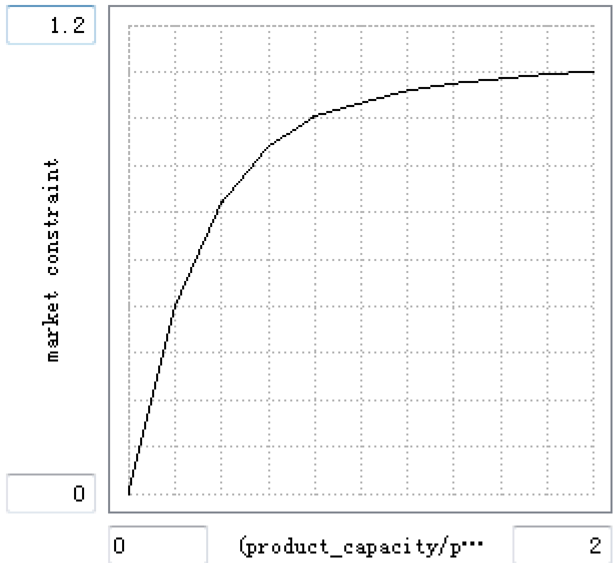

Figure 36 Market Constraint

PID Experiments

Since this model was focusing on the physical system of water filtration industry, I also wanted to test if engineering control systems which use forecasting approaches that combine proportional, integral and derivative (PID) evaluations to accomplish the kinds of smooth adjustments to desired goals could improve the performance of the inventory ordering system and reduce order delivery delay.

PID control was discussed in "Trend forecasting for stability in supply chains" (Saeed 2008) and "Can trend forecasting improve stability in supply chains? A response to Forrester's challenge in Appendix L of Industrial Dynamics" (Saeed 2014a). Three controls together are to correct the difference between the inventory goal and a forecast of inventory. The proportional control is driven by a part of production orders for inventory on the basis of inventory discrepancy. The proportional control weight Wp is to adjust the inventory discrepancy. The trend in inventory discrepancy is used to modify production orders, which drives the derivative control. The derivative control weight Wd is to adjust the process of using the trend to modify production orders. The integral control is driven by a part of cumulative production orders for inventory. The integral control weight Wi is to adjust the cumulative inventory discrepancy.

I added PID control into the production control sector. (see Figure 37) The equations in this sector are shown in Appendix B.

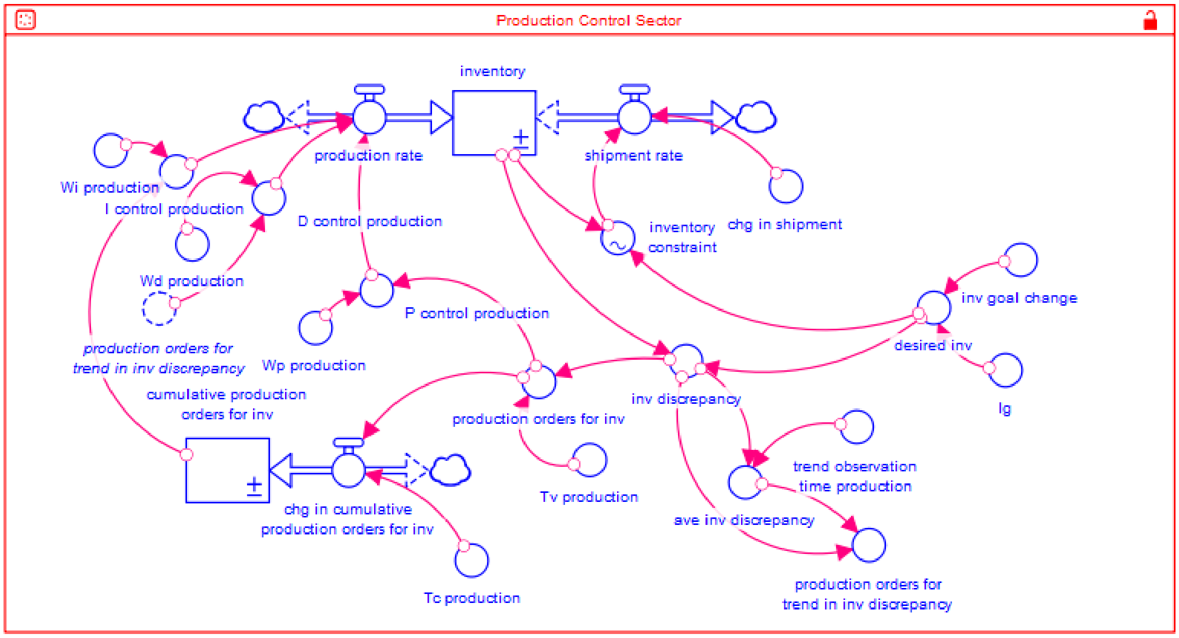

Figure 37 PID Control--Production Control Sector

By running the five experiments shown in Table 7, we can see the results of these experiments in Figure 38. The results indicate that more kinds of controls and higher weight assigned to controls can reduce order delivery delay and make order delivery delay more quickly approach normal order delivery delay. However, these experiments do not have effects on the market share of water filtration systems.

Table 7 Policy Parameters for PID Experiments in Production Control

Policy	Description	Wi	Wd	Wp
#1	An ordering policy based on inventory discrepancy combining proportional, derivative, and integral control.	2	1	2
#2	An ordering policy based on inventory discrepancy only using proportional control.	0	0	1
#3	An ordering policy based on inventory discrepancy combining proportional and derivative control.	0	1	1
#4	An ordering policy similar to policy 1, by with a lower weight assigned to integral control and proportional control.	1	1	1
#5	An ordering policy similar to policy 1, by with a higher weight assigned to each control.	5	5	5

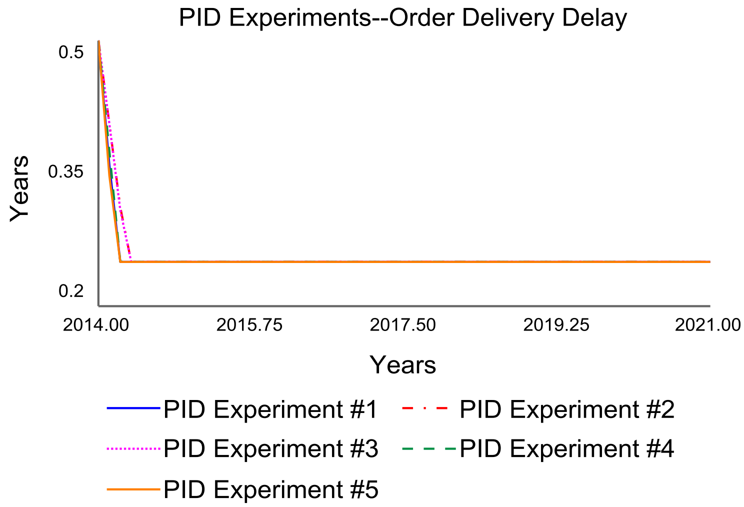

Figure 38 PID Experiments--Order Delivery Delay

Similarly, I also added integral control and derivative control into the service capacity sector. (see Figure 39) The equations in this sector are shown in Appendix B.

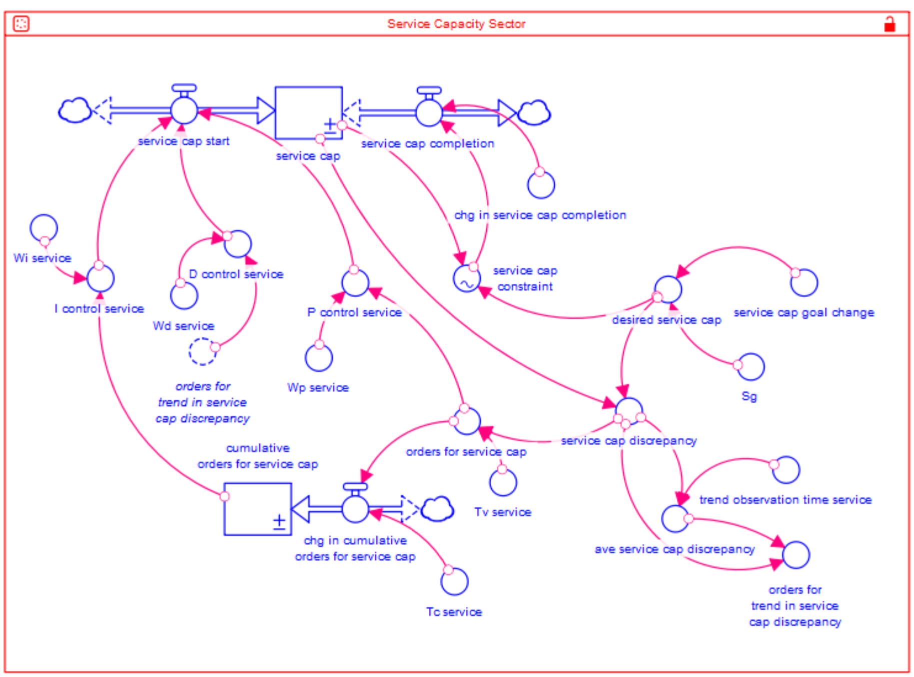

Figure 39 PID Control--Service Capacity Sector

By running the five experiments shown in Table 8, we can see the results of these experiments in Figure 40. The results indicate that more kinds of controls and higher weight assigned to controls can reduce service time and make service time more quickly approach desired service time. However, these experiments do not have effects on the market share of water filtration systems.

Table 8 Policy Parameters for PID Experiments in Service Capacity

Policy	Description	Wi	Wd	Wp
#1	An ordering policy based on inventory discrepancy combining proportional, derivative, and integral control.	2	1	2
#2	An ordering policy based on inventory discrepancy only using proportional control.	0	0	1
#3	An ordering policy based on inventory discrepancy combining proportional and derivative control.	0	1	1
#4	An ordering policy similar to policy 1, by with a lower weight assigned to proportional control.	1	1	1
#5	An ordering policy similar to policy 1, by with a higher weight assigned to each control.	5	5	5

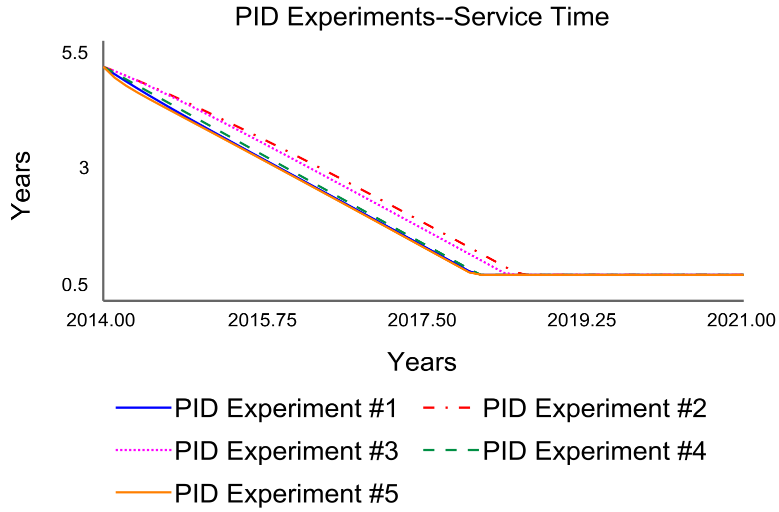

Figure 40 PID Experiments--Service Time

Why are parameters in the production control sector and the service capacity sector insensitive to market share and adoption rate? There are three balancing feedback loops in this model, which makes this model robust. That means when reducing order delivery delay, the number of water filtration adopters increases, which brings more new service calls and increases service call backlog, increasing service time. More service time means less product attractiveness, which makes the number of water filtration adopters decline. Therefore, the policy of reducing order delivery delay or reducing service time cannot increase the number of water filtration adopters.

Limitations and Future Work

Data Limitations

This paper collected the annual consumption data of home water filtration systems in urban China. However, more detailed data and information need to be collected for the future work, such as consumption of home water filtration systems in different geographical regions of China, price of different brands of home water filtration systems, pricing strategies of home water filtration systems, functions of different brands of home water filtration systems, current policies about home water filtration systems, etc.

For a future study it would be important to use a much more complete data set. While this paper was able to identify the reasons that cause a low adoption rate of home water filtration systems and recommend policies to improve the current situation, an in-depth study about this problem would give a deeper insight and a more comprehensive analysis.

Recommendations for future study

There is additional work that could be done with the model, which falls into two categories: correcting the limitation of the data collected and expanding the structures in the model. The current model does not take the financial system and technology growth into account. A possible change is to add financial and technology growth into the model. This change will bring three additional reinforcing feedback loops. (see Figure 41)

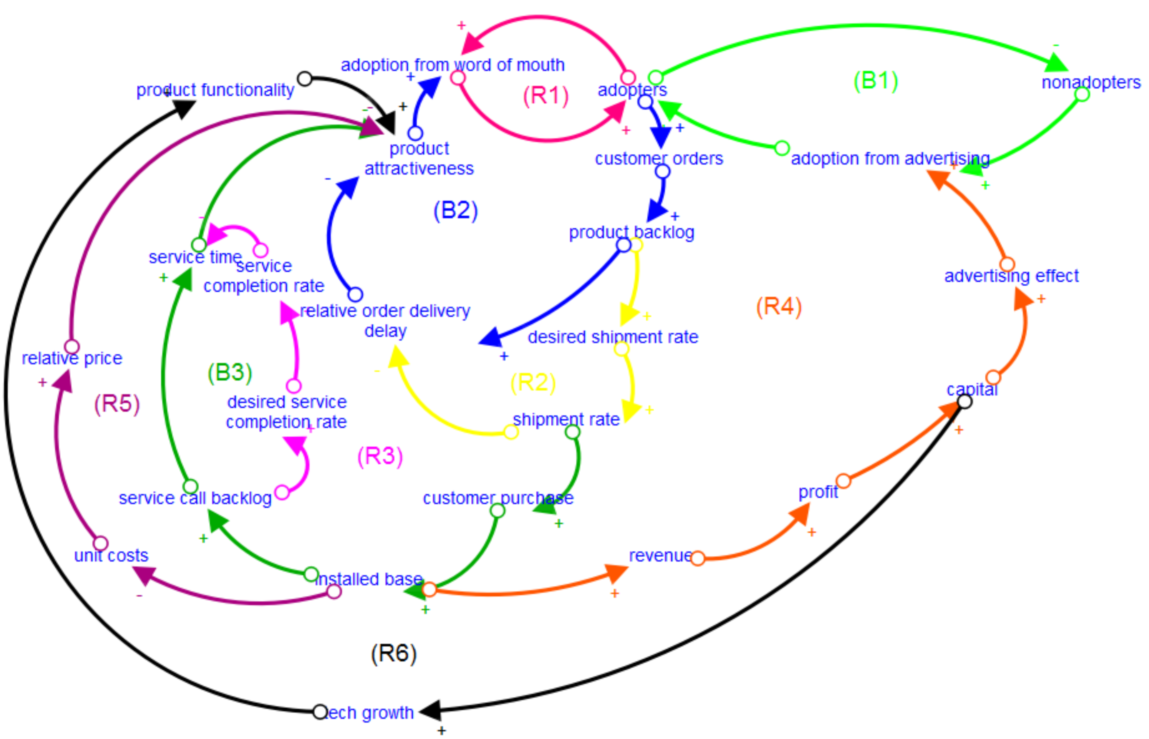

Figure 41 Future Dynamic Hypothesis

R4: More adopters mean more customer orders, increasing product backlog. More product backlog increases desired shipment rate and then shipment rate. A higher shipment rate means more customer purchases, increasing installed base. More installed base increases revenue, profit, and capital. More capital will invest in advertisement, increasing advertising effect, which drives more adoption from advertising and thus increases the number of adopters.

R5: More adopters mean more customer orders, increasing product backlog. More product backlog increases desired shipment rate and then shipment rate. A higher shipment rate means more customer purchases, increasing installed base. More installed base reduces unit costs, which decreases relative price. Lower relative price means higher product attractiveness, which brings more adoption from word of mouth, increasing the number of adopters.

R6: More adopters mean more customer orders, increasing product backlog. More product backlog increases desired shipment rate and then shipment rate. A higher shipment rate means more customer purchases, increasing installed base. More installed base increases revenue, profit, and capital. More capital will bring technology growth, increasing the product functionality, which makes the product more attractive. Higher product attractiveness means more adoption from word of mouth, increasing the number of adopters.

Furthermore, although I suggested that governing authorities should subsidize customers, in the future work, initial cost subsidy by companies should also be studied. Specifically speaking, initial cost subsidy and its impact on company profitability in the short and long run should be included in the future work. Based on the future study, it is possible for companies to subsidize customers. Not only should the impact of initial cost subsidy on company profitability be studied, but the impacts of different policies on company profitability should also be included in the future work. For example, the costs of market policy such as advertising and customers' incentives and their impacts on company profitability. Thus according to the benefits and costs of different policies, a more comprehensive policy suggestion could be offered to companies.

Conclusion

This paper has attempted to identify the reasons why the market share of the home water filtration industry in urban China has declined when home water filtration systems have a number of advantages over bottled water. This paper has developed a system dynamics model to analyze the reasons and test policies in order to improve the current situation. The key conclusions can be summarized as following:

- Order delivery delay and service time are some of the reasons for a low adoption rate of home water filtration systems. However, order delivery delay and service time are not limiting factors in the current scenario.
- Initial cost is a limiting factor to the growth of the market of home water filtration systems. Low income families and landlords in urban China have low intentions of paying a high initial cost for water filtration systems.
- The following parameters are sensitive to market share and adoption rate. They include contacts per adopter, normal adoption fraction, advertising effect, and average product life.
- Companies should combine market policy and demand policy. Although advertising policy has a big influence on the water filtration market share, it cannot eliminate the initial cost barrier. Word of mouth plays an important role in expanding market in real life. Companies should combine customers' incentives and advertising policy in order to increase the market share.
- Governing authorities should subsidize customers for their initial purchases of home water filtration systems, especially for low income families and landlords.
- Companies should also improve product quality and produce more durable home water filtration systems in order to increase the market share. This policy is helpful to improve inventory management as well.
- Multiple policies have better policy effects. When average product life equals 20, normal adoption fraction equals 0.4, contacts per adopter equals 0.4, and advertising effect equals 0.02, the market share reaches 14.91% by 2021.

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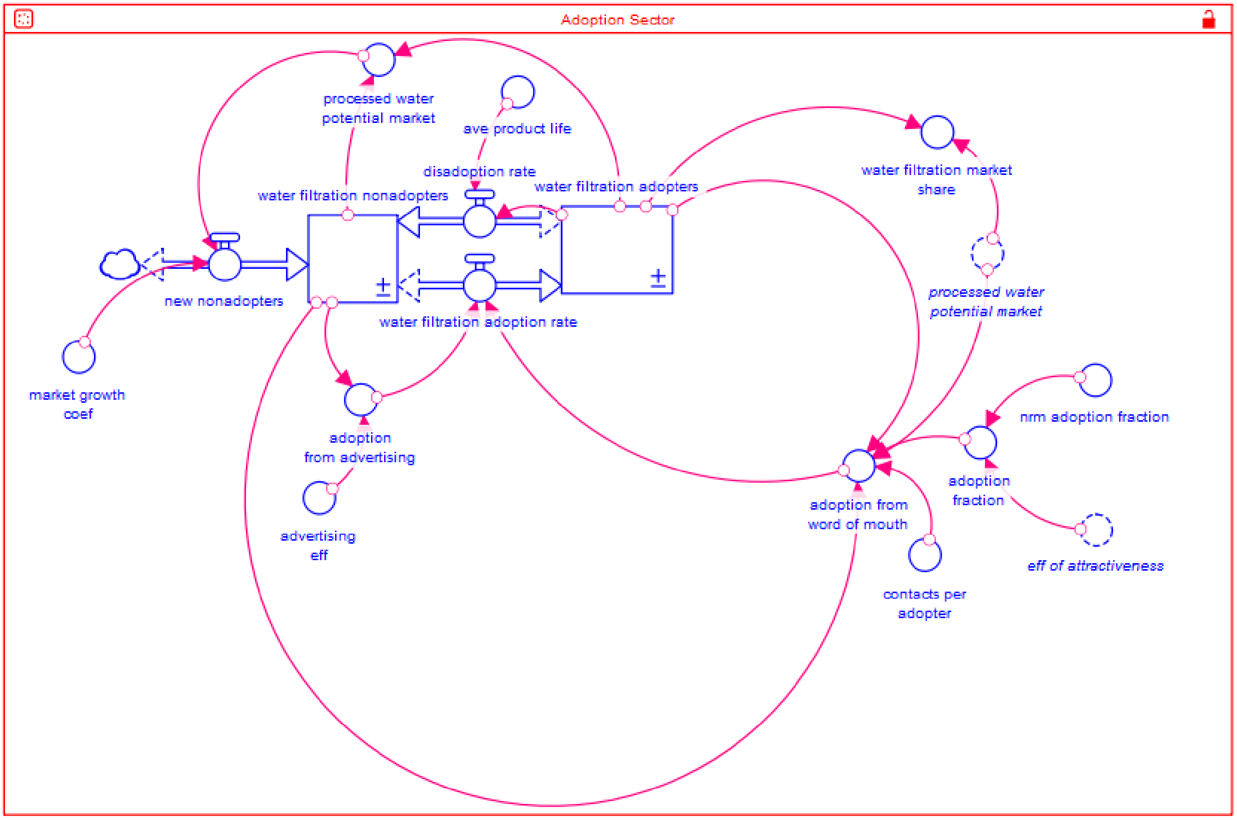
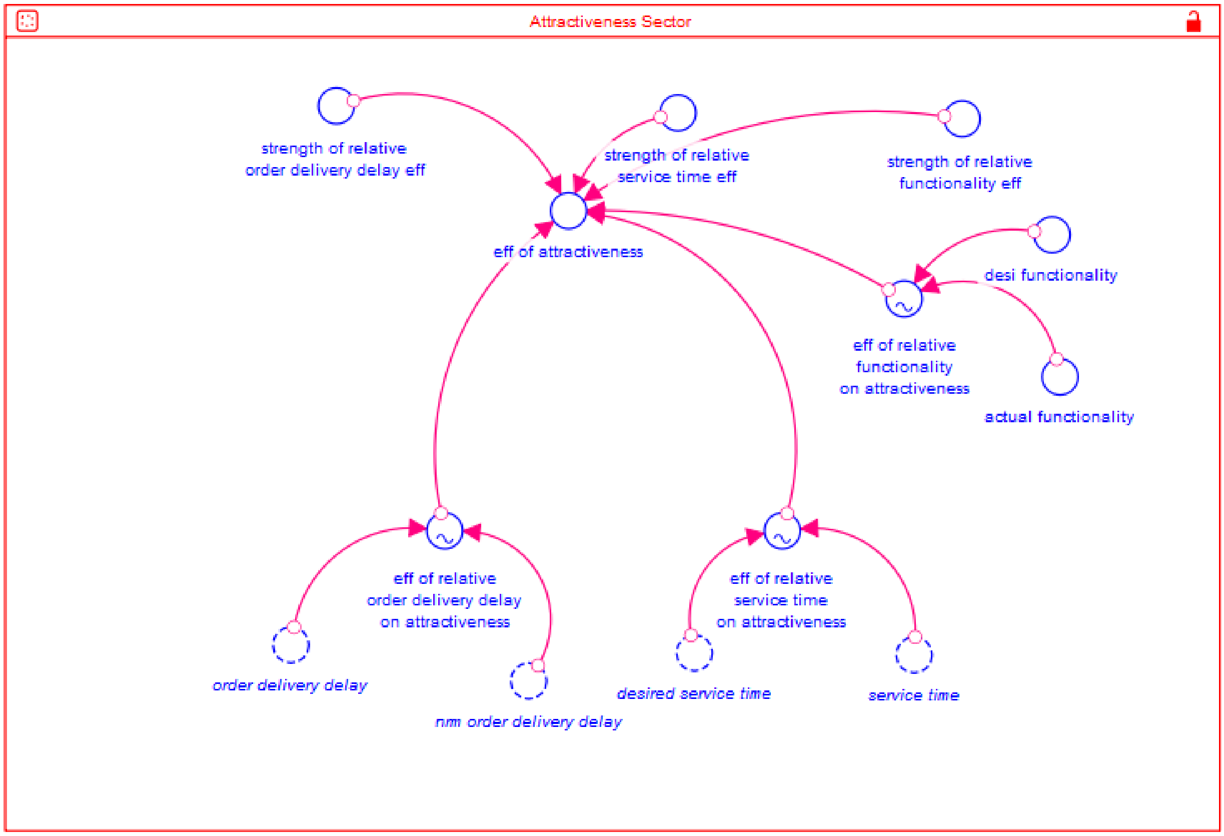
Appendix A



Adoption_Sector:

adoption_fraction = nrm_adoption_fraction*eff_of_attractiveness
UNITS: 1
adoption_from_advertising = water_filtration_nonadopters*advertising_eff
UNITS: Million Households/Year
adoption_from_word_of_mouth =
contacts_per_adopter*water_filtration_adopters*(water_filtration_nonadopters/processed_water_potential_market)*adoption_fraction
UNITS: Million Households/Year
advertising_eff = 0.012
UNITS: 1/Year
ave_product_life = 12.5
UNITS: Years
contacts_per_adopter = 0.04
UNITS: Households/Household/Year
market_growth_coef = 0.12
UNITS: 1/Year
nrm_adoption_fraction = 0.04
UNITS: 1
processed_water_potential_market = water_filtration_nonadopters+water_filtration_adopters
UNITS: Million Households
water_filtration_adopters(t) = water_filtration_adopters(t - dt) + (water_filtration_adoption_rate - disadoption_rate) * dt

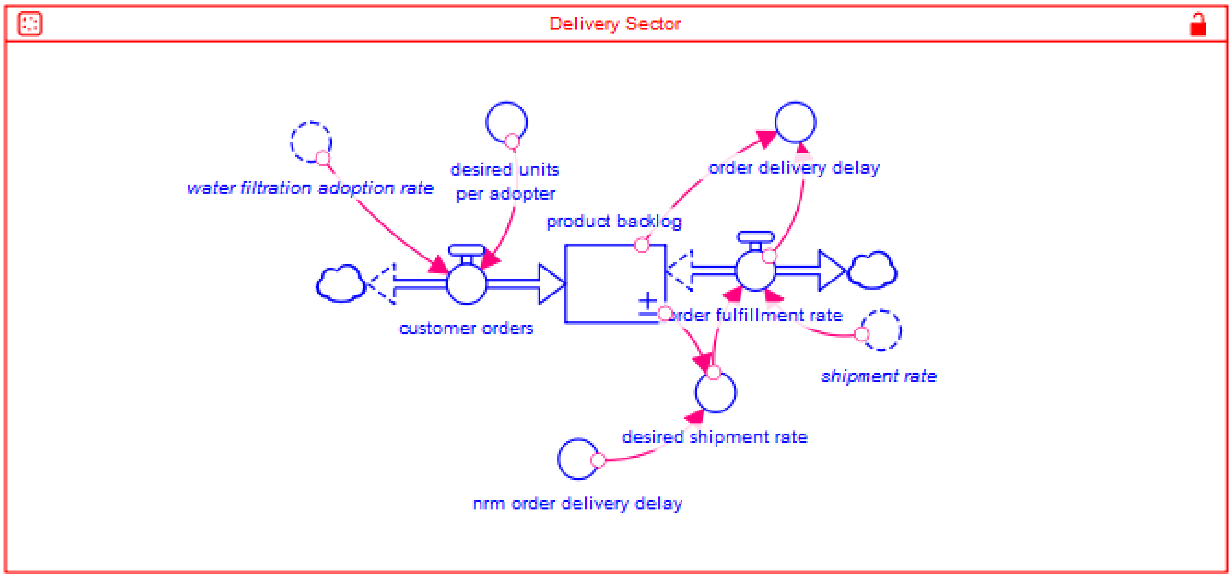
INIT water_filtration_adopters = 10
UNITS: Million Households
INFLOWS:
water_filtration_adoption_rate = (adoption_from_advertising+adoption_from_word_of_mouth)
UNITS: Million Households/Year
OUTFLOWS:
disadoption_rate = water_filtration_adopters/ave_product_life
UNITS: Million Households/Year
water_filtration_market_share = water_filtration_adopters/processed_water_potential_market
UNITS: 1
water_filtration_nonadopters(t) = water_filtration_nonadopters(t - dt) + (new_nonadopters + disadoption_rate - water_filtration_adoption_rate) * dt
INIT water_filtration_nonadopters = 92
UNITS: Million Households
INFLOWS:
new_nonadopters = market_growth_coef*processed_water_potential_market
UNITS: Million Households/Year
disadoption_rate = water_filtration_adopters/ave_product_life
UNITS: Million Households/Year
OUTFLOWS:
water_filtration_adoption_rate = (adoption_from_advertising+adoption_from_word_of_mouth)
UNITS: Million Households/Year



Attractiveness_Sector:

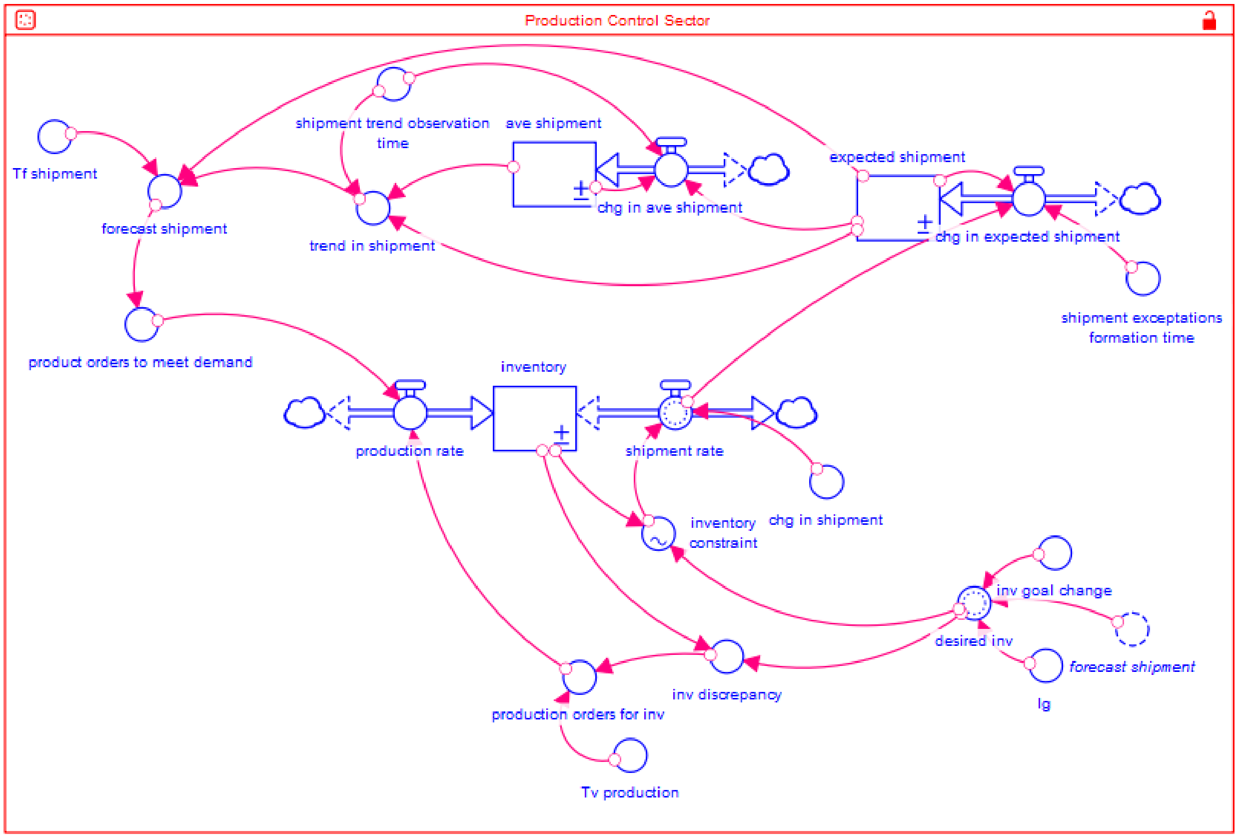
actual_functionality = 1
UNITS: 1
desi_functionality = 1
UNITS: 1
eff_of_attractiveness = ((eff_of_relative_service_time_on_attractiveness ^ strength_of_relative_service_time_eff) * (eff_of_relative_order_delivery_delay_on_attractiveness ^ strength_of_relative_order_delivery_delay_eff)*(eff_of_relative_functionality_on_attractiveness^strength_of_relative_functionality_eff)) ^ (1 / (strength_of_relative_service_time_eff + strength_of_relative_order_delivery_delay_eff+strength_of_relative_functionality_eff))
UNITS: 1
eff_of_relative_functionality_on_attractiveness = GRAPH(actual_functionality / desi_functionality)
(0.000, 0.000), (0.200, 0.090), (0.400, 0.240), (0.600, 0.420), (0.800, 0.670), (1.000, 1.000), (1.200, 1.330), (1.400, 1.610), (1.600, 1.790), (1.800, 1.930), (2.000, 2.000)
UNITS: 1
eff_of_relative_order_delivery_delay_on_attractiveness = GRAPH(order_delivery_delay/nrm_order_delivery_delay)
(0.000, 2.000), (0.200, 1.950), (0.400, 1.840), (0.600, 1.670), (0.800, 1.410), (1.000, 1.000), (1.200, 0.690), (1.400, 0.480), (1.600, 0.340), (1.800, 0.240), (2.000, 0.160)
UNITS: 1
eff_of_relative_service_time_on_attractiveness = GRAPH(service_time/desired_service_time)
(0.000, 2.000), (0.200, 1.950), (0.400, 1.840), (0.600, 1.670), (0.800, 1.410), (1.000, 1.000), (1.200, 0.690), (1.400, 0.480), (1.600, 0.340), (1.800, 0.240), (2.000, 0.160)
UNITS: 1

strength_of_relative_functionality_eff = 1
UNITS: 1
strength_of_relative_order_delivery_delay_eff = 1
UNITS: 1
strength_of_relative_service_time_eff = 1
UNITS: 1



Delivery_Sector:

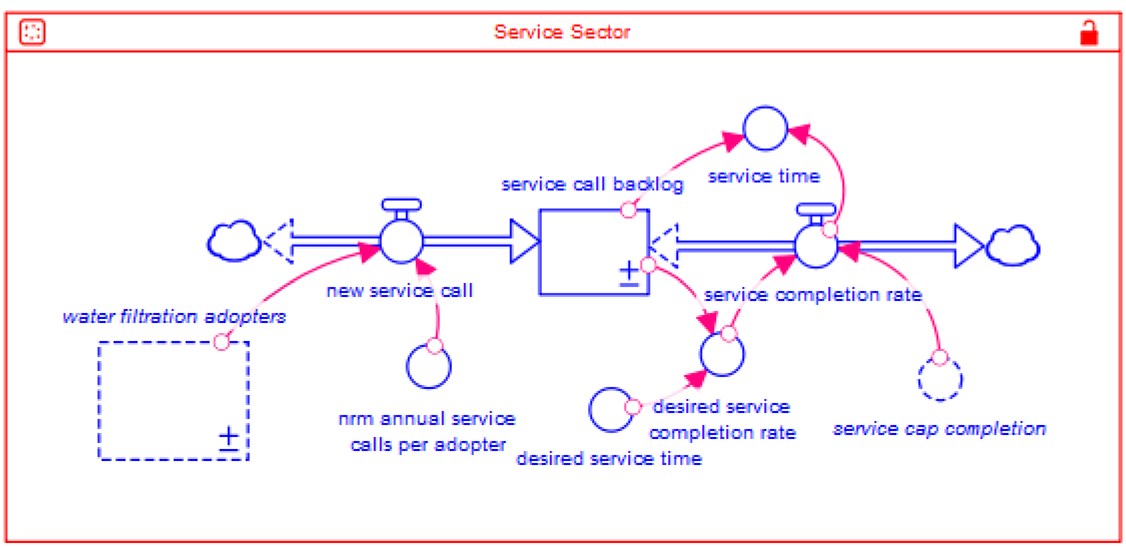
desired_shipment_rate = product_backlog/nrm_order_delivery_delay
UNITS: Million Widgets/Year
desired_units_per_adopter = 1
UNITS: Widgets/Household
nrm_order_delivery_delay = 0.25
UNITS: Years
order_delivery_delay = product_backlog/(order_fulfillment_rate+0.00001)
UNITS: Years
product_backlog(t) = product_backlog(t - dt) + (customer_orders - order_fulfillment_rate) * dt
INIT product_backlog = desired_inv
UNITS: Million Widgets
INFLOWS:
customer_orders = desired_units_per_adopter*water_filtration_adoption_rate
UNITS: Million Widgets/Year
OUTFLOWS:
order_fulfillment_rate = MIN(shipment_rate, desired_shipment_rate)
UNITS: Million Widgets/Year



Production_Control_Sector:

ave_shipment(t) = ave_shipment(t - dt) + (chg_in_ave_shipment) * dt
INIT ave_shipment = 0
UNITS: Million Widgets/Year
INFLOWS:
chg_in_ave_shipment = (expected_shipment-ave_shipment)/shipment_trend_observation_time
UNITS: Million Widgets/Year/Years
chg_in_shipment = 4000*1+0*5*SIN(TIME)
UNITS: Million Widgets/Year
desired_inv = Ig+inv_goal_change*forecast_shipment
UNITS: Million Widgets
expected_shipment(t) = expected_shipment(t - dt) + (chg_in_expected_shipment) * dt
INIT expected_shipment = 0
UNITS: Million Widgets/Year
INFLOWS:
chg_in_expected_shipment = (shipment_rate-expected_shipment)/shipment_exceptations_formation_time
UNITS: Million Widgets/Year/Years
forecast_shipment = expected_shipment+trend_in_shipment*Tf_shipment
UNITS: Million Widgets/Year
Ig = 2000
UNITS: Million Widgets
inv_discrepancy = desired_inv-inventory
UNITS: Million Widgets

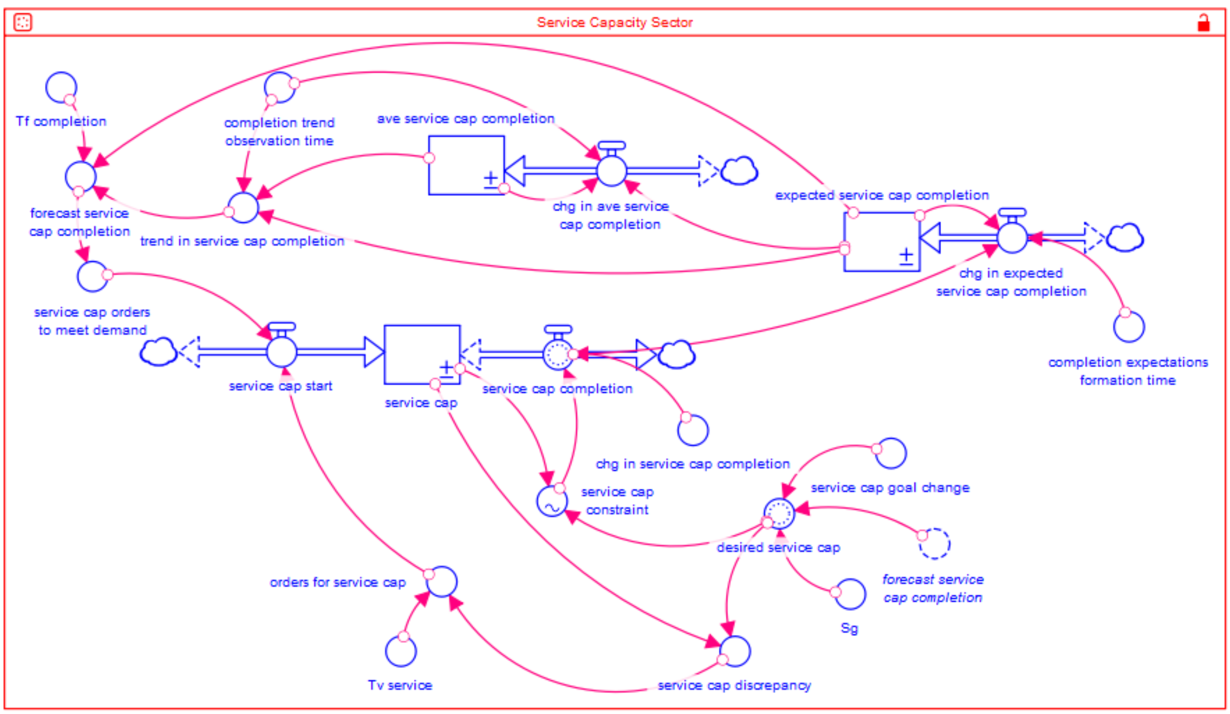
inv_goal_change = 1
UNITS: Years
inventory(t) = inventory(t - dt) + (production_rate - shipment_rate) * dt
INIT inventory = product_backlog
UNITS: Million Widgets
INFLOWS:
production_rate = production_orders_for_inv+product_orders_to_meet_demand
UNITS: Million Widgets/Year
OUTFLOWS:
shipment_rate = (0+STEP(chg_in_shipment,2))*inventory_constraint
UNITS: Million Widgets/Year
inventory_constraint = GRAPH(inventory/desired_inv)
(0.000, 0.000), (0.200, 0.558), (0.400, 0.756), (0.600, 0.870), (0.800, 0.942), (1.000, 1.000), (1.200, 1.038), (1.400, 1.062), (1.600, 1.068), (1.800, 1.074), (2.000, 1.080)
UNITS: 1
product_orders_to_meet_demand = forecast_shipment
UNITS: Million Widgets/Year
production_orders_for_inv = inv_discrepancy/Tv_production
UNITS: Million Widgets/Year
shipment_exceptations_formation_time = 1
UNITS: Years
shipment_trend_observation_time = 3
UNITS: Years
Tf_shipment = 0
UNITS: Years
trend_in_shipment = (expected_shipment-ave_shipment)/shipment_trend_observation_time
UNITS: Million Widgets/Year
Tv_production = 2
UNITS: Years



Service_Sector:

desired_service_completion_rate = service_call_backlog/desired_service_time
UNITS: Calls/Year

desired_service_time = 1
UNITS: Years
nrm_annual_service_calls_per_adopter = 1
UNITS: Calls/Year/Household
service_call_backlog(t) = service_call_backlog(t - dt) + (new_service_call - service_completion_rate) * dt
INIT service_call_backlog = desired_service_cap
UNITS: Calls
INFLOWS:
new_service_call = water_filtration_adopters*nrm_annual_service_calls_per_adopter
UNITS: Calls/Year
OUTFLOWS:
service_completion_rate = MIN(service_cap_completion, desired_service_completion_rate)
UNITS: Calls/Year
service_time = service_call_backlog/(service_completion_rate+0.0000001)
UNITS: Years

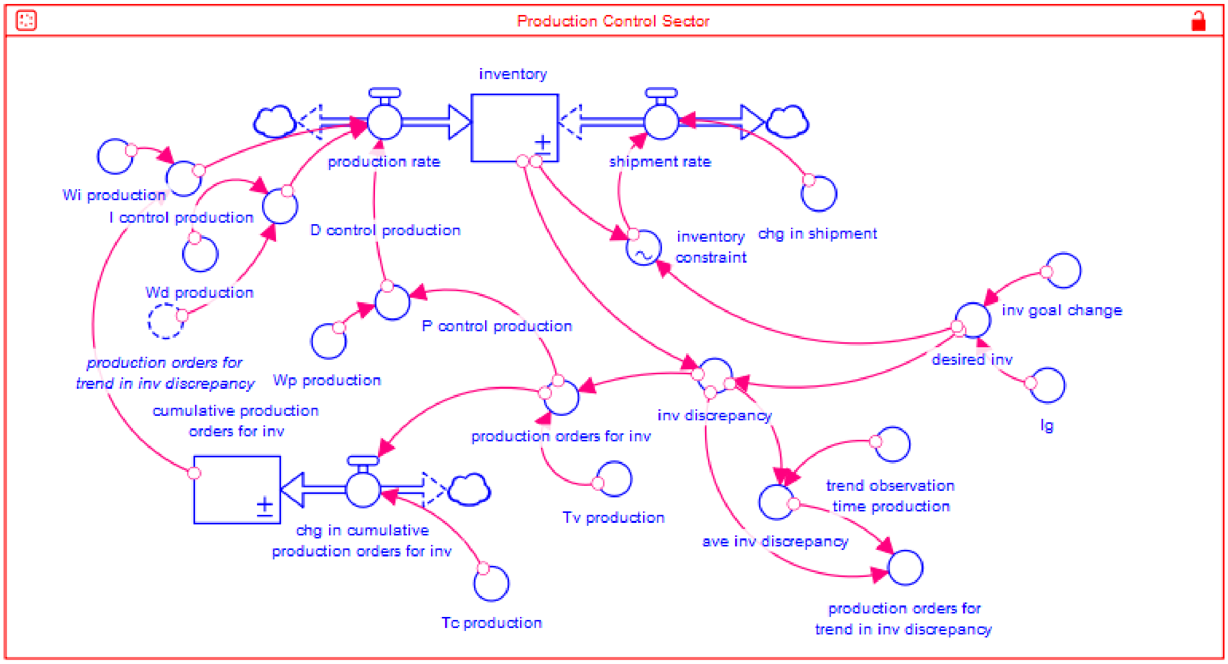


Service_Capacity_Sector:

ave_service_cap_completion(t) = ave_service_cap_completion(t - dt) + (chg_in_ave_service_cap_completion) * dt
INIT ave_service_cap_completion = 0
UNITS: Calls/Year
INFLOWS:
chg_in_ave_service_cap_completion = (expected_service_cap_completion-ave_service_cap_completion)/completion_trend_observation_time
UNITS: Calls/Year/Years

chg_in_service_cap_completion = 400*1+0*5*SIN(TIME)
UNITS: Calls/Year
completion_expectations_formation_time = 1
UNITS: Years
completion_trend_observation_time = 3
UNITS: Years
desired_service_cap = Sg+service_cap_goal_change*forecast_service_cap_completion
UNITS: Calls
expected_service_cap_completion(t) = expected_service_cap_completion(t - dt) + (chg_in_expected_service_cap_completion) * dt
INIT expected_service_cap_completion = 0
UNITS: Calls/Year
INFLOWS:
chg_in_expected_service_cap_completion = (service_cap_completion-expected_service_cap_completion)/completion_expectations_formation_time
UNITS: Calls/Year/Years
forecast_service_cap_completion = expected_service_cap_completion+trend_in_service_cap_completion*Tf_completion
UNITS: Calls/Year
orders_for_service_cap = service_cap_discrepancy/Tv_service
UNITS: Calls/Year
service_cap(t) = service_cap(t - dt) + (service_cap_start - service_cap_completion) * dt
INIT service_cap = service_call_backlog
UNITS: Calls
INFLOWS:
service_cap_start = orders_for_service_cap+service_cap_orders_to_meet_demand
UNITS: Calls/Year
OUTFLOWS:
service_cap_completion = (0+STEP(chg_in_service_cap_completion,2))*service_cap_constraint
UNITS: Calls/Year
service_cap_constraint = GRAPH(service_cap/desired_service_cap)
(0.000, 0.000), (0.200, 0.558), (0.400, 0.756), (0.600, 0.870), (0.800, 0.942), (1.000, 1.000), (1.200, 1.038), (1.400, 1.062), (1.600, 1.068), (1.800, 1.074), (2.000, 1.080)
UNITS: 1
service_cap_discrepancy = desired_service_cap-service_cap
UNITS: Calls
service_cap_goal_change = 1
UNITS: Years
service_cap_orders_to_meet_demand = forecast_service_cap_completion
UNITS: Calls/Year
Sg = 2000
UNITS: Calls
Tf_completion = 0
UNITS: Years
trend_in_service_cap_completion = (expected_service_cap_completion-ave_service_cap_completion)/completion_trend_observation_time
UNITS: Calls/Year
Tv_service = 1
UNITS: Years

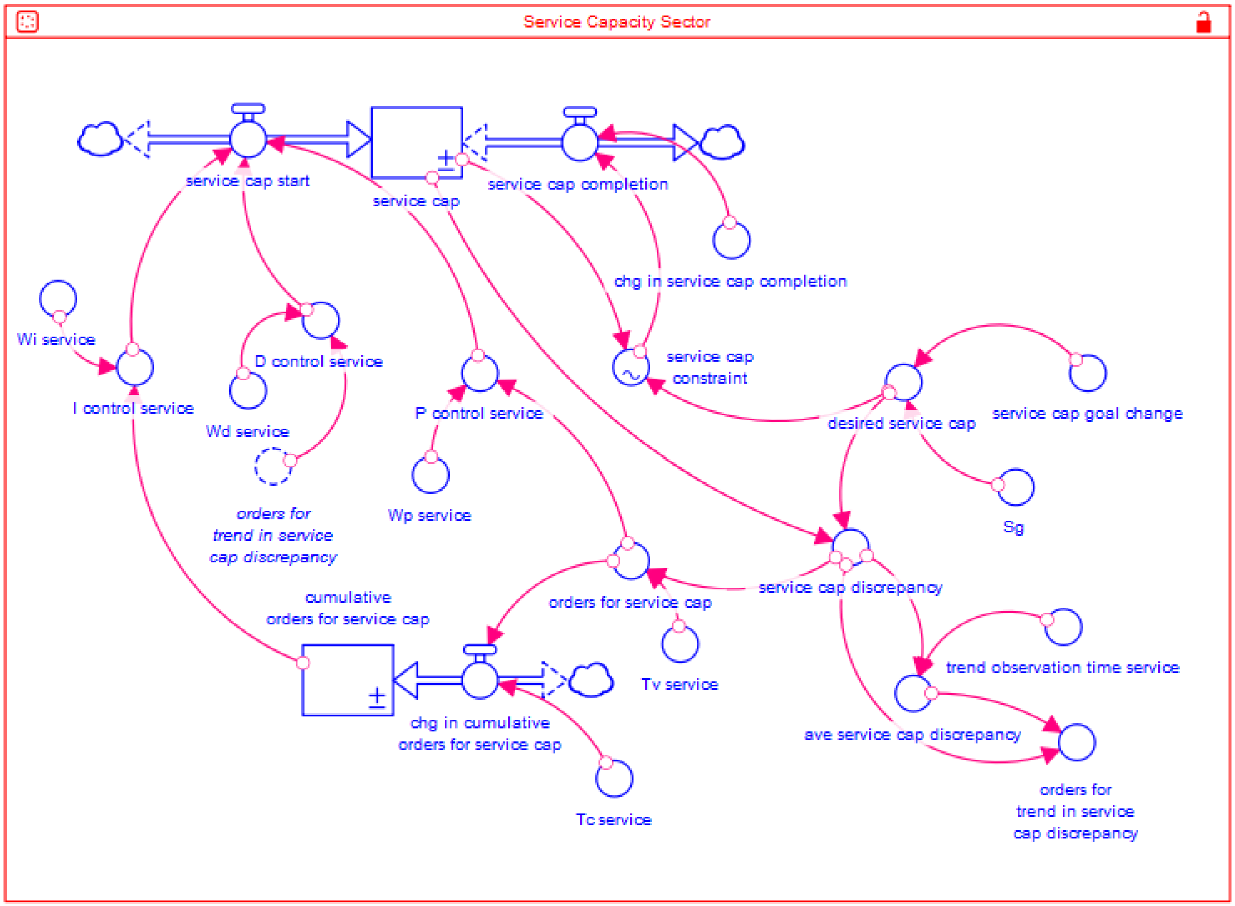
Appendix B



Production_Control_Sector:

ave_inv_discrepancy = SMTH1(inv_discrepancy,trend_observation_time_production,0)
UNITS: Million Widgets/Year
chg_in_shipment = 4000*1+0*5*SIN(TIME)
UNITS: Million Widgets/Year
cumulative_production_orders_for_inv(t) = cumulative_production_orders_for_inv(t - dt) + (chg_in_cumulative_production_orders_for_inv) * dt
INIT cumulative_production_orders_for_inv = shipment_rate
UNITS: Million Widgets/Year
INFLOWS:
chg_in_cumulative_production_orders_for_inv = production_orders_for_inv/Tc_production
UNITS: Million Widgets/Year/Years
D_control_production = production_orders_for_trend_in_inv_discrepancy*Wd_production
UNITS: Million Widgets/Year
desired_inv = Ig+STEP(inv_goal_change,2)
UNITS: Million Widgets
I_control_production = cumulative_production_orders_for_inv*Wi_production
UNITS: Million Widgets/Year
Ig = 2000
UNITS: Million Widgets
inv_discrepancy = desired_inv-inventory
UNITS: Million Widgets
inv_goal_change = 1
UNITS: Years
inventory(t) = inventory(t - dt) + (production_rate - shipment_rate) * dt
INIT inventory = product_backlog
UNITS: Million Widgets

INFLOWS:
production_rate = I_control_production+P_control_production+D_control_production
UNITS: Million Widgets/Year
OUTFLOWS:
shipment_rate = (0+STEP(chg_in_shipment,2))*inventory_constraint
UNITS: Million Widgets/Year
inventory_constraint = GRAPH(inventory/desired_inv)
(0.000, 0.000), (0.200, 0.558), (0.400, 0.756), (0.600, 0.870), (0.800, 0.942), (1.000, 1.000), (1.200, 1.038), (1.400, 1.062), (1.600, 1.068), (1.800, 1.074), (2.000, 1.080)
UNITS: 1
P_control_production = production_orders_for_inv*Wp_production
UNITS: Million Widgets/Year
production_orders_for_inv = inv_discrepancy/Tv_production
UNITS: Million Widgets/Year
production_orders_for_trend_in_inv_discrepancy = (inv_discrepancy-ave_inv_discrepancy)/2
UNITS: Million Widgets/Year
Tc_production = 2
UNITS: Years
trend_observation_time_production = 3
UNITS: Years
Tv_production = 2
UNITS: Years
Wd_production = 1
UNITS: 1
Wi_production = 2
UNITS: 1
Wp_production = 2
UNITS: 1



Service_Capacity_Sector:

ave_service_cap_discrepancy = SMTH1(service_cap_discrepancy,trend_observation_time_service,0)
UNITS: Calls/Year
chg_in_service_cap_completion = 400*1+0*5*SIN(TIME)
UNITS: Calls/Year
cumulative_orders_for_service_cap(t) = cumulative_orders_for_service_cap(t - dt) +
(chg_in_cumulative_orders_for_service_cap) * dt
INIT cumulative_orders_for_service_cap = service_completion_rate
UNITS: Calls/Year
INFLOWS:
chg_in_cumulative_orders_for_service_cap = orders_for_service_cap/Tc_service
UNITS: Calls/Year/Years
D_control_service = orders_for_trend_in_service_cap_discrepancy*Wd_service
UNITS: Calls/Year
desired_service_cap = Sg+STEP(service_cap_goal_change,2)
UNITS: Calls
I_control_service = cumulative_orders_for_service_cap*Wi_service
UNITS: Calls/Year
orders_for_service_cap = service_cap_discrepancy/Tv_service
UNITS: Calls/Year
orders_for_trend_in_service_cap_discrepancy = (service_cap_discrepancy-
ave_service_cap_discrepancy)/2

UNITS: Calls/Year
P_control_service = orders_for_service_cap*Wp_service
UNITS: Calls/Year
service_cap(t) = service_cap(t - dt) + (service_cap_start - service_cap_completion) * dt
INIT service_cap = service_call_backlog
UNITS: Calls
INFLOWS:
service_cap_start = I_control_service+D_control_service+P_control_service
UNITS: Calls/Year
OUTFLOWS:
service_cap_completion = (0+STEP(chg_in_service_cap_completion,2))*service_cap_constraint
UNITS: Calls/Year
service_cap_constraint = GRAPH(service_cap/desired_service_cap)
(0.000, 0.000), (0.200, 0.558), (0.400, 0.756), (0.600, 0.870), (0.800, 0.942), (1.000, 1.000), (1.200, 1.038), (1.400, 1.062), (1.600, 1.068), (1.800, 1.074), (2.000, 1.080)
UNITS: 1
service_cap_discrepancy = desired_service_cap-service_cap
UNITS: Calls
service_cap_goal_change = 1
UNITS: Years
Sg = 2000
UNITS: Calls
Tc_service = 1
UNITS: Years
trend_observation_time_service = 3
UNITS: Years
Tv_service = 2
UNITS: Years
Wd_service = 1
UNITS: 1
Wi_service = 2
UNITS: 1
Wp_service = 2
UNITS: 1