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Modeling and Analyzing Market Performance in Infrastructures

Adam L. Turk and Margot Weijnen
Delft University of Technology,
Interfaculty Research Center "Design and Management of Infrastructures",
PO Box 5069, 2600 GA Delft, The Netherlands
+31.15.278.3410, +31.15.278.3422, a.l.turk@tbm.tudelft.nl

Abstract
Accurate and appropriate performance of an infrastructure is important due to society's dependency on its service. This research tries to examine the performance of an infrastructure and the potential causes for its failure. Specifically, the objective is to model the dynamics of an infrastructure market and to examine it with respect to performance criteria. The theoretical and observable dynamics of an infrastructure market are represented as a causal model. In turn, relevant criteria, based upon society's desire, can be used to analysis the performance of the system. This analysis helps to determine the potential performance failures in the infrastructure market. In this paper, a causal model of a generic infrastructure market is presented and analyzed against performance criteria for possible failures. The identified failures from this causal model were supported by illustrations from the California energy crisis.
Keywords: Infrastructures, System Dynamics, Performance Criteria, Feedback Loops, and Regulation

1. Introduction

Over the past decade, many countries through out the world have privatized and liberalized their infrastructures into competitive markets. This restructuring is supposed to have introduced competitive market forces where possible in hope of increasing infrastructure efficient. A prime example of this restructuring can be seen in the electricity sector throughout the European Union. The electricity sector based upon directives was divided into three separate sub-systems: generation, transmission, and distribution. Both the transmission and distribution sub-systems were left as regulated monopolies. However, the generation sub-system was transformed into a competitive market with several private players. The main goals behind this transformation were to reduce the price for the service and to increase efficiency of the system. The California energy crisis illustrated that potential performance failures were still possible in a restructure infrastructure. The question now upon everyone's mind from the California energy crisis is whether market forces will achieve the desired system performance in a liberalized infrastructure.

Similar to this question, the focus of this research is to study the dynamics exhibited by an unregulated infrastructure market in terms of achieving desired performance criteria. Understanding of the dynamics and their impact on performance is critical to controlling or regulating a given infrastructure market. The overall research goal is to illustrate how the dynamics of the system along with minimal regulation can be used to control an infrastructure's performance. The main ideas behind this goal are to demonstrate that an infrastructure market can be designed and controlled in a similar manner to the technical infrastructure systems and that its dynamics can be exploited for control purposes. Nonetheless, the work in this paper focuses on the modeling and analysis of a causal model of a infrastructure market with respect to performance. In particular, this paper presents a causal model of a generic liberalized infrastructure market and analyzes the effect of the feedback loops from the representation on system performance.

2. Background

Present-day society would not be possible without the different infrastructures such as energy and transportation. These infrastructures provide society with the basic services that are essential to its proper functioning of society. For example, the energy sector provides gas and electricity for heating, lighting, and cooking. In turn, one realizes that individuals can not live and work with out the energy for these tasks. The illustration demonstrates society's dependence on the services provided by these complex social-technical systems. This dependence reinforces the need to for reliable infrastructure performance. Avoidance of possible technical and market failures is at the heart of creating reliable infrastructure performance. In terms of the market, we are concerned with the failure of the system to match supply and demand. Based upon the need to reliably balance supply and demand, it is necessary to understand the dynamics of an infrastructure market

2.1 Economic Theory on Supply and Demand

Basic economic theory provides a foundation for understanding the supply and demand of a service or commodity . Specifically, the theory demonstrates that the supply and demand curves for the product are balance by their intersection at a given price and quantity (fig. 1a). The placement of these curves to each other are dependent on numerous influences. The supply curve is primarily effected by technological advances, production costs, and government regulation while demand is influenced by the price of related goods, the incomes of consumers, and the preferences of these consumers (Begg, Fisher et al. 2000; Nordhaus 2001). This theory provides a strong foundation for the relationship among price, supply, and demand for a given set of influences. The resulting supply and demand curves only provide the resulting equilibrium point for an industry based upon its current conditions. Nevertheless, this theory does not illustrate the dynamics of a market in reaching equilibrium between supply and demand.

2.2 The Cobweb Theorem

The cobweb theorem was developed in order to explain the dynamics of a market in balancing supply and demand. The cobweb theorem is based upon "the idea of carrying production, price, and production readjustments back and forth between the supply and demand curves" (Ezekiel 1938). In other words, the price and production values for the current time period are dependent on the ones from the previous period. This concept can be illustrated using figure 1b, which contains a supply and demand curve for an arbitrary industry. It should be noted that the supply and demand influences identified by economic theory are assumed negligible in the example. This assumption results in the slopes and y-intercepts of the curves remaining fixed. If the industry was operating at price P_1 in the previous time period, then the consumer will want quantity Q_1 while the industry will supply quantity Q_2. In order to sell quantity Q_2 in this time period, the price has to fall from P_1 to P_2. However, the industry will want to supply quantity Q_1 in the next time period based upon the new price P_2. In the end, the price will have to increase to P_1 from P_2 in order to limit demand to the quantity that the industry will produce. This example illustrates that price will determine quantity in one time period and in the next time period quantity will establish the price. This sequence of events will be repeated as the system either converges to equilibrium, diverges from equilibrium, or continues to oscillate among the same points. Overall, the cobweb theorem demonstrates the dynamics of a market as it balances supply and demand. The problem with the cobweb theorem is that it assumes negligible supply and demand influences. Unfortunately, these influences are critical to modeling and analyzing the dynamics of a market.

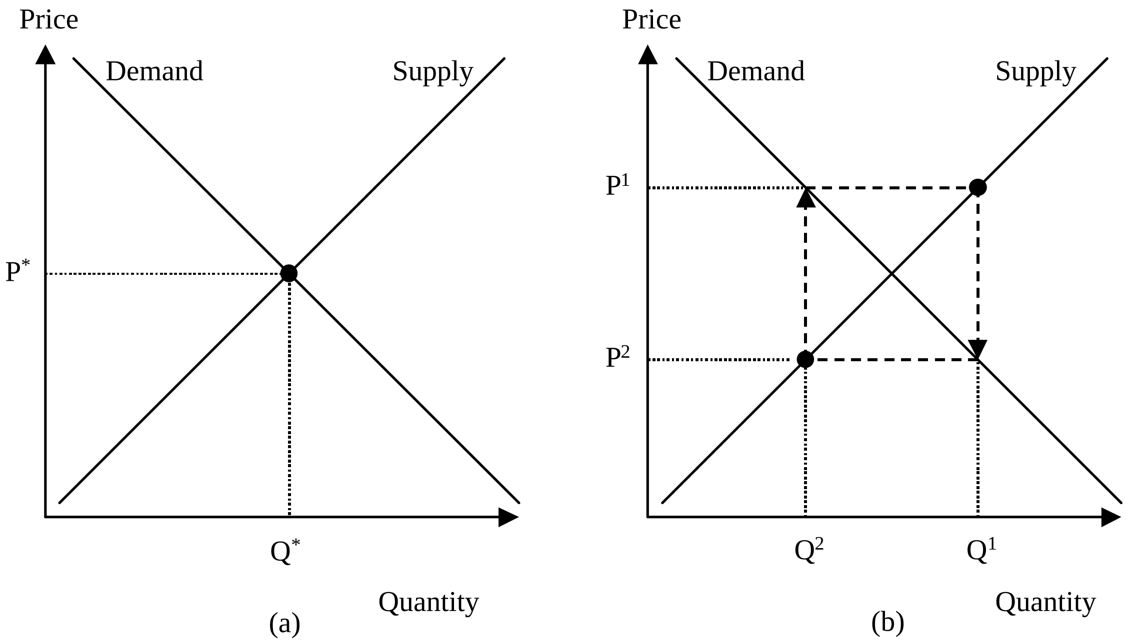

Figure 1 Supply and Demand Curves: a) Market Equilibrium from economic theory b) Dynamic equilibrium based upon the cobweb theorem

2.3 System Dynamics Model

System dynamics is based upon the application of control theory, specifically feedback loops, to business and social systems [Forrester 1973]. These feedback loops help to illustrate the interaction of variables and their resulting behavior on the system. With respect to this work, the theory of system dynamics will be beneficial in representing the dynamics of an infrastructure market with respect price, supply, demand, and their influences by building upon the concepts from basic economic theory and the cobweb theorem.

Currently, system dynamics has been used to describe a wide variety of business and social systems (Lyons, Burton et al. 1997; Parker 1997; Sterman 2000). With respect to infrastructures, system dynamics has been used to represent and analyze primarily the energy sector (Ford 1983; Lyneis and Geraghty 1983; Sterman 1983; Geraghty and Lyneis 1985; Ford, Bull et al. 1987; Bunn and Larsen 1992; Naill 1992; Bunn, Larsen et al. 1993; Bunn 1994; Bunn and Larsen 1994; Bunn, Dyner et al. 1997; Ford 1997; Salama 1997; Ford 1999; Larsen and Bunn 1999; Lomi and Larsen 1999; Dyner 2000; Gary and Larsen 2000; Ford 2001; Qudrat-Ullah and Davidsen 2001). For example, Ford used system dynamics to describe the impact of an electricity infrastructure on environmental issues (Ford 1983; Ford 1997). Other researchers, such as Brunn and Larsen, analyzed the impact of restructuring on the strategic behavior of the companies (Bunn and Larsen 1992; Bunn and Larsen 1994).

These applications in the energy sector did not focus on the infrastructure market or its structure. Nonetheless, the application of system dynamics to other industrial markets and the energy sector provide a basis for developing a general model of an infrastructure market model.

Sterman presents a causal model of a general commodity market (Sterman 2000). The description of the market structure can be decomposed into a basic set of pathways and mechanisms. These pathways and mechanisms expand upon the causal relations among price, supply, and demand presented in the cobweb theorem. Specifically, the pathways in Sterman's model represent the availability of the commodity, the acquisition of new capacity, the utilization of built capacity, and the substitution of the commodity. These pathways represent the basic feedback loops within a commodity market that balance supply and demand. The capacity utilization path adjusts the rate that a commodity is supplied based upon its asking price and inventory. On the other hand, the substitution pathway changes demand according to the commodity and possible substitutes prices. Based upon these descriptions, both feedback loops are dependent upon the price of the commodity. It appears that the commodity's price acts as a linchpin, connecting the different supply and demand pathways together. In fact, price is determined by cost and inventory of the commodity, which result from the interaction of supply and demand pathways. The cost of the commodity helps in setting the minimum value for price while inventory adjusts the price to reflect its scarcity or abundance in the market. This description of a generic commodity market provides an understanding of the significant pathways and mechanisms.

3. Causal Model of an Infrastructure Market

The generic commodity market described by Sterman forms a basis for modeling an infrastructure one. However, some of the properties that a commodity possesses do not match those of an infrastructure service such as self life. The commodity in Sterman's model is non-perishable and can be stored for an indefinite period. On the other hand, we view an infrastructure service as perishable and needs to be consumed right away. Services generated by the various infrastructures can not be stored for future consumption with respect to the time scale of the market. This immediate consumption originates from the characteristics and properties of the service or the infrastructure. For instance, electricity begins dissipating toward a sink as it is generated while microscopic organisms that can cause disease start to multiple in drinking water as soon as it is purified. On the other hand, the physical system in the telecommunication sectors causes an individual to consume the service of making a telephone call as it is simultaneously provided. Based upon these examples, infrastructure services are consumed as quickly as possible after being produced. It should be noted that some infrastructures due have storage units but these components do not affect the consumption of the service. Overall, it can be assumed that the infrastructure service is perishable and can be inventoried.

This assumption effects the pricing mechanism in the causal model for a generic commodity market. In the pricing mechanism, inventory is used to determine the influence of abundance or scarcity on the market. Inventory, which is not feasible for an infrastructure service, can not be used pricing mechanism to reflect the scarcity or abundance. However, reserve production capacity, which reflects the difference between supplied and demanded service, can be used to determine scarcity/abundance affect on the price in an infrastructure market. The concept of reserve capacity is already widely used in various infrastructures. The air transportation sector sizes their planes so that seventy percent of the seats are filled on average while those remaining are used to adsorb extra demand. The remaining thirty percent of the seats can be viewed as reserve capacity for the air transportation sector. In the electricity sector, the idea of reserve capacity is already used to describe the extra generation capacity that the infrastructure can bring online in order to satisfy demand. These examples illustrate that reserve capacity is used by many infrastructures to describe effect of supply and demand of available service. In terms of the infrastructure market model, reserve capacity can be used in place of inventory to represent the effect of scarcity or abundance on price.

The causal model of an infrastructure market is given in figure 2. It should be noted that the causal model makes use of total cost and revenue instead of marginal cost and revenue. This use of total cost and revenue is based upon the idea that marginal cost and revenue is not generally available due to imperfect information. Nonetheless, this figure represents the major feedback loops that are exhibited by the dynamics of an infrastructure service market.

As noted earlier, price is the linchpin between the supply and demand feedback loops. Price is determined by the average cost of the infrastructure service, the reserve production capacity, and the market power of the participating companies. Both the average cost and reserve production capacity assume the previously described roles of setting a minimum price bound and adjusting to service scarcity/abundance, respectively. Market power describes the ability of the participating companies to set a higher price than the optimal one set by theory. If the companies in an infrastructure have high market power, which can reflect either an oligopoly or collusion between the companies, then they will be able to demand a higher price for their service. These simplified descriptions illustrate how market power, average cost, and reserve production capacity combine to determine the service price in an infrastructure market.

In addition to the pricing mechanism, figure 2 describes the supply and demand feedback loops within an infrastructure market. These feedback loops match some of those from the causal model for a generic commodity market, which are new capacity acquisition, service availability, and service substitution. The causal model also includes pathways that use the acquisition of new technology to increase service capacity or decrease service demand. For the moment, let us examine one of these feedback loops in greater detail such as the capacity acquisition one. If price increases while all else remains constant, then total revenue will increase. In turn, an increase in revenue will lead to more investment in capacity in order for the various companies to acquire more profit. The investment in capacity will increase the total amount of service capacity along with increasing technology investment. The total production capacity will effect both the total fixed costs and the available production capacity. The total fixed costs will increase the average cost per unit of service through total costs while available production capacity will add to the reserve production capacity. The increase in average cost will increase the lower price bound. The added reserve capacity will decrease the final price due to an abundance of the service. The abundance of service, unfortunately for the participating companies, can drive the price below the bound set by average cost. This event is possible since the price signal from reserve capacity will swamp the one from average cost because at least one company will try to earn their investment back by gaining market share through a lower price. Ironically, the capacity acquisition feedback loop is initiated by a high price but results in this price being lowered by reserve capacity. This description highlights just some of the dynamics exhibited by the infrastructure market.

The interactions that comprise this and other feedback loops are based upon theoretical and observed relationships. Examples of a theoretical relationship is given by the mathematical definitions of the various costs. For instance, total cost is determined by the sum of total fixed

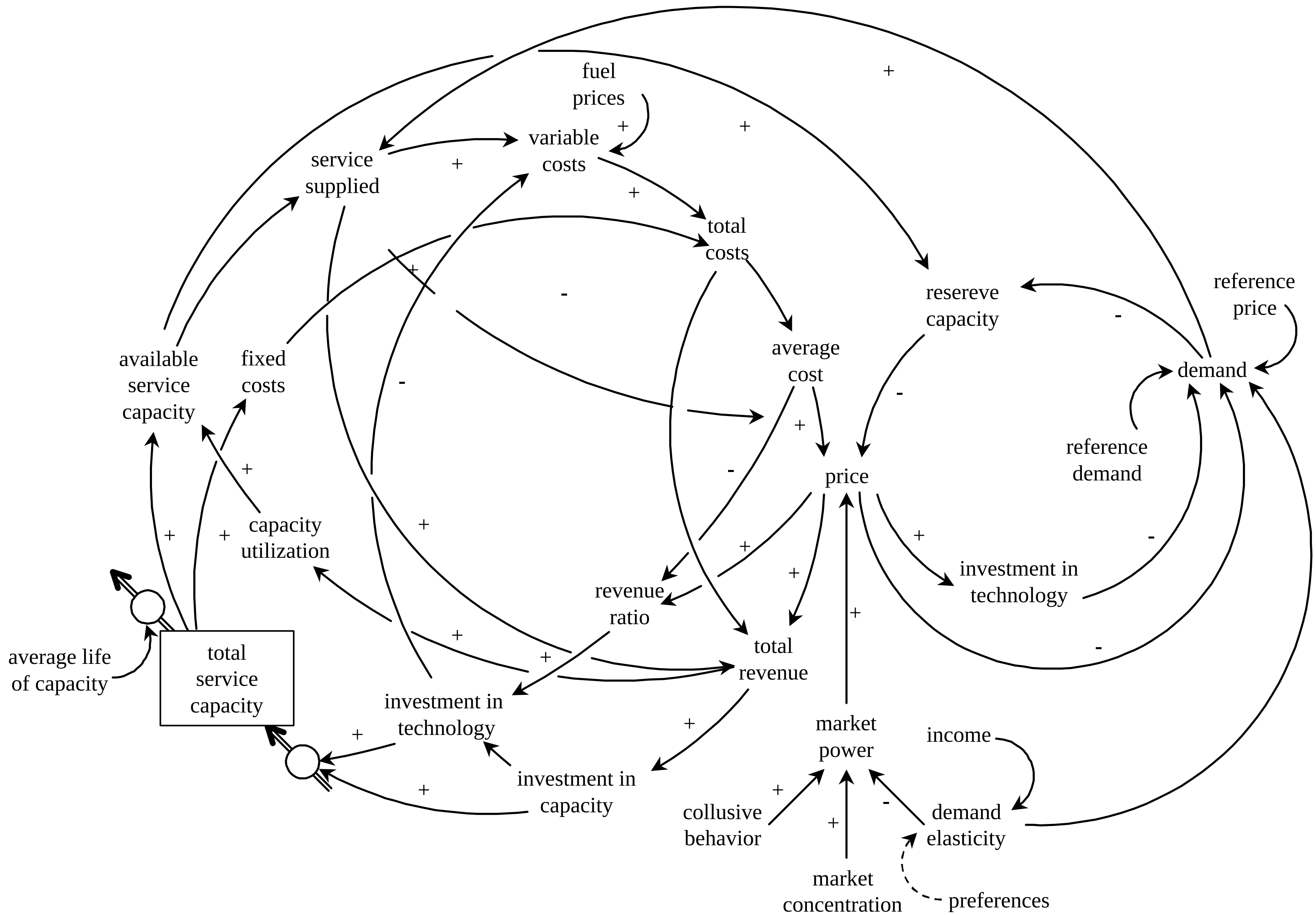

Figure 2 Causal model of a generic infrastructure market

and variable costs while variable cost, itself, is calculated by multiplying an average variable cost per service unit against the capacity supplied. On the other hand, the relation between total revenue and investment in capacity is based upon observation. The relationship is based upon a break point where revenue increases to a point where new investment in capacity can be earned back. This relationship can take on the form of a discrete triggering event or a continuous nonlinear curve. Altogether, the theoretical and observable relationships create the pathways that describe the dynamics of an infrastructure market.

Nonetheless, it should be noted that the detail of the infrastructure model was kept at the causal level even though some of the relationships are based upon mathematical equations. The main reason for a causal model is that data for a liberalized infrastructure market does not exist. Unfortunately, use of any other infrastructure data would only create a biased model that would only generate already observed results. The biased model also could not truly be used for predictive purposes since it would only be valid for specific conditions. Therefore, creating a more quantitative model may not be beneficial to the research goal of controlling a infrastructure market with its dynamics and minimal regulation.

Fortunately, a qualitative model does not hinder the analysis of the market dynamics in terms of performance. The first reason is that our goal is to develop a generic infrastructure model that can be used as a basis for investigating specific sector and that can be used as an overview of common problems among the different sectors. The second reason is that the analysis of the model with respect to performance criteria does not need to rely upon the explicit determination of the delays or gains within the feedback loops. Instead, the existence of a potential pathway that allows the infrastructure from not satisfying its performance criteria will provide enough of a desired result. In other words, the analysis is concerned with the possibility of performance failure and not its actual occurrence in a given infrastructure. This assumption also allows the interaction of multiple inputs to be unknown or non-deterministic. The impact of the pathway can be analyzed with either having a large or small gain. The result of either gain in turn can be carried forward in the performance analysis. In the end, a qualitative model over a quantitative one will provide a larger set of possible dynamics that can lead to performance failures.

4. Performance Criteria

Performance criteria are the goals that an system needs to satisfy by it existence and operation. This research is concerned with the specific performance goals that society wants from an infrastructure. For example, society desires an infrastructure that delivers an affordable service at the appropriate times such as waste removal. This desire can be more formally stated as a service that meets a basic standard of quality while being affordable and available to the largest segment of the population possible at any given time. This desire can then be broken down into four performance objectives: producing a standard service, setting the lowest price for the given service, providing the greatest connection of individuals to the service, and deliver the service according to an accepted schedule. Theoretically, each of these objectives would need to be achieve by the infrastructure in order to be perceived as performing correctly. Altogether, this description highlights just a few of the performance criteria for an infrastructure. The question is what are the basic performance criteria sought after by society for an infrastructure.

A set of generic performance criteria for infrastructures were originally developed by the National Council on Public Works (NCPW) and then augmented by the Committee on Measuring and Improving Infrastructure Performance (CMIIP) (NCPW 1988, CMIIP 1995).

The performance criteria from the NCPW outline the objectives for the operations and physical system of an infrastructure such as physical assets and product delivery. The performance criteria from the CMIIP are based upon a broader perspective than the NCPW project. The CMIIP criteria were not limited to the condition of the physical system like those by NCPW but also tried to examine the effectiveness of the system in producing the desired service. The performance criteria proposed by the CMIIP are effectiveness reliability, and cost. These generic performance criteria were originally developed with only the transportation, water, and waste sectors in mind since the focus of these organizations on public utilities or works. However, these results can be extended for use with other infrastructures such as energy and telecommunications. The only problem is that these performance criteria do not include the performance of the infrastructure market such as affordable price or market power

Using the results from the NCPW and CMIIP as a basis, a set of performance criteria for an market infrastructure can be formed as follows: price, cost, and revenue; service quality; environmental effects; and social effects. The term for price, cost, and revenue in general describes the price level that an infrastructure market should achieve so that the service is affordable to all consumers while all of its costs are being covered. market function can be divided into more detailed objectives. Service quality can be divided into access, attractiveness, and reliability. Access refers to the availability of the service to the largest segment of the population. Attractiveness describes the benefit that the service provides to individuals and society. Reliability refers to the potential of the infrastructure to continue delivery of the service irrespective of failures. Environmental effects describe the preference of society with respect to the infrastructure's impact on the surroundings. Social effects refers to the health, safety, and privacy of individuals in connection with the infrastructure or its service. These goals reflect the demands of society on the performance of an infrastructure and its service. In turn, these goals can be used to examine the dynamics of an infrastructure market in achieve the desired performance.

5. Analysis of an Infrastructure Market

In this paper, The only a couple of the performance goals presented will be used in analyzing the infrastructure market. These performance criteria or objectives are service reliability and price, cost, and revenue.

To begin with, the ability of a infrastructure market to generate an affordable price. In other words, can an infrastructure market drive price down to its lowest possible value, which will cover average service costs and provide some profit for sustaining the operating company. In figure 2, price is determined by the average cost, reserve production capacity, and market power. The effect of average cost on price is negligible since it will only change the value that is considered as affordable. On the other hand, scarce reserve production capacity will cause the price to be above the value that is considered as affordable. However, this high price will cause investment in capacity, which will lead to a decrease in price. This decrease in price will in time cause a lack of investment and a new high price. Therefore, scarcity or abundance will cause the price to oscillate between an affordable and high value. The market power also has an effect on the service price. Under high market power such as an oligopoly, the operating companies can set a high price due to their control over the service supply. In a competitive environment which reflects low market power, no individual company can set a high price. An infrastructure market only under competition will be able to achieve an affordable service price. Unfortunately, the service price will oscillate from this affordable value to a high one due to impact of scarcity/abundance.

In order to achieve a low price, the conditions in the infrastructure market would need to be set so that they create a competitive system. Market power is determined from collusive behavior among operating companies, demand elasticity, and market concentration. In this particular analysis, the effect of collusive behavior and demand elasticity will be neglected. Theoretically, market concentration is determined by the number of operating companies and their market share (fig 3.). For instance, an increase in the number of operating companies will decrease their market share and lower the market concentration. On the other hand, a decrease in the number of operating companies does not imply a increase in market concentration since it depends on the redistribution of the market shares. Therefore, market concentration id determined from the number of operating companies and mean value of the market shares (fig. 3) The mean value shares should reflect the redistribution of market shares among operating companies. This causal model illustrates that a competitive market can only be possible if the number of operating companies are keep constant and their mean market share value low.

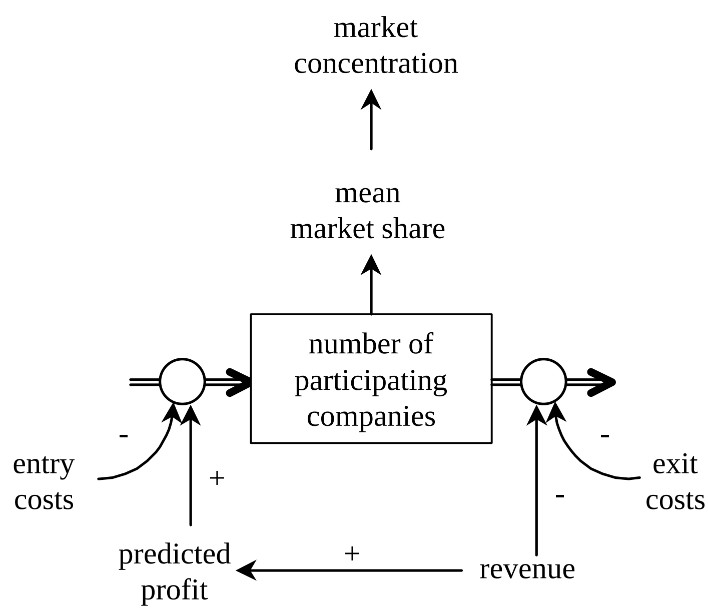

Figure 3 Causal model of the market concentration

Service reliability is the other goal that will be used to analyze performance of an infrastructure market. In particular, service reliability is achieved when supply is greater than demand. Therefore, a condition where reserve production capacity assumes a constant high value is desired. Reserve production capacity is in turn dependent on total service capacity, investment in capacity, revenue, and price. Unfortunately, an abundant service, which is marked by large reserve capacity, would lead to a decline in revenue and investment. An infrastructure market would never have a reliable supply of service based upon this causal pathway. The question is whether other conditions exist that might negate the revenue signal for investment in capacity. Figure 4 shows an expand view of the causal pathways for capacity investment. The investment in capacity is dependent upon current cash reserves, predicted future revenue, and expected investment costs. A company will be cautious in committing to investment unless stronger signals are received from these influences. For instance, the current cash reserves and predicted revenue need to be greater than the expected investment costs by a given factor in order for the investment to take place. If the assumption of low revenue is kept, then either investment costs needs to be lowered or predicted future revenue needs to be increased. Investment costs can be affected by influencing the cost of a loan to the operating companies for new capacity. Predicted future revenue can not necessarily be increased except by promised subsidies. Another solution for increasing the impact of predicted future revenue is to improve the certainty of forecasted demand and price. The idea would be to develop methods by which the effect of the uncertainties associated with forecasting demand and price can be minimized. Based upon this overall analysis, an infrastructure market will not provide a reliable service unless investment in capacity is stimulate through lower investment costs or better predicted future revenue.

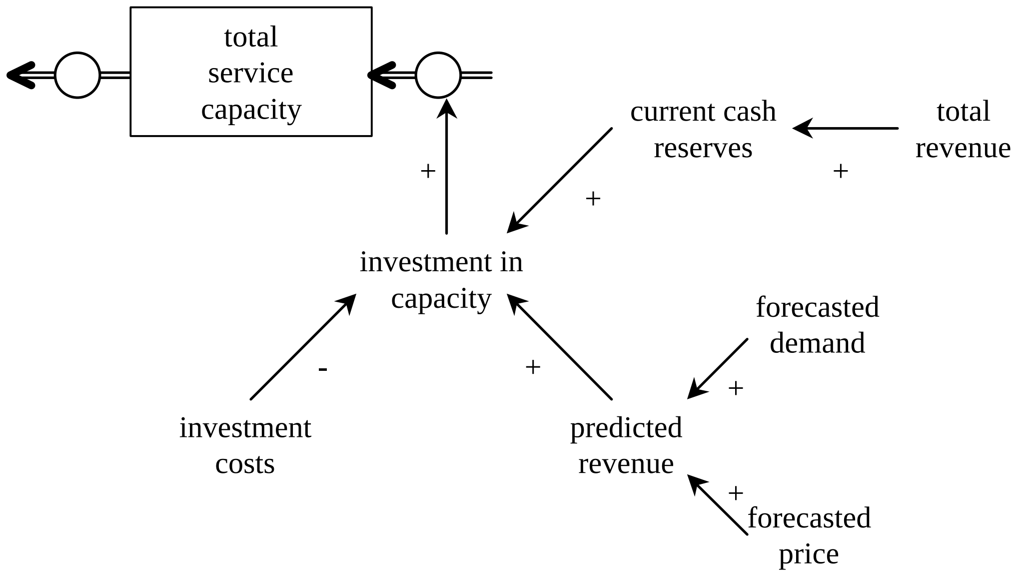

Figure 4 Expanded causal model for investment in capacity.

6. Validation of Analysis

These performance failures in an infrastructure market can be seen in California's electricity crisis during 2001. As the closest example of a completely liberalized energy market the California experience will help to validate the observations made from the causal model for a general infrastructure market. Joskow and Borenstein noted that the energy crisis was the result of several events (Joskow 2001, Borenstein 2001). The first was the occurrence of an dry and hot weather along the west coast of the United States. The hot weather caused an increase in electricity demand as consumers sought relief from the heat by turning on their air conditioners. The dry weather decreased the amount of water available to hydro-electrical facilities. In addition to the weather, the California electricity infrastructure had not invested in new generating plants in the previous ten years due to low prices and regulator uncertainty. In fact, the approval process for new generation facilities in California had become difficult and lengthy. These conditions altogether created a tight supply. These events validate the observation that any infrastructure market will not provide a reliable supply unless investment is stimulated

Ironically, the market system did signal the scarcity of electricity generation with an increase in price. However, the difficult and lengthy approval process meant that new generation capacity would not be available for several more years. The greater delay of the capacity feedback loop would result in greater amplitude in oscillations from scarcity to abundance.

The scarcity of electricity also meant that the price would increase beyond the point were it would be affordable to consumers. In addition to scarcity, collusive behavior among generating companies pushed the price of electricity even higher. These events illustrate that an affordable price will only be guaranteed with competition and an abundant supply. If companies are able to collude or supply becomes scarce then price of the given service will begin to increase above an affordable level.

7. Conclusions

The California electricity crisis was caused by a set of extreme events such as the weather, collusive behavior, and long period of no investment. These events would have caused any market system to failure no matter their gains and dynamics. The issue to see in this statement is that the infrastructure system could have been designed and controlled in a manner that would limit the impact of these events upon performance. The model and analysis presented in this paper would have help with understanding the effects of an infrastructure market on performance. The causal model of a general infrastructure market identifies the key pathways and relationships that affect performance. This causal model of a generic infrastructure market is based upon economic theory and previous applications of system dynamics The analysis of the pathways and their interactions with respect to specific performance criteria resulting in finding potential failures. In particular, the paper illustrates that an infrastructure market would fail to reach an affordably priced or a reliably supplied service. Of course, these performance criteria could be achieved by controlling the conditions of the market such as encouraging competition or investment. The failure to achieve these performance criteria can be seen in the California electricity crisis. Overall, this paper presents a causal model for a generic infrastructure market and demonstrate how analysis of this representation using performance criteria will lead to identifying possible failures. The identification of potential failures will allow for the infrastructure market to be better designed and controlled.

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