System Dynamics Simulation of the Telecom Industry

by

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ABSTRACT

The primary goal of this research effort was to integrate several pieces of relatively simple dynamics simulations into a full blown system dynamics simulation of the telecom industry. The economic simulation model was used to analyze potential dynamics, reaching basic qualitative insights on the forces behind the industry. Examples of the pieces which comprised the model include the product adoption life cycle, product substitution models, stochastic R&D investment models, as well as an economic model for determining market share under price competition. The work focused on key attributes and areas of the telecom industry, including network externalities, investment strategies, regulation, standardization of products, and behavior of consumer welfare.

Main conclusions include the convexity of risk/return tradeoff in R&D investment under severe network externalities, as well as substitution as a matching device for innovation clockspeed in competing industries. Accordingly, it is shown that mismatch in innovation clockspeed, pricing clockspeed or product introduction timing may lead to an unsustainable competitive position. The work shows the advantages of R&D competition in driving consumer welfare. A theoretical framework has been put in place for considering the dynamic influence of regulation and standardization on investment incentives and choices. Through this framework, we can consider regulation and standardization effects in short-term and long-term, and how these correspond to the competitive stability of the industry.

Thesis Supervisor: Charles H. Fine
Title: Professor of Management
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The research work was conducted under the supervision of Professor Charles Fine. I would like to express my deepest gratitude to Charlie for giving me the opportunity to work on this project, as well as other research topics we worked on during the last two years. His patient guidance, encouragement and excellent advice throughout this study were tremendously helpful. Without his help, support, and friendship, this work would not be possible.

Lastly I would like to thank and dedicate this work to my dear wife, Na’ama who had to put up with me through this long and somewhat painful process.
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A. Background

A.1. System Dynamics

System dynamics, as a theoretical framework for analyzing the dynamics of various complex systems, was developed at MIT by Jay W. Forrester, the author of the 1958 article, “Industrial Dynamics – A Major Breakthrough for Decision Makers,” in the Harvard Business Review, and later the author of Industrial Dynamics, considered the main textbook on the subject. System dynamics can be defined as a method for studying complex system behavior, not by dissecting the system into little pieces, but rather looking at the dynamic interactions between the different pieces, with special focus on feedback mechanisms. In essence, system dynamics is an application of engineering control theory to management decisions and system analysis.

System Dynamics modeling was used by Forrester to model Urban Dynamics, showing the detrimental effect of policies surrounding low-cost housing\(^1\). Additional work included World Dynamics which dealt with the dynamics of population growth and world resource utilization\(^2\). Professor John Sterman, of MIT, conducted additional research on various other topics, ranging from corporate growth and stagnation, the dynamics of infectious diseases, and business cycles, to transportation policymaking\(^3\).

System Dynamics is highly applicable to a dynamic simulation of the telecom industry. Key attributes, such as network externalities, involve strong feedback loops, and therefore lend themselves easily to a systematic approach. By creating a complex and sufficiently rich description of the industry, we will be able to analyze and study dynamics revolving around competition, R&D investment, regulation, standardization, and pricing strategies.

A.2. Initial Example - Regulation Dynamics

This research effort is a continuation and expansion of previous work conducted by Prof. Fine, Prof. DeFigueiredo and the author on dynamic simulation of the effects of regulation in the wireline telecom industry. The wireline phone industry is heavily regulated, suffering from severe limitations of operational flexibility in the form of regulated pricing, universal service requirements and regulated competition. Wireline incumbents must provide entrants access to their networks at cost, with the aim of facilitating competition in the marketplace.

Despite the noble aspired goal of free competition and increased consumer value, current regulation severely restricts the incumbents' capability to respond effectively to increasing competition in the form of price changes as well as entry or exit of services, resulting in reduced profitability and increasing risk of overall industry instability.

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2 The Beginning of System Dynamics, Jay W. Forrester, Banquet Talk at the international meeting of the System Dynamics Society, Stuttgart, Germany, July 13, 1989
The ability of entrants to target lucrative market segments and price effectively results in
cream-skimming, while limiting incumbents' ability to respond. Historically, due to the
universal service requirements, wireline services were based on cross-subsidization. The
highly profitable customers, typically the business sector, would cross-subsidize the losses
associated with low revenue residential customers. Today, due to increasing competition in the
high profit segments of the market, the basic industry structure is becoming unsustainable.

The work conducted on the regulation topic included a historical comparison to the railroad
industry, which, like the telecom industry before the breakup of AT&T, was monopolized with
a very large degree of market power in the late 1900s. In much the same manner as the
telecom industry, regulation was introduced, including price regulation, and severe limitations
on entry and exit of railroad lines. The long-term effect was reduced profitability, stifled
innovation, inability to exit unprofitable lines or to change pricing effectively, which, coupled
with the increasing competition posed by the trucking industry, led to reduced market power
and the decline of the whole railroad industry. The rails share of the US intercity surface
freight market, measured by ton-miles, decreased from 65% to only 35% by the 1970s.

Finally, when regulation was lifted, in 1980 under the Staggers Act, it seemed that some of the
damage inflicted was irreversible. Today, the trucking industry still accounts for the large
majority of shipping revenue in the US. When compared to the railroad industry structure in
other modern western countries, the US railroad industry is still lagging behind.

Today, wireline incumbents suffer from rapidly increasing competition. Substitute products in
the form of wireless phones, voice over cable, VOIP and the like, represent a growing share of
the market and rapidly erode the incumbents' actual market power. In much the same setting
as the railroad and trucking industries, the question arises - when is the right time to remove
regulation? When is it too early, potentially hurting the introduction of competing substitute
services which positively affect consumer welfare? When is too late, potentially hurting the
existing industry, resulting in overall reduced consumer welfare?

By looking at previous historic examples we concluded that a simple model captures the basic
dynamic behavior of the regulatory bodies. Depicted as the Hysteresis Model, the model
allows us to observe the relationship between market power of an industry and imposed
regulation, as seen in Figure 1. As market power of an industry increases, so does the pressure
of regulatory intervention. At some point in time, regulation will kick in with the proper aim of
protecting consumer welfare. Regulation will eventually stifle the innovation and
competitiveness of the industry. When substitute products enter the market, the regulated
industry will not be able to compete effectively and will therefore lose market power. As
market power decreases, the industry will employ increasing pressure on the regulatory bodies
to lift regulatory limitations. Generally speaking, the decision to remove regulation is usually a
very long one, representing a large delay in the system. The length of the delay and the speed
of substitute product market capture will eventually decide the outcome of the regulated
industry. Regulation removal may be too early, too late, or just in time. History, however,
shows us that in most instances, the political nature of regulation removal lends itself to very

Sam Peltzman, editor, Clifford Winston, editor, AEI-Brookings Joint Center for Regulatory Studies}
large delays and regulation removal only after severe damage has been inflicted on the regulated industry.

![Hysteresis dynamics of regulation](image)

The hysteresis regulation model is a simple example of dynamic modeling of a key piece of the telecom industry. We can assume that additional basic models can be applied to other components of the industry such as pricing, product life cycle, investment or product entry and exit. By combining all of these simple dynamic models into one comprehensive model, under this research, we aim to capture more detailed dynamic behavior and new insights. As such, the regulation modeling acted as a first and small scale example of the proposed simulation approach.

**A.3. The Communications Futures Program**

This research work is funded by the Communications Futures Program of the MIT Media Lab. The program aims to create, through interdisciplinary research, technological road-mapping of the telecom industry “… by taking a radical new approach to communications technology, economics, management, and regulation. Building a research collaboration across the MIT campus, the Communications Futures program addresses research in areas ranging from ultrahigh-speed radio, to spatial diversity, to photonics and networking, to policy and regulatory issues—areas of key interest to both the existing and emerging communications sectors.”

By creating a theoretical framework and a simulation model for the dynamic economic behavior of the telecom industry, this research effort acts as a building block in the research agenda of the Communications Futures Program.

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5 [http://cfp.mit.edu/about.html](http://cfp.mit.edu/about.html)
B. Goal

B.1. Integrating a Full-Scale Model

The primary goal of this research effort is to integrate several pieces of relatively simple dynamics simulations into a full blown system dynamics simulation of the telecom industry and analyze possible dynamics that can play out over time, reaching basic qualitative insights on the forces behind the industry. Examples of such pieces include previous work conducted on regulation, such as the hysteresis model, or the product adoption life cycle model, as it pertains to the introduction of new products⁶ [Figure 2].

![Technology product adoption life cycle](image)

Accordingly, the work is divided into two separate portions – implementation and analysis. In the first part, a full blown simulation will be implemented, taking into account as many aspects of the industry as possible. For example, the dynamics incorporated into the model will include supply and demand, substitution effects, market entry and exit, investment strategy, capital markets, standardization and regulation. In the second phase, the simulation engine will be utilized to run several scenarios and generate qualitative insights resulting from complex system behavior.

⁶ Crossing the Chasm, Geoffrey A. Moore, 1999, Harper Perennial
B.2. **Insights into Complex Dynamic Behavior**

It is the goal of this research to try and capture complex dynamics which result from a combination of simpler trends, and which are difficult to foresee in advance. System dynamics, as a research topic, has demonstrated time and time again, how a system comprised of simple, well understood dynamics, when hooked together, can result in complex unforeseeable dynamics. It is our attempt to try and capture as many of these as possible. Although the simulation can be adjusted to represent any industry, we will try and focus on and fine tune the simulation to the telecom industry. To achieve this, we must find and insert into the model unique dynamic characteristics associated with the telecom market. Examples include very rapid product life cycles, high fixed cost, huge upfront investments for product entry, large network externalities, as well as efforts to standardize communications protocols resulting in lower barriers to entry and commoditization.

B.3. **Building Block for Continuing Research**

This research work provides a building block and a first step in the long-term research agenda focused on reaching a comprehensive system dynamics model of the telecom industry which captures the entire complexity of potential dynamic behavior. As such, it was our attempt to implement a model that lends itself to further improvements and is built in a modular fashion.
C. Simulation Design

C.1. Simulation Methodology

C.1.1. Basic Methodology
A fully realistic simulation of an industry is a very challenging task. The complexity of true industry behavior is far beyond what a single simulation can capture. However, we shall attempt to simulate certain portions of the dynamics that may play out, enabling us to derive new insights and conclusions. To accomplish this, the simulation will be constructed of pieces, each of which will depict a simple, well defined dynamic. The underlying assumption of the full blown simulation is that a combination of a few simple pieces can generate complex system behavior which will result in new conclusions and academic value. The design of each separate piece, although capturing a simple dynamic behavior, should be true to reality in the simplest way possible. The final purpose is to reach qualitative insights on potential industry behavior.

C.1.2. Implementation Language
The system dynamics model was implemented in Matlab. Matlab was chosen for its flexible capabilities in simulating stochastic dynamic models, as well as its rich graphic engine for easy generation of output data.

C.1.3. Unique Attributes of the Telecom Industry
The system dynamics model is based on an economic model containing simulation of supply and demand behavior, pricing, investments, as well as many additional features. In essence, the underlying model can be viewed as a general economic model which can apply to a variety of markets and industries. However, we have made a focused attempt to calibrate the model and its assumptions to fit the telecom industry’s key attributes.

One such key attribute of the telecom industry is the very high upfront investment required to enter the business. This huge capital cost required for a new entrant to enter the market acts as a large barrier to entry and should be part of the simulation.

Large network externalities are also a crucial part of the telecom market dynamics. We have therefore, enabled the model to include varying degrees of network externalities so we could test the dynamic effect of this basic characteristic.

Overall, the percent of personal income spent on telecom products is constrained. This figure may grow or fluctuate over time, but putting a cap on the total money spent on telecom products helps us simulate cross-product substitution as a result of a capped spending budget.

Additional features which are unique to the telecom industry and will be part of the simulations include the effect of telecom regulation and the introduction of standards. In general, regulation plays an important role by limiting or driving competition in certain market segments, while also affecting innovation and R&D investments. Standards influence demand
behavior, cost structures and barriers to entry. The model will be flexible enough to allow us to simulate all of these effects.

C.2. Data Structure

The market will be comprised of a vector of firms and a vector of possible products. Each firm may decide to produce (or not) a certain product. The combination of firms and products creates a firm/product matrix which includes all possible combination of firms and products.

The firm vector will include data which is solely firm specific and cannot be broken down into products. This will include the following:

- Current asset value (overall current money of firm)
- Total value of firm

The product vector will include data which is product specific:

- Active flag indicating whether the product is produced by at least one firm
- Price which is the weighted average price of the product in the marketplace

The firm/product matrix will include all data fields which can be broken down into firm and product:

- Active flag – 1 if firm is producing product, 0 otherwise
- Delay – time periods from decision to launch product until product will be introduced
- NumOfActive – number of consecutive time periods product was active
- FixedCost – the fixed cost associated with producing product
- MC – the marginal cost associated with producing additional units of product
- Price – the price asked for the product
- ProdPricePrem – the price premium firm has in selling product (due to differentiation)
- NetPricePrem – the price premium firm has due to network externalities
- Quant – the quantity of products demanded of firm
- Revenue – the total revenue generated by firm/product in time period
- Cost – the total cost associated with firm/product in time period
- Profit – the total profit generated by firm/product in time period
- ProfitVec – a vector of historic profit in previous time periods
- NumOfProf – length of vector of historic profits
- CumProfit – the cumulative profit of firm/product since product launch
- NumOfNegProf – number of time periods with negative profits
- NumOfDecProf – number of time periods with decreasing profits
- Monopoly – flag indicating whether firm is a monopoly in product line
- CumRND – the cumulative money spent by firm in product R&D
- InvRND – the portion of product revenue to be spent on product R&D by firm
- Beta – the beta (cost of capital) associated with firm/product
- Value – the total value of future product sales (discounted by beta)

The simulation also includes a substitution matrix which gives a substitution coefficient for every combination of products in the market.
C.3. Supply and Demand Dynamics per Product

The goal of the supply and demand segment is to simulate the dynamic behavior of supply and demand as a function of prices and quantities of products produced by competing firms in the product segment.

Every product may be produced by one or more companies. In case of a single producer, it is expected that the firm will take advantage of its monopoly pricing power to capture higher surplus. In case of several competing companies, the demand for the product will be shared amongst the competitors, looking at supply and demand as an aggregate number.

The value chain consists of a simple single-tier structure – manufacturers of goods and buyers. There are currently no additional tiers in the value chain such as an upstream or downstream producer. The ability to simulate an additional dimension of the industry along the value chain may enrich the model further and is a great candidate for further research. It was previously shown that delays in flow of information along the value chain will result in significant over-stocking and under-stocking of inventories, also known as the bullwhip effect.

The demand curve for each product is given by the following function

\[ Q_T = A - BP_T \]

where \( Q_T \) is the overall product quantity demanded and \( P_T \) is the overall weighted average price requested for the product.

The overall weighted average price is calculated according to the price and market share of each separate producer:

\[ P_T = \sum_{n=1}^{N} S_n P_n \]

where \( S_n \) denotes the market share of the n-th producer.

Market share is divided between the competing companies according to price. A lower price relative to others means a higher market share. A higher price will result in decreased market share. The function used to calculate the division of market share as a function of price is:

\[ S_n = \frac{t_n}{\sum_{i=1}^{N} t_i} \]

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7 Industrial Dynamics, Jay W. Forrester, 1961, Pegasus Communications
\[ t_n = e^{-c \sum_{i=1}^{N} P_i} \]

where \( c \) is a parameter that controls sensitivity to price difference. A higher \( c \) will result in higher sensitivity. When \( c \) equals zero, pricing does not matter and the shares will be divided equally.

This basic supply/demand model is based on a model developed and used by Prof. Robert Pindyck of the Sloan School of Management at MIT\(^8\).

It is further assumed that supply is optimal and will meet any demand for the product, meaning that there is no under inventory or excess inventory, resulting in additional costs to the producers.

The current method used to calculate market share assumes no immediate differentiation between firms producing the same product, resulting in market share that is purely pricing dependent. The model, however, can implicitly allow for product differentiation by introducing the concept of a "price premium". According to this method, each firm will have a certain price premium which will be denoted by \( D_n \). The market share will be recalculated as:

\[ S_n = \frac{t_n}{\sum_{i=1}^{N} t_i} \]

\[ t_n = e^{-c \sum_{i=1}^{N} (P_i - D_i)} \]

With respect to generating demand, the price premium is equivalent to a price reduction. However, conceptually, the premium is simply higher demand resulting from differentiation and higher attractiveness of a firm's offering as compared to the competition. For example, investment of a firm in R&D can result in a better product and a higher price premium. Moreover, it is assumed that a given premium will erode over time and is mean reverting to zero, because product differentiation is hard to maintain over time and requires constant investment. Mean reversion will be implemented using a simple multiple coefficient in the form of:

\[ D_n(t + dt) = d_c \cdot D_n(t) \]

with \( d_c \) having a value which is smaller than one.

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\(^8\) Industrial Economics for Strategic Decisions, 15.013, Strategy Game Economic Model, Prof. Robert Pindyck
C.4. **Pricing Dynamics**

As was described in the previous section, market share, and consequently revenues and profits are a direct function of pricing, relative to the competition. In order to model dynamic pricing, we must make assumptions on the way firms will price their products versus the competition.

One method which may be used is to try and derive an analytical framework, which can be used to find the optimal price resulting in optimal profits, given that the competitors’ prices remain constant over time. This method assumes that firms will price their products as to extract maximal profits in the short term, as opposed, for example, to pricing low so as to drive a specific competitor out of business resulting in higher profits later on which will compensate for the short term losses. Moreover, we will need to find an analytic solution to the pricing problem by deriving the profit as a function of pricing and finding the first derivative and optimal solution.

A second method, which is the one implemented in this model, assumes an iterative pricing decision that will eventually reach a Nash equilibrium. Under this model, each firm has to make, in each point in time, one of three decisions – lower the price, keep the same price, or up the price. Each firm will choose the option leading to maximal profits, assuming all other firms remain with the same prices. Accordingly, prices will continue to fluctuate until a Nash equilibrium is reached. At that point, no firm will change its pricing.

The second method requires us to make assumptions on the price increase/decrease tested by the different firms, as this will result in the basic sensitivity of the pricing decision, as well as the rate at which pricing decisions are made. Moreover, it is very important to note that due to the fact that the multi-dimensional pricing function is not perfectly smooth, and the fact that it is sampled over a predefined grid of sub-optimal precision, we will encounter more than one Nash equilibriums and the final resting place is a direct function of the path we followed. This is a basic drawback of the second method, but one we are willing to entertain in order to allow flexible adaptive decision making which may be sub-optimal in nature, but still follows the basic dynamics we expect to see in real life.

C.5. **Product Life Cycle Dynamics**

The market acceptance of every new product will follow the dynamic behavior of a technology product life cycle.

At first, the product is new and demand for the product is low. The initial customers are technology enthusiasts who are highly insensitive to price and willing to pay a large amount to be among the first who try out the new technology.

Accordingly, both quantity and price will go through a typical life cycle dynamic, which are illustrated in the following graph:

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9 Crossing the Chasm, Geoffrey A. Moore, 1999, Harper Perennial
As can be seen in Figure 3, the quantity of new customers in each time period follows the well known life cycle dynamics. The cumulative quantity, as seen in Figure 4, has a rapid acceleration as the early and late majorities start purchasing the product. When the market for the product reaches maturity, the rate of cumulative quantity increase declines and levels off. We expect price to decline over time as we shift towards more price sensitive segments of the market. The rate of decline should be very rapid at the beginning due to the low price elasticity of the initial customers, and should slow down over time. An exponential decay function seems to fit this behavior very well, as seen in Figure 5.

When introducing a new product, several parameters of the model have to be assumed. These include the life cycle time, the overall quantity of the potential market, as well as the initial and final price sensitivity. For example, a shorter life cycle will result in a much faster growing customer base, with quicker revenue buildup and faster payback on the investment. By varying the life cycle time, we can simulate products which are a "hit", catching on at a high pace, as opposed to slowly growing products which take a long time to penetrate. This is useful, since technology product life cycles have become, in general, shorter and shorter over the last two decades.

One problem that must be addressed is that we can not force prices and quantities to behave in a certain way over time, since we control only the demand function which is given by the parameters $A$ and $B$. In order to obtain true life cycle dynamics, a vector of values for $A$ and $B$ has been derived which, when performing monopoly pricing, results in the desired dynamics for both quantity and price. These will be used as a look up table for the creation of life cycles for the product in the simulation.

**C.6. Product Entry**

The decision to enter a product space may depend on many factors. In order to simplify the basic dynamics of entry decisions, we will assume that firms are active in several product segments and that entry decisions are limited to entry into existing product segments.

Entry in this case will include any decision of a firm to start selling a product where competition already exists. The decision will depend on the following factors:
- Cost required to introduce the product
- Net present value of expected profits from product
- Overall return in the money market
- Overall investments in the market

The first two points deal with the objective decision and analysis of potential profitability. The last two points deal with subjective perception due to market dynamics and market attitude towards investments. We assume that in times of market rally and large return-on-investments, as well as in times of high overall investment, the probability of firms to enter new product lines is higher.

The cost required to introduce the product will be randomly selected from a uniform distribution, having a reasonable lower and upper limit. We assume that the upfront cost taken into account as part of the decision mechanism is stochastic and is separate from the actual upfront cost that will be incurred by the firm. We further assume that the actual upfront cost will follow the same distribution but since it is randomly assigned separately, situations of under/over estimates in up front cost analysis will occur.

The net present value will be calculated according to the mean profits of firms competing in the product segment, assuming the same profits will be maintained indefinitely and the future profits should be adjusted according to an interest rate with beta of 1, meaning the sum of the risk free rate and the market premium.

The return of the money market will be determined by compounding the returns of the money index over a predefined time horizon.

The number of investments in the market will be the sum of product entries minus the sum of product exists over a predefined time horizon.

An entry decision will be made only if the introduction cost is lower than the NPV. Assuming this is the case, a probability of investment will be calculated according to

\[ prob = \min\{R \cdot (I + 1), 1\} \]

where \( R \) is the return on the money market and \( I \) is the overall number of investments in the market. After the probability is calculated a draw is made, according to the probability, to decide whether to go forward with the project.

In case of a positive entry decision, the new product will be priced according to the weighted average price of other firms selling the same product. The new firm will join the product life cycle at the same exact stage all other firms are at. Since the product already exists, the entry will not result in the initialization of a new product life cycle.
C.7. **Product Exit**

Exit decisions will be based on the following two metrics:

- Number of consecutive time periods of losses in selling product
- Negative future projections of profitability for product

The combination of both of these indicates that the product is a loosing proposition which will not improve in the foreseeable future.

The model will track and record the number of consecutive time periods where a loss was incurred on the product. Assuming that this number crosses a predefined threshold, we will move on to the next test, the future profits projection, focused on testing whether profitability will be achieved in the future.

The future projections will be based on fitting the past earnings data to a polynomial function of the second degree. The fitting procedure will calculate the polynomial coefficients. These coefficients will be used to project the earnings at some future point in time, assuming the earnings will continue to behave according to the second degree function. If the future projection will also be negative, the exit decision will be made.

C.8. **Firm Value**

We will calculate the overall firm value for each firm. The value of the firm will be a sum of the current assets (existing money) value and the value of the future discounted earnings. The current asset value will be discounted according to a cost of capital of beta=1 every time period. The value of future earnings will be calculated as the sum of values of the separate active product lines.

\[ V_i(n) = \frac{A_0}{(1 + r_i)^{n-1}} + \sum_{k=1}^{N} \frac{\pi_{i,k}(k)}{(1 + r_i)^{n-k}} + \sum_{l=i}^{N} \frac{\pi_{i,l}(n)}{r_l} \]

\( V_i(n) \) is defined as the value of firm i at time n. \( A_0 \) is the initial value of the firm at incorporation, \( r_i \) is the interest rate, \( \pi_{i,k}(k) \) is the profit of firm i due to product l at time k.

As we can see, firm value consists of initial incorporation asset value (first term), past and present earnings (second term) and discounted future earnings (third term).

C.9. **Money Market**

The goal of this module is to calculate the value of the “economy” which can be defined as the aggregate sum of all activities of all firms in the industry. The economic value is a sum of current and future profits, discounted according to the relevant cost of capital.

At each point in time we will calculate the value of each product for each firm. The value will be defined as the net present value of current and all future profits, discounted according to the cost of capital, as given by the product’s beta and the market rates. This value will assume that the future profits will be the same as the current profits, or in other words, that the market is in
equilibrium. Accordingly, entry and exit of firms, including changes in pricing will cause shifts in profitability and fluctuations in overall market value.

It will also be assumed that each firm has some initial asset value when incorporated, which will also be accounted for as part of the overall value of the economy. The overall market value is the sum of values of all firms in the industry.

A money index will be defined as a stock index that will inform investors of trends in economic value. The money index, will be calculated by fitting the overall market value to a polynomial function of the third degree, and projecting the value expected at some future point in time. Accordingly, the money index will follow the actual economic value closely, but will also amplify short term noises and trends.

**C.10. R&D Investment by Industry**

Each firm in the industry can decide how much to spend on R&D as a percentage of incoming revenue. Spending on R&D will be subtracted from the firm’s bottom line. However, it is expected that R&D spending will enable competitive advantage in the form of either lower marginal costs or introduction of a price premium as defined in the supply and demand model.

Spending on R&D is not optimized or iteratively tested like pricing. The decision of each firm can be either hard coded into the model, or left as a random variable, resulting in a variety of investment decisions, from intensive investing to firms that hardly invest at all. Once investment is made, there will be a predefined threshold on the total investment needed to actually create a product enhancement. The periodic investments will be aggregated until the threshold is reached. According to this model, the cumulative R&D investment will be calculated according to:

\[
R \& D_{i,k}(n) = \sum_{l=0}^{n} c_{i,l,k}(l)Rev_{i,k}(l)
\]

where \( R \& D_{i,k}(n) \) is the cumulative R&D investment by firm \( i \) into product \( k \) by time \( n \), \( c_{i,l,k}(l) \) is the investment coefficient for firm \( i \) product \( k \), and \( Rev_{i,k}(l) \) is the revenue of firm \( i \) product \( k \) at time \( l \).

A threshold will be defined for maximal cumulative investment. Whenever the threshold is passed, an innovation will introduced and the cumulative R&D variable reset to zero. The innovation may have two key attributes. It may reduce marginal cost (cost innovation), or it may introduce a price premium due to differentiation. The possibilities are defined in the following equations:

\[
MC_{i,k}(n) = MC_{i,k}(n-1) \cdot (1 - c_{MC\cdot rnd}(l))
\]

\[
PP_{i,k}(n) = PP_{i,k}(n-1) + c_{PP1} + c_{PP2} \cdot rnd(l)
\]

where \( rnd(l) \) is defined as a uniform probability function over the interval \([0,1)\).
C.11. Substitution Effects

In order to simulate true dynamics involving product switching, we must introduce product substitution modeling into our simulation. The simplest way is to assume competition across products, meaning that we will adjust the supply/demand function according to the following method:

\[ Q_{T,n} = A_n + \sum_{i=1}^{N} B_{i,n} P_{T,i} \]

where \( Q_{T,n} \) is the overall product quantity demanded for product \( n \), \( B_{i,n} \) is the coefficient describing the affect of product \( i \) on product \( n \), and \( P_{T,i} \) is the overall weighted average price requested for product \( i \).

Through the \( B \) coefficients, we can simulate substitution effects across products in the market. Substitution coefficients will be a product dependent quantity and will be the same for all firms producing this product.

C.12. GDP Growth

Macroeconomic fluctuations play an important role in the dynamics of the industry and affect not only availability of money for further investments, but also the overall aggregate spending of consumers and businesses.

Our modeling of GDP behavior consists of a superposition of two separate effects. The first is a steady constant growth rate. The second is a fluctuation over time in the form of a sinusoidal function. Overall GDP behavior will follow the following function:

\[ E_c(t) = G_r (1 + C_a \sin(2\pi t / C_t)) \]

where \( E_c(t) \) is defined as the economic cycle coefficient at time \( t \), \( G_r \) is the constant growth rate of the economy, \( C_a \) is the economic cycle amplitude and \( C_t \) is the economic cycle time length.

The total money in the market will evolve according to:

\[ M_T(t) = M_T(t_0)E_c(t) \]

where \( M_T(t) \) denotes the overall money in the market at time \( t \), and \( M_T(t_0) \) the overall money at simulation start.
This basic model allows us to introduce and test the effects of both sustained growth (or decline) and fluctuations of various severity.

C.13. Total Money Cap

A very important attribute of the telecom economic model is a cap on the overall aggregate money spent on all products by all firms. The rationale behind this cap is that the overall expenditure of businesses and consumers on telecom products is limited and should be constrained in the model. Success of one product segment will come at the expense of profitability decline in other segments. However, the overall aggregate spending may increase or decrease over time as a function of economy GDP changes.

Modeling will be done according to the following formula:

\[ f_c(t) = M_{S,T}(t - dt) / M_T(t) \]

where \( f_c(t) \) denotes a correction factor at time \( t \), and \( M_{S,T}(t) \) is the overall money spent in the market at time \( t \). The correction factor aims to compensate for the differences between availability of money in the marketplace and actual expenditures. Since at the beginning of each time period we compute the new value of the aggregate money in the market, but we only know the previous aggregate money spent, we must use compare these figures to derive the correction factor.

The correction factor will be applied to the product demand calculation in order to adjust for overflow or underflow of money in the market. Adjustment to the demand curve will be performed according to the following formula:

\[ f_{cd}(t) = f_{c}^d(t) \]

\[ Q_{T,n} = \frac{A_n + \sum_{i=1}^{N} B_{i,n} P_{T,i}}{f_{cd}(t)} \]

where \( f_{cd}(t) \) is the dampened correction factor. We will employ a dampening factor on the previously calculated correction factor to allow some “delay” and an additional degree of freedom in demand behavior relative to overall aggregate money in the marketplace.

Introduction of such a spending cap on overall spending plays a very important role in the dynamic behavior of competition.

C.14. Network Externalities

Network externalities play a crucial role in the dynamics of the telecom industry. Typically, telecom products have very large network externalities. A straightforward example of this
phenomenon is the wireless industry. Most carriers offer significant savings when talking to other members of the same network, or higher prices when talking with other networks. As such, the value of each network highly depends on the number of subscribers.

Network externalities will often drive competition for the market instead of competition in the market, resulting in domination of a single company as in the example of Microsoft in operating systems, or a few large players as in the case of the current wireless industry.

We aim to incorporate a model which will allow us to test various degrees of network externalities. The model is built of the following structure:

\[ X_{i,n} = \frac{X_{\text{MAX}} \left( S_{i,n} - 1/N_{f,i} \right)}{1 - 1/N_{f,i}} \]

where \( X_{\text{MAX}} \) is defined as the maximal network externalities coefficient, \( S_{i,n} \) is the market share of firm \( i \) in product \( n \), and \( N_{f,n} \) is the number of firms competing in product \( n \). \( X_{i,n} \) is defined as the network externalities price premium for firm \( i \) in product \( n \). If the market share is equal between all competitors, the network externalities price premium will be zero. In case of full market domination, the premium will be equal to \( X_{\text{MAX}} \).

C.15. Regulation

The ability to simulate regulation will allow us to test potential effects of regulatory intervention including analysis of potential regulatory structures. One caveat is the time dependence of regulatory introduction and removal versus other dynamics simulated in the model. Typically, regulation takes a very long time to be introduced and an even longer time to be removed. As such, the most interesting dynamics have to do with the delays in these decisions.

We will assume regulation is a function of market power. Since we have no direct measure of market power, we will use market share as the indicator of market power.

Whenever the market share of a specific firm in a specific product line crosses a predefined threshold, we will mark that firm as a monopoly in that specific product line.

Regulation will be introduced a predefined time delay after the monopoly flag has been raised. Regulation may have many forms including any or all of the following:

- Fixed price – prices are frozen and cannot be changed by firms
- No exit – the monopoly firm may not exit the product line
- No entry – new firms are not allowed to enter the product line
- Cross transfer of innovations - as in UNE-P pricing, any innovations of the monopoly firm are transferred, at cost, to competing firms
C.16. Standards

One of the unique characteristics of the telecom industry is the rapid introduction of standards. Standards are aimed at enabling interoperability and hence increasing demand in the market. We will randomly choose time periods when a certain product line will reach a definition of a standard. The immediate effect of the standard will be:

- No differentiation – all price premiums due to differentiation will be set to zero
- No network externalities – all price premiums due to network externalities will be set to zero
- Reduced cost – all marginal costs of firms will be reduced
- Increased demand – demand for the product will be increased

Since overall spending in the market is capped, introduction of a standard may have a significant impact, especially in cases of strong substitution.
D. Simulation Results

D.1. Outline

Simulation results are given according to simulation topic. The topics include the following:

- R&D Investments
- Mismatch in Pricing Clockspeed
- Product Introduction Timing Mismatch
- Disruptive Product Introduction
- Regulation Dynamics
- Standards Dynamics

Each simulation section will provide the basic goal of the simulation topic, the results and a preliminary analysis of conclusions and insights derived from the simulation runs.

D.2. R&D Investments

According to the model, investment in R&D can lead to two basic advantages over competing firms. R&D advancements can result in lower marginal costs (manufacturing innovation), or in a higher price premium. The later refers to product differentiation, meaning consumers will value one product more due to, for example, advanced functionality. The simulation allows us to factor in any combination of these including insertion of randomness into the benefits derived from R&D. Such randomness will result in failed R&D investments as well as successful ones.

We begin by looking at a simple example, involving 10 firms competing over 5 product lines. For now, we eliminate the possibility of entry or exit, meaning all firms will serve all product lines throughout the simulation run. However, we will look at different amounts of R&D investments by the competing firms.

The initial scenario assumes 8 firms do not invest in R&D at all, resulting in a constant marginal cost and no product differentiation. 2 firms however, will invest 15% of their revenues into product R&D. Such an investment represents a considerable R&D effort in any given industry. These investments will reduce marginal costs and create some product differentiation. However, the success of the R&D process is random, allowing different results for the two investing firms. It is also assumed that all firms experience the same initial marginal and fixed costs, and begin by pricing the product identically. We will look at total firm value, resulting from the aggregate profits of all product lines, over time.
As can be seen in Figure 6, all firms begin at the same position. In the initial time period of \( t=0 \) to \( t=20 \), firm value declines, as the initial capital invested in the firms is used to launch a product but no revenues are generated. At time \( t=20 \), all firms launch their products simultaneously, resulting in additional expenditures, mainly fixed costs, and as a result, lower profits. The products go through the initial phase of the product life cycle and start catching on towards \( t=70 \). At that point in time, all firms are profitable. However, the investment made by the two firms, results in lower marginal costs and product differentiation, allowing them to capture a large share of the market very quickly, and basically squeeze the non-investing firms out of the market. We can see that the profitability of the non-investing firms, again, declines and remains negative as they lose market share. The difference in outcome of the two investing firms is highly dependent on the randomness of the R&D process.

R&D investment is equivalent to faster clockspeed\(^{10}\), meaning that such an investment will increase the internal innovational clock of the company. Investing in R&D will give a firm a definite advantage in cases where a minority of firms invests and the majority does not, allowing the investing firms to generate a competitive edge. In this case, falling behind on R&D clockspeed will result in market exit. As such, investment decisions are a multi-player

\(^{10}\text{Clockspeed, Winning Industry Control in the Age of Temporary Advantage, Charles H. Fine, Sloan School of Management, MIT, Perseus Books}\)
strategy game, with an unclear equilibrium point, which may rely not just on the dynamics of the industry, but also on the risk tolerance of each individual player.

The next scenario will analyze a case involving equal and massive investment in R&D by all firms. Although the investment as a percentage of revenue is identical for all firms (15%), the results may vary due to the stochastic behavior of R&D outcome. This case represents equal clockspeed across the industry, coupled with strong network externalities for each product line. The results are given in Figure 7.

![Equal R&D Investment by All Firms](image)

**Figure 7 – Equal R&D Investment with network externalities**

Due to equal investment, all firms generate the same profits and losses until $t=68$, when the first R&D investment outcome is evaluated. Following these results, a stochastic competition evolves, where the final winner, capturing the majority of market share is determined by the random innovation outcomes. It is important to note, that the outcome will vary across product lines, with different winners for different product lines. The result will also include exit of non profitable product lines. At the end point of this simulation, the number of profitable firms in each product line ranged from 3 to a maximum of 6. It is safe to assume that due to the strong network externalities, the final outcome over the long-term will be a monopoly in each product line, if investment level remains constant over time.

An additional point to stress is that the first firm to innovate is not necessarily the one to win the market. It is possible for a certain firm to develop a competitive advantage due to
innovation, only to loose that edge later to an innovation by a competing firm. However, strong network externalities will severely limit the ability to recapture market share through innovation, since they act as a strong reinforcing feedback mechanism. To stress this point further, we will run the same simulation without any network externalities. The results are given in Figure 8.

![Figure 8 - Equal R&D investment with no network externalities](image)

We can see that as a result of the stochastic innovation model, a firm, although having lower value at some point in time, can get ahead of the competition through innovation. However, this ability to bootstrap through innovation is limited, since, once more profitable, a firm has more resources for the innovation process, resulting in an reinforcing feedback mechanism, even without network externalities.

An initial and straightforward conclusion is that companies should minimize the stochastic variability of the R&D process. Such actions can directly translate into a higher probability of success over the long term. Since each innovation is, in essence, a draw of a coin, and strong reinforcing feedback exists, even by improving one’s odds slightly, one can enjoy a big jump in overall probability of success.

When all firms invest an equal amount, resulting in an identical clockspeed across the industry, the final outcome is not clear and is highly dependent on the underlying stochastic innovation process. It is obvious that if the innovation process was completely deterministic, the final
outcome would be identical across firms, given equal investments. Accordingly, the risk associated with the R&D investments, enables us to look at the R&D process as a lottery ticket to winning significant market share. The end results of the innovations are unknown, but investing buys us a probability to jump ahead of the competition.

This statement is strengthened further by the existence of strong network externalities. In this case as well, it is unknown, at the initial phase, who will be the firm to win the market, given equal investments. We can conclude that the need to invest is highly dependent, both on the randomness of the outcome and on the level of network externalities existing in each product line. Strong network externalities result in a very high potential investment gain. However, we have said nothing about the risk of such investments.

As a result, we should see a tendency towards high R&D investment in industries having strong network externalities.

An additional scenario of interest involves a random amount of R&D investment by each firm. Each firm will pick an amount to invest in R&D, uniformly distributed between 0% and 20% of revenues. We will assume no network externalities, and a limited amount of benefit from each innovation. The benefit of the innovation is random as well. Looking at a longer time horizon (t=200), we obtain the following results as depicted in Figure 9 and Figure 10.

![Figure 9 – Distribution of cumulative profits for random R&D investment](image1)

![Figure 10 – Random R&D investment, single outcome](image2)

Figure 54 shows us the results of a scenario involving a mismatch in R&D investments. In general, firms investing more in R&D obtain a higher value over time, due to the benefits derived from the innovation. Some of the benefits result from the ability to fuel further innovation through the benefits of current innovations, a bootstrapping enforcing feedback effect. However, when we look at the distribution of cumulative profit over the specific product, we obtain a more complex picture, as seen in Figure 9. Additional investment in R&D may result in higher profits over time, but there are many examples of high investments resulting in lower cumulative profits. In short – high investments are a risky proposition.

We can certainly see that the higher the investment, the larger the volatility of the profits over product lines, meaning that high R&D investment is a risky business. Actually, we are trading
expected return on our investment with risk or volatility. Larger investments result in large potential profits, but, if the innovation fails, may lead to results poorer than those of non-investing firms.

A decision to invest in R&D is equivalent to a decision to increase the innovation clockspeed. In industries, like telecommunication, which experience large network externalities, firms cannot allow themselves to have a mismatch on innovation clockspeed over a significant period of time, as this may result in obsolescence. However, one must bear in mind that a faster investment clockspeed adhered to by all firms, will lower profits and turn the industry into a less predictable and riskier one.

The tradeoff between risky R&D investment and expected profits is similar to the basic investment problem, trading off variance and expected return. It is well known that the optimal solution is a function of the preference or the utility function of the individual/organization. However, Figure 9 shows a very interesting and non-intuitive tradeoff. It appears from the statistical distribution of profits, that the function describing the possible R&D "portfolios" in the risk/return space is convex and not concave. The function is described in Figure 11.

![Figure 11 - Risk/return tradeoff in R&D investment](image)

In Figure 11 we can also see a typical utility function showing parabolic behavior in the expected return/variance space, which is representative of a firm’s risk preference, and is used in frequently in investment management. The black line represents the tradeoff function between risk and return, while the green line represents a utility function of a given firm. As we can see the optimal investment strategy, for this specific firm, will be a very aggressive one.

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The intersection of such a utility curve with the risk function of the R&D investment, when convex, may also result in only two possible outcomes – either heavy R&D investing (the risky but potentially highly rewarding option) or very small investing to no investing at all (the zero risk but decent return option). If the mathematical description of the tradeoff is indeed convex, we should see a distinct separation into R&D intensive firms, which we will refer to as innovators, and zero innovation firms, which we will refer to as operators.

It is obvious that the mathematical optimization of the choices under a given set of risk preferences will depend, to a great extent, on the measure of convexity of both the utility curve and the R&D payoff function. As such, we should try and take a closer look at the factors which may influence the convexity of the R&F payoff function. These may include network externalities and the measure of underlying risk in the R&D outcome.

![Figure 12](image1.png)  
Figure 12 – Convexity of R&D risk/return tradeoff with network externalities

![Figure 13](image2.png)  
Figure 13 – Convexity of R&D risk/return tradeoff with network externalities (zoom in)

We will now introduce network externalities and look at how those affect the convexity and the implied risk of different investment strategies. As we can see, by comparing Figure 13 to Figure 11, adding network externalities increases the expected payoffs for larger R&D investments, sometimes by close to an order of magnitude. We have also tried to fit the distribution to a parabolic function, using a least squares estimation method. It is clear that a parabolic function does not capture the entire dynamics very well.

Another factor which may play a crucial role in shaping the tradeoff between risk and expected return is the stochastic process behind the R&D outcome. We will run the simulation again, this time without network externalities and with reduced variability of R&D outcome. The results are given in Figure 14 and Figure 15.
As we can see in Figure 14 and Figure 15, the overall variance in outcome for a given level of R&D investment has decreased significantly. Moreover, although being convex, the tradeoff function does not exhibit a decreasing slope for low to medium R&D investments. We must remember that even without network externalities, there is a reinforcing feedback in the system, since overall investment is defined as a % of revenue and not as an absolute amount. The main conclusion is that a higher probability of success for the R&D process will increase the expected return for large investments.

Additional analysis on the reasons behind the convexity of the tradeoff and the forces affecting it can be found in Appendix A.
D.3. *Mismatch in Pricing Clockspeed*

Another scenario of interest involves firms with different pricing flexibilities. We run a scenario of 10 firms, a random 4 of which have a much faster response time for pricing changes, when those need to be introduced. Pricing changes occur mostly during the first phases of product introduction (movement through the product life cycle phases with changing price elasticity) or when an innovation enters the market, either through reduced marginal cost or through product differentiation. The results are given in Figure 16 and Figure 17.

![Figure 16 – Pricing mismatch with network externalities](image1)

![Figure 17 – Pricing mismatch without network externalities](image2)

Figure 17 demonstrates the distinct difference in behavior between the two groups of firms having different pricing flexibilities. When network externalities are introduced, pricing effectively is more important due to the bootstrapping effect. In this case, faster pricing adjustments resulted in higher profits and firm value even before an innovation was introduced (t<80). Due to the higher profitability, the fast adjusting group was able to innovate at t=80, much earlier than the slowly adjusting group. This increased profits further, which, coupled with the network externalities, allowed the fast adjusting group to sprint ahead and take over the market.

In the case of no network externalities, there is no discernible difference before the introduction of an innovation. However, after such introduction, the fast adjusting group is much better at capturing the value of the innovation through optimal pricing, allowing them to outperform the slow adjusting group.

The basic phenomena describing the benefits of optimal pricing and the ability to change pricing structure rapidly is rather straightforward. However, we should keep it in mind and should return to it when talking about the effects of regulation, as regulation often involves some pricing rigidity. Inability to price effectively may also result from ineffective corporate processes, such as in relatively big firms which may be very slow to adjust to changing market conditions.
D.4. Product Introduction Timing

A timing mismatch that often occurs is a product introduction mismatch. Due to differences in product research and development across firms, some firms are more efficient and can introduce products earlier. In an industry, such as telecom, where network externalities exist, an early introduction can have enormous value. In this scenario we have 10 firms competing over 5 product lines. As an initial step, we will assume each firm introduces all five products simultaneously. The timing of the introduction for each firm is chosen randomly, using a uniform distribution between $t=10$ and $t=50$. Network externalities are added to the model and the same amount of R&D is assumed across all firms (10% of revenue). The outcome of the R&D investments is random.

Figure 18 – Introduction mismatch with network externalities

Figure 19 – Introduction mismatch with network externalities, zoom in

Figure 18 displays the results for the entire run, while Figure 19 zooms in on the time frame of product introductions. In this particular run, the firm that was second in line for product introduction (introduced at $t=16$) ended up taking the market. The firm to introduce the products first, at $t=12$, started developing a competitive advantage as can be viewed in Figure 19 by the peak in its value at $t=37$, but lost it to the second firm due to the stochastic nature of the R&D outcome. The value of the second firm, although peaking at $t=65$, falls drastically due to the entry of competing products. This is a great example emphasizing the first mover advantage, while demonstrating that the stochastic process involved with product enhancement, may erode this advantage in some cases.

In order to assess this statement it would be interesting to look at the distribution relating introduction time to overall cumulative profitability and firm value. To accomplish this task, we ran the same scenario described above ten times and aggregated the results to get some statistical characterization. Figure 20 shows the results. Each colored point on the plot represents a combination of introduction time and final firm value. As we can see, there is a large distribution of possible events. The blue line represents the best fit to a linear curve using a linear regression technique. We observe that a negative correlation holds, meaning that the later we introduce the product, the lower the expected profits, yet, due to the strong randomness of the R&D process, the negative correlation is not very strong for this example (correlation of $\sim 0.3$).
Next, we wish to see how this behavior is affected when each firm does not introduce all products at the same time, but rather, each introduction time is chosen randomly. We look at two runs, each of which has 5 product lines. The results are given in Figure 21.

The results show a weaker dependence on introduction time. The linear regression is highly biased by some very spectacular performance figures obtained, with a low probability, when introducing the products early. The correlation coefficient is also lower (~0.13). We can see that when the firm is diversified over multiple products, the timing of a specific product line is less crucial to the outcome. However, early introduction earns the early innovative firm a higher probability to obtain market dominance.
D.5. **Product Substitution**

When a disruptive innovation, and therefore strong substitution, is introduced to the marketplace, complex dynamics may arise. Some questions which may be of interest include assessment of R&D investment strategies, exit and entry tactics, as well as how these are affected by the existence of network externalities.

The basic disruptive scenario involves 2 firms producing distinct products. The first firm, denoted as Firm 1, introduces the first product (product A) to the marketplace at time $t=20$. The second firm, denoted as Firm 2, introduces a competing product (product B) at $t=60$. It is assumed that the product B is superior to product A and thus introduces a disruptive innovation with very strong substitution. The disruption is simulated through an asymmetric substitution effect. This means that it is much more likely that consumers switch from product A to product B than vice versa. The results are given in Figure 22 and Figure 23.

![Figure 22 - Disruptive product introduction, product profits and price](image1)

![Figure 23 - Disruptive product introduction, firm value](image2)

Figure 22 shows several outcomes from the simulation run. On the top, we can view the product entry timing showing that product A was introduced much earlier than product B. In the middle sub-graph we can see the overall profit per product line, showing that although the introduction of product A was successful, the competition of the superior product B deteriorates profits for product line A, making it a marginal business. On the other hand, product B captures the market and is much more profitable.

The bottom graph shows pricing behavior. The initial linear rise in prices is a result of the pricing optimization algorithm and is not indicative of optimal pricing, but rather that the optimal price at the given time is higher than the price charged. However, looking at price behavior once the price starts to decline tells us an interesting story. Prices for product A continue to plummet, due to decreasing market demand, whereas product B prices slowly rise, demonstrating the increasing aggregate demand due to product switching.

The dynamics described here, created by increasing substitution of a superior product, will play a significant role in cases involving substitution across industries. For example, when one
firm/industry is regulated, while a substitute product is not, the dynamics presented here will be amplified. We must keep this in mind when dealing with more complex dynamic problems such as regulation, standardization, or the question of investment strategies.
D.6. Regulation

The goal of the regulation simulations is to study the effect of regulation as it is implemented in the telecom industry, and its potential impact on the industry dynamics.

We start out by testing a case involving a single product line, where free competition exists, without regulatory intervention. Very strong network externalities drive a large probability of market takeover by a single firm. We will view the dynamics of competition as they relate to behavior of price, quantity, profits as well as market share and consumer welfare. The results are given in Figure 24-Figure 27.

![Figure 24](image1.png)  
Figure 24 – Entry, exit, profit and price behavior for free competition with strong network externalities

![Figure 25](image2.png)  
Figure 25 – Market power dynamics for free competition with strong network externalities

![Figure 26](image3.png)  
Figure 26 – Product quantity for free competition with strong network externalities

![Figure 27](image4.png)  
Figure 27 – Consumer welfare for free competition with strong network externalities

As we can see in Figure 25, strong competition exists in the market until roughly $t=140$, when a single firm gains market dominance, through innovation. The effects of this strong transition ripple throughout the industry. Industry profits, which are captured almost entirely by the
dominant firm, see a very large increase. This causes entries of other firms into the product space (vertical lines at \( t=150 \) in Figure 24), only to be driven out of the market a short time later by the clear dominance of the big firm and the network externalities effects. By \( t=205 \), there is only one firm active in the market – the dominant firm. Over time, there are multiple attempts to enter the market, most of which are unsuccessful. Only at \( t=800 \) do we see a slightly successful attempt involving multiple entries into the market. The dominant firm looses some market share but at the end is able to recapture its dominant position (see Figure 25).

Beginning at \( t=140 \), as the firm gains dominance, there is clear pressure to increase prices and take advantage of the monopoly position. Quantities also increase dramatically due to the enforcing feedback loop of network externalities. However, as prices go up and the firm takes full advantages of its monopoly position, quantities greatly decline, reaching a stable level by \( t=300 \) [Figure 26].

Consumer welfare also goes through a rapid jump once the dominant firm takes over the market, mainly due to increased quantities which are driven by the network externalities [Figure 27]. However, as time moves on, prices go dramatically up and quantities decrease driving consumer welfare down to a level which is even below that experienced at the initial stages of product introduction. Once successful competition kicks in driving prices down and quantities up at \( t=800 \), consumer welfare also picks up, showing the importance of competition for consumer welfare over time.

We will now look at the same scenario when regulation is introduced. We will introduce regulatory intervention whenever a dominant firm gains a market share of over 90% for a subsequent 20 time periods. Regulation will include a price freeze of $5 which is considered a fair level of price under severe competition. This price regulation will hold for the dominant firm only, while other firms may price freely. Regulation will also transfer the marginal cost of the dominant firm to its competitors, simulating the effects of (unbundled network element platform) UNE-P pricing in the wireline phone market. Additional effects will include gradual erosion of product differentiation and network externalities. The results are given in Figure 28 - Figure 33.
Looking at Figure 28 to Figure 33, we can see that competition existed until roughly $t=200$, where one firm emerged as the market winner. The product price increases gradually due to the increasing market power, and profitability goes up. At the same time, consumer welfare and quantities increase substantially due to the high demand generated through network externalities. The increased profitability encouraged other firms to try and enter the market. At the same time, the dominance position of the firm triggered regulatory intervention, in the form of a price freeze. Price drops dramatically, quantities shoot up, and profitability greatly declines. As the dominant firm adjusts to the new conditions under regulation, it is still able to command a leading role with maximal profits. These, however, erode quickly until the regulated firm ends up with the lowest profit in the industry [Figure 31], mainly due to its pricing rigidity. Consumer welfare enjoys a large spike, when regulation is introduced, due to the price drop and quantity surge, a spike which quickly declines as network effects are eroded.

Overall, we observe that consumer welfare, while not growing, is still higher than the free competition case, which ended in a natural monopoly. However, incentives to innovate seem
to be very low once innovation is introduced. Innovations of the incumbent firm are passed on at cost, which, coupled with the pricing freeze, transfers most of the economic benefits of the innovation to the competition and the consumers. Accordingly, we expect regulation to slow down the clockspeed of this industry.

The regulated firm, while adjusting to the new conditions of the market, ends up doing poorly relative to the competition over the long-term. The regulated price forces an equilibrium point which is lower than what is needed (for example, the equilibrium price given free competition and the same number of firms), resulting in lower profits and, again, lower incentive to innovate.

By regulating the industry, the regulatory body prevents a monopolized market, at the expense of lower innovation, and lower consumer welfare, relative to a free competition case.

An important question which naturally arises from the scenario above relates to the optimal timing for deregulation. We can state that the time horizon may be separated into three parts. The first includes all time periods where deregulation would be "too early" meaning that the regulated firm will regain market dominance. The third includes the "too late" period, where deregulation will not save the regulated firm and it will continue to loose profitability and exit the market. The second which is the most interesting is the "just right" timing where removal of regulation results in a stable competitive market. It is obvious, however, that removal of regulation can always result in a new firm gaining dominance over the long-term.

We will try tying deregulation to the market share of the dominant firm, showing examples of too early, and just right. Accordingly, we will set deregulation to market shares of 0.7 and 0.2 respectively. We will look at the behavior of market share before, during, and after regulation, as well as the behavior of profits in the industry as an indication of healthy and sustainable competition.
Figure 34 – Firm profit over time with deregulation at 70% market share

Figure 35 – Market share of dominant firm over time with deregulation at 70% of market share

Figure 36 – Firm profit over time with deregulation at 20% market share

Figure 37 – Firm profit over time with deregulation at 20% market share, zoom in

Figure 38 – Market share of dominant firm over time with deregulation at 20% of market share
Figure 34 and Figure 35 show the results for the 70% market share case. As can be seen, deregulation at 70% results in immediate market recapture and a return to monopoly power. There is no chance of real competition evolving.

Figure 36, Figure 37, and Figure 38 show the results for deregulation at 20% market share. Deregulation occurs at around $t=180$. We can see that stable competition evolves, with the previously dominant firm slowly capturing additional market share, only to level off at a stable share of around 20%. Zooming in on firm profits, we see that a healthy competition resulted, with multiple profitable firms in the market. This shows an example of deregulation which triggered healthy and stable competition.
D.7. Standardization

Standardization is simulated by making changes to the underlying product model in a singular point in time. These changes include the following:

- Once a standard is in place, there is no product differentiation, hence no price premium resulting from differentiation
- All firms creating product will enjoy the same network externalities which will be strong due to the standard
- There will be a jump in demand, created by the jump in overall network externalities
- Marginal costs will decrease and will take on the minimal marginal costs of all producers
- Due to the standardization, the entry barriers, given by the sunk cost required to enter the product line, will decrease
- The variability of the sunk cost for product entry will also decrease

We begin by running a scenario involving 30 firms and 4 product lines, 3 of which are regular products with competition both on pricing and R&D, while the 4th product goes through standardization at time t=100. The introduction of the standard affects price behavior, quantities as well as overall profit in the industry and consumer welfare. Figure 39 shows product price movement over time. We can see that the introduction of the standard created a slight pressure upwards in prices in the very short term due to increased demand, which was soon reversed and resulted in a continuous decline in prices over the long run as additional firms entered the market. Figure 41 shows the market entry that resulted from the introduction of the standards. Total number of firms competing in the product line almost doubled.

While prices declined, the quantity of products sold increased substantially over time and reflected both increased demand overall and better penetration due to lower prices. Overall product profit, which is defined as the aggregate profit across all firms competing in the product line increased substantially immediately after standardization, and leveled off to a stable constant value with mild fluctuations. However, the profit per firm decreased since the same profit of the industry is divided across more firms, as entry barriers are lower and the inability to differentiate the product enables coexistence of many competitors with increased stability.

Figure 39 – Price behavior following standardization

Figure 40 – Quantity behavior following standardization
Figure 41 – Product entry following standardization

Figure 42 – Overall profit following standardization

Figure 43 and Figure 44 show the average profit per firm, which is defined as the aggregate product profit of all firms competing in the product line divided by the total number of firms in the product line. We see that the industry represented by the standardization process experiences lower average firm profitability over time. Figure 44 shows a zoom on the range of average profits relevant to the standardized product line. We see that although average profits per firm are high in the short term, they decline by the end of the run to become the lowest average profits in all product lines. Specifically, the inability to capture innovation by differentiation creates a very stable dynamics which provides constant but low profitability to a large number of firms. In other product lines, differentiation through innovation creates market winners over time, and therefore the potential for higher average profits. This shows the average picture but not the variability of profits. One can easily assume that the standard product line will have very low variability while “regular” product lines show higher average profits but much higher variability. Again there is a clear tradeoff between risk and expected return. The strategic decision of standard introduction is therefore somewhat equivalent to a shift in the risk/return tradeoff, choosing a predictable but lower outcome over the prospect of very high returns with the obvious chance of losing the game.

Figure 43 – Average firm profit for standard and non-standard product lines

Figure 44 – Average firm profit for standard and non-standard product lines, zoom in
Figure 45 – Consumer welfare for case of standard introduction

Figure 45 shows consumer welfare behavior under standardization. We can clearly see that the introduction of a standard fueled significant and stable growth in consumer welfare. This is explained mainly through the reduction in prices, the increase in quantities, and the stable competition in the market. We can see, that for this specific example, the standard product line, while having the lowest average profit per firm, has the highest consumer welfare of all product lines.

Next we wish to observe behavior when introducing a standard which later on becomes a strong substitute to different product line. We will create a model containing 30 firms competing over 2 products. Initially, there will be zero substitutability between product lines. At t=100 a standard will be introduced for the second product line (green line), and at t=150 a gradual increase in substitution will occur until t=250, when full substitution will be reached, stating that in the eyes of the consumer, the standard product is essentially equivalent to the non-standard product (but not the other way around).

Figure 46 – Entry, exit, price and profitability for standardization under increasing substitution

Figure 47 – Product quantities for standardization under increasing substitution
The red vertical lines in Figure 46 correspond to product entry points. The green vertical lines correspond to product exit points. We can observe that once a standard is reached, there is massive entry into the standard product space, which later on continues at a slower pace. As we observed before, overall aggregate industry profit for the standard product jumps and remains at a relatively stable level with mild fluctuations, meaning that the average profit per firm will decline. Prices for the standard product gradually decline over time while quantities increase. The non-standard product is not affected immediately, but as substitution grows, more firms producing the non-standard become unprofitable as can be viewed by the profitability curve in Figure 46. When overall industry profit for the non-standard product dips below zero, many product exits are triggered as can be seen around $t=200$. These exits have a drastic effect on the dynamics of the non-standard industry. While everyone exists, one firm remains, gaining a monopoly position in the market. Since strong network externalities exist, this company sees a surge in demand and quantities sold [Figure 47], increasing prices, and a huge increase in profitability. This positive turn of events is very short lived and soon turns around as additional pressure from the standard product finally pushes even the monopolist out of the market.

We can conclude that substitution, again, acts as a channel, transferring the dynamics of one product line to its neighbors. Accordingly, substitution should be considered very carefully when supporting or introducing standards, as these may create an impact much broader than just their own product line.
D.8.  Consumer Welfare Behavior

Of great interest should be the dynamic behavior of consumer welfare under various scenarios. For example, the relation of R&D investment and resulting consumer welfare should be examined. Is consumer welfare maximized under constant competition? Do consumers gain by any innovation war, even if short lived?

We shall start by looking at R&D investment effects as they relate to aggregate consumer welfare. Consumer welfare is calculated per product line according to the aggregate demand curve.

The initial scenario involves a single monopolistic company, introducing a single product. We will study two cases, the first involving a monopolist with no investment in R&D, while the second includes a monopolist with large R&D investments. The results are given in Figure 48 and Figure 49.

![Firm value and consumer welfare under monopolistic firm scenario with no R&D investment](image1)

![Firm value and consumer welfare under monopolistic firm scenario with 10% R&D investment](image2)

Figure 48 – Firm value and consumer welfare under monopolistic firm scenario with no R&D investment

Figure 49 - Firm value and consumer welfare under monopolistic firm scenario with 10% R&D investment

Comparing both scenarios, we see that investment in R&D can increase both the firm value and the total consumer welfare. The monopolistic company has an incentive to innovate since it can capture a significant portion of the economic value of the innovation. Its decision on whether to carry out a specific investment in R&D will be based on the amount required and the economic benefits derived, but we can clearly state that an incentive exists.

We will turn to two comparable scenarios involving two firms, competing over the same product line, either with no investment in R&D, or with a 10% investment by both. The results are given in Figure 50 and Figure 51.
When comparing Figure 50 and Figure 51, which display the results under competition, to Figure 48 and Figure 49 which show results for only one firm, we can see that consumer welfare is always higher under competition. This is relatively straightforward, since competition creates pricing pressure downwards. However, when no R&D at all is involved, consumer welfare is higher by roughly 70% (~4200 vs. ~2500), whereas, when R&D is conducted by both firms, consumer welfare skyrocketed by over 350% (~36,000 vs. ~10,000). We have to point out that firm value under the R&D + competition scenario was an order of magnitude lower than the monopolistic firm value with R&D.

We can view this as a two dimensional competition problem. The first dimension of competition is pricing. The pricing problem has a deterministic model, as long as we do not account for stochastic effects of the R&D outcome on the pricing question. The second dimension is R&D which may lead to innovation in cost and product differentiation. This competitive landscape is stochastic, meaning we can not build a deterministic payoff table for both firms and try to find the Nash equilibrium. The payoff table will consist of random variables and rational players will make decisions based on the stochastic model and their own set of risk preferences. This turns the final equilibrium point into a stochastic dynamic variable as well.

We can conclude, however, when looking at the examples, that R&D can increase firm value and consumer welfare for both monopolistic and duopolistic cases. In the first, most value is captured by the firm. In the second, most value is captured by the consumer. One may ask – why should competitive firms innovate if most value is handed off to the consumer? That may be true, but the zero R&D point in unstable, since each firm may increase its value by committing to R&D. Similar to a pricing war, once R&D investment kicks in, the other firm cannot sit idle, since there is a higher probability of loosing the market. As such, consumers are better off by enabling or even encouraging competition over the R&D dimension.
Another interesting case involves mismatch in R&D spending. The scenario includes competition between two firms, one investing 10% of revenue in R&D while the second invests only 2% of revenue.

Figure 52 – Consumer welfare and firm value under competition with a mismatch in R&D investment

We clearly see how the firm which invested heavily in R&D outperformed the low investment firm over time, capturing the lion share of the market. The final firm value of the winning firm is very similar to the monopolistic case. Even more interesting is the observation that under this case, final consumer welfare is higher than the monopolistic case, meaning that consumers gained from the competition, and added overall investment in R&D, even if there is a final winner at the end, taking over the market.
E. Conclusions

E.1. R&D Investment

Investment in R&D by a firm is equivalent to an increase in clockspeed in its industry. By doing so, other firms in the industry are forced to compete through innovation as well, or bear the risk of loosing the market. This innovation war is fueled further by the existence of network externalities. These alter the shape of the risk/return tradeoff, or in other words, the efficient investment frontier, by increasing the expected return for high levels of risk. A low investment, or low clockspeed choice, is unsustainable in the long run, when other firms are heavily invested in R&D, especially when large network externalities exist.

In the simulation runs we showed that a convex risk/return tradeoff function may exist. This is proven in Appendix A for large network externalities. The basic notion of a convex tradeoff function may lead to very complex investment decisions by firms in the industry, depending on their risk preferences. In investment management, a function which is often used to describe a specific preference includes a parabolic function in the risk/return space of the following shape:\(^{12}\):

\[
\text{Expected Utility} = a \times \text{Expected Return} - b \times \text{Variance}
\]

Since risk is defined as the standard deviation or the square root of the variance, the function above also describes a convex contour in risk/return space. This means that under a given risk preference, the actual choice of optimal investment may be very unclear and very unstable. We illustrate this in Figure 53. The solid line represents the underlying risk/return tradeoff. The dashed/dotted lines represent various utility functions of various firms in the industry. The long dashed line corresponds to the most risk averse firm, which will therefore prefer the smallest investment possible under the current tradeoff. The short dashed line corresponds to the most risk seeking firm, which will choose to invest heavily. The dotted line corresponds to a firm which is, in between, with respect to risk preferences. As we can, the dotted line crossed the investment frontier in two distinct places, marked with dots. These points have essentially the same utility but very different investment strategies. As such, a firm with a clearly defined risk preference, may have a very ambiguous position on R&D investment. This insight is of great importance, since industry dynamics, such as competition, regulation, standardization and the like, may alter the underlying risk/return tradeoff, resulting in nonlinear disruptive motions in R&D investment by firms.

Such a risk/return tradeoff function may create a separation in the market place into two distinct groups – firms with very large R&D investments, and firms with very low R&D investments. In certain cases of risk preference and a convex tradeoff function, it would make no sense to have a medium investment. Accordingly, it is possible that two firms with the same risk preferences will have a very different investment strategy, due to the ambiguity of the solution.

\(^{12}\) Quantitative Investment Management, 15.408, Andrew Lo, Sloan School of Management
The time horizon, over which the game is played, may have a very big impact on the underlying tradeoff. As shown in Appendix A, increasing the time horizon, under strong network externalities, will greatly strengthen the position of the high investment firm. Moreover, the expected return of the zero investment strategy will tend to zero as the time horizon increases. We sum both of these in Figure 54.

![Figure 53](image1.png) ![Figure 54](image2.png)

**Figure 53** – Investment choice under various risk preferences

**Figure 54** – Time effect on risk/return tradeoff under large network externalities

We have also shown in Appendix A, that the cost involved in innovation can alter the underlying investment frontier significantly. The higher the cost of innovation, the lower the expected return for the investing firms. The penalty will be bigger, obviously, the bigger the investment is. The graphical effect is that of turning the function with the zero investment strategy as the axis of motion. We display this dynamics in Figure 55.

![Figure 55](image3.png)

**Figure 55** – Cost effect on risk/return tradeoff

The effect of network externalities is very similar to the time horizon effect. Strong network externalities greatly reward the risky investor. As such, the existence of network externalities increases the expected return for risky investments, while lowering the expected return for low investments. We display this dynamics in Figure 56. Strong network externalities also give rise to the convexity nature of the function by lowering the expected return of “risk neutral” investors, relative to those of the risk loving group.

![Figure 56](image4.png)

**Figure 56** – Network externalities effect on risk/return tradeoff
The combination of strong network externalities and high innovation cost, which is the essence of the telecom industry, can create a tradeoff function which is not only convex, but may also not be monotonously increasing. An example of such a function is given in Figure 57. Such a function may have an even greater potential of causing disruptive shifts in R&D investment. The underlying conclusion is that industries, like the telecom industry, which exhibit large network externalities and huge investment costs, will tend to be very unstable with respect to R&D investment by competing firms.

![Figure 57 - Convex and decreasing tradeoff function](image)

![Figure 58 - Substitution effect on risk/return tradeoff](image)

Substitution across product lines, or across industries acts as a route through which clockspeed in a given industry affects its substitute neighbors. Thinking of industries has entities having an internal clock, substitution acts as a transfer gear which links both clocks at a certain ratio. If full substitution exists, the clocks of both industries should maintain the same speed. Low substitutability of an industry will act as a buffer between its competitive dynamics and innovations in neighboring industries. However, when substitution increases, so does the transfer of innovational pressure across industries, and the need to increase R&D investment. If we assume a different risk/return tradeoffs for R&D investment in two different industries, the first having a low clockspeed (denoted by Industry A), and the second having a high clockspeed (denoted as Industry B), substitution will shift the investment frontier of Industry A to that of Industry B, as depicted in Figure 58.

### E.2. Regulation

Regulatory intervention arises whenever a market falls under monopoly power. The telecom industry, like any other industry exhibiting large network externalities, has a tendency to be competitively unstable and to result in a monopolized market in the long term. Regulation is aimed at leveling the playing field and encouraging competition. An example is the regulation currently imposed on the wireline phone industry. Such regulation includes regulation on pricing, universal service (no exit), as well as the requirement to give entrants access to the incumbents' network at cost (unbundled network element platform – UNE-P pricing). While encouraging entry, such regulation influences investment incentives in a complex manner. For
example, the existing wireline incumbents have a very low incentive to innovate, since most of the economic value of the innovation will be passed on to the competition.

We wish to incorporate some of these basic insights into the same framework used previously to analyze risk/return tradeoffs. We can state that regulatory intervention greatly reduces the payoffs for risky investments. Moreover, we can also assume that a regulated industry will exhibit less network externalities. As such, the effect of regulation will be to reduce the convexity of the tradeoff function, while lowering the return of high investments and therefore increasing the returns of low investments. This effect is displayed in Figure 59, and represents the opposite effect of network externalities. Accordingly, regulation created a disincentive to innovate, slowing down the clockspeed of the industry.

![Figure 59 – Regulation effect on risk/return tradeoff](image1)

![Figure 60 – The problem of a regulated industry under substitution](image2)

Regulation will also result in market power of the dominant firm decreasing over time. Substitution may play a crucial role in this process, further fueling the market power shift. The combination of regulation and increasing substitution with a non-regulated, high-clockspeed industry, will create an unsustainable position over the long term. On one hand, due to substitution, the regulated industry must increase its internal innovation clock. On the other hand, the regulation enforced takes out the economic incentives to do so and creates an artificial imbalance.

An example of such a position is the wireline and the wireless industries. The first is heavily regulated, resulting in lower profits, increasing competition, cream skimming by entrants, and low incentives to innovate due to the UNE-P pricing structure. The second is deregulated with a very fast clockspeed, large investments, higher profitability, and large network externalities. As substitution increases, and more consumers view the wireless phone as a full substitute to the wireline phone service, the big incumbents in the wireline industry will continue to lose market power while lacking the economic incentives to innovate in their own industry. This creates a clear mismatch of clockspeeds which is unsustainable in the long run. The dynamics are described in Figure 60.

**E.3. Standardization**

Standardization is another key attribute of the telecom industry, whether it is a wireless phone service standard such as GSM, or the most influential standard of the last few years – the
wireless LAN 802.11 standard, with all its subgroups denoted by a/b/g. The later had a profound influence on market penetration, driving costs down, demand up, while commoditizing the underlying technology.

Looking at our simulations, we see a difference between the short term and long term effects of standardization. In the short term, profitability shoots up, quantities increase substantially and there is a surge of market entry due to the reduction in entry barriers and entry cost. However, over time, prices plunge, overall industry profit levels off, leaving less average profit for each competing firm, while the introduction of the standard itself reduces incentives of firms to innovate, since product differentiation is hard to impossible. We illustrate the underlying dynamics in Figure 61.

![Figure 61 - Standard effect on risk/return tradeoff](image)

We differentiate between the short and long term movements by drawing both on the same graph. The solid line represents the original industry tradeoff. Introduction of a standard will first shift the tradeoff to the dotted line, showing much higher return for low investments and a reduction in the payoff for the high risk investment. As more firms enter the market, due to low barriers of entry, the tradeoff function will be pushed down, reducing the profits across the board and reducing even further the incentive to risk high investments. Although the short term effect may be to increase the incentive to invest across most investment options, the long term effect will be reduced incentives and therefore lower clockspeed, quite similarly to a regulated industry.

Again, like in the regulation case, introduction of a standard will affect neighboring industries which contain substitute products. These may feel the pressure of both the upturn of the standardized product line, mainly a jump in quantities and profitability, only to be replaced later by a saturated commoditized market with very low margins and slow clockspeed. Accordingly, a substitute product line will feel big disruptive shifts in clockspeed, finalizing in a slowdown of overall incentives to innovate.

The type of substitution, whether symmetric or not is of crucial importance. In the scenario simulated, we looked at a case of asymmetric substitution, stating that the standard product acts as a substitute to the non-standard product, but not the other way around. Accordingly, as
substitution developed, the low prices of the standard product created immense pricing pressure on the non-standard products, driving profitability down to an unsustainable level. The non-standard industry will therefore have fewer incentives to innovate, since they can no longer take over the market, or get a huge return, for taking on the additional risk. In the same way, network externalities in the substitute product lines are also greatly reduced.

E.4. Consumer Welfare

Consumer welfare is greatly influenced by all of the above considerations – R&D investment incentives and decisions, regulation if an industry, as well as standardization of a product line. First, we saw how consumer welfare benefits from an innovation war which is generated by a high clockspeed industry. As we saw, even cases ending up with a single player dominating the market, may increase overall consumer welfare.

Accordingly, it should be in the interest of society to or of any government intervention in the market, to keep strong incentives to innovate. This is equivalent to an increasing risk/return tradeoff function. Fueling innovation wars will drive consumer welfare up over time. In cases of a strong monopoly, regulatory intervention is required to reduce the market power of the dominant firm. However, and this is the crucial part, regulation must be removed as soon as possible, once the market has been returned to a sustainable level of competition, to allow new innovation incentives and increase consumer welfare.

Finally, due to the convex nature of the risk/return tradeoff function, a small shift in payoff may result in a disruptive shift in R&D investments, moving highly investing firms to a non-investing position. The existence of network externalities drives this unstable behavior, making regulation or any intervention in the market, very challenging.
F. Continuing Research

Although this research effort and the simulation scenarios used cover many topics relevant to industry dynamics, there are still many issues to research further. These include topics which can be investigated using the current simulation engine, and topics which require an extension of the current simulation through additional software modules.

F.1. Potential Topics Using Existing Simulation Capabilities

The conclusions, mainly as they relate to the investment decision and the tradeoff between expected return and risk, create a framework for illustration and basic understanding of the industry dynamics. We have looked at the long term dynamics of certain regulatory, standardization, and investment decisions, and how these affect the tradeoff between return and risk. We did not, however, look closely at the transition effects. The short-term behavior may be quite different, and since we acknowledge the fact that there are delays in the flow of information in the marketplace, such transitional changes may be very important.

The conclusion that strong network externalities leads to a convex tradeoff function in risk/return space requires further investigation. Specific effort should be targeted at understanding the underlying drivers of the convexity on a quantitative level, so as to pinpoint factors that may cause disruptive changes in investment incentives. Moreover, it would be an interesting topic of research to prove the assertion that industries with very large network externalities and investment costs will tend to separate firms into distinct groups of low innovators and high innovators.

The optimal timing of deregulation is another important topic. It is clear that there is a time which is too early, and a time which is too late, but the specific indicators of the “right” time to deregulate are still unclear. Is market-share a strong predictor of optimal timing? Should some clear measure of substitution be taken into consideration for regulatory decision making?

The simulation currently contains a money market and an aggregate stock index which is strongly correlated to the overall value of all firms in the industry. We have not analyzed the behavior of this market index and how it influences decision making or investment in the industry. It is logical that such a connection exists and that there may be some delays in the flow of information from the firms to the money market, potentially creating interesting investment dynamics.

Finally, it would be of value to calibrate the developed model to actual costs and market sizes which are typical of the telecom industry, so as to give the qualitative output more of a quantitative aspect. Such an undertaking will also allow us to test some of the conclusions further by comparing to actual documented dynamics of the market.

F.2. Potential Topics Requiring New Simulation Capabilities

The current simulation system contains only one level of the value chain. We currently have only sellers and buyers, but know wholesale market or downstream and upstream providers. Moreover, the simulation assumes demand will be met in full by the supply side with no overstock or understock of items. To make the simulation richer it would be beneficial to
include an additional layer of production (or more), while also adding the simulation of the supply side. By doing so, introduction of dynamics, like the bullwhip effect, may play out and affect overall market behavior including investment incentives and basic tradeoffs.

The existing simulation system assumes a predetermined number of firms and products which interact over time. Adding the ability of new firms to enter the market with new products, while eliminating total firms and products in case of total failure, will enrich the model further. The same goes for enabling outside investment in the form of venture capital and start-up activity which is aimed at high risk, innovative products which can disrupt the market.
Appendix A – Convexity of Risk/Return Tradeoff in R&D Investment

During analysis of the R&D scenarios, attention was focused on the convexity of the risk/return tradeoff. Although this basic insight resulted from a Monte-Carlo based simulation, it warrants additional explanation as to why convexity exists and what are the sources of this behavior.

We shall look at a simple example involving 3 firms over 2 time periods. The first firm does not invest in R&D at all. The second invests enough to have only one innovation at the end of the second time period, while the third firm invests heavily, gaining two innovations, one in each period. This setup is described in Figure X.

![Diagram](image)

Each innovation acts as a coin toss with a predefined probability of success. We will begin by setting this probability to 10%. We will define the market size as 100. We will also assume the most extreme case of network externalities, stating that the first firm to innovate successfully will take over the entire market. If two firms innovate successfully at once, we will assume a 50%/50% split of the market. If no one innovates, the market will be split three ways equally. The table below summarizes the possible outcomes of this game and their resulting probabilities. W stands for successful innovations, while L stands for unsuccessful ones.
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<th>Firm 3 Innovation2</th>
<th>Firm 1 Market</th>
<th>Firm 2 Market</th>
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<td>0</td>
<td>50</td>
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<td>W</td>
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<td>0</td>
<td>0</td>
<td>100</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Expected market value | 24.3 | 32.85 | 42.85 |
Standard deviation    | 14.8 | 23.7  | 28.4  |

If we plot the results on a two dimensional space spanning expected market value vs. standard deviation we get the following, as given by Figure 62. However, we must remember that innovation has a cost. If we assume a linear connection between the number of innovations in a given time period and the cost, we can map the efficient frontiers for multiple costs, as given in Figure 63.

![Figure 62 – Convexity of risk/return tradeoff](image1)

![Figure 63 – Cost effect on convexity of tradeoff](image2)

As we can see, the cost of innovation cannot change the basic convexity of the tradeoff, but can significantly change the firm’s decision as it relates to its risk preferences. Specifically, for the largest cost mapped out in Figure 63, the function declines, meaning that one would have to be very risk loving to take on the cost of innovation. This is important to emphasize, since small changes in cost can have a huge impact on investment choices.

Another important attribute to note is that this example was calculated over a one horizon game. If we take into account a repeated game over multiple periods or an infinite horizon, the mapped risk/return tradeoff will be significantly different. Simply put, if one has a probability of taking over the market in any given period, the overall probability over time, for the non-investing firm not be pushed out of the market, tends to zero. Accordingly, the effect of time is
to lower the expected value for the non-investing firm, while raising the expected value for the high investment firm. This acts as a rotation of the efficient frontier, as depicted in Figure 64.

Figure 64 – Time effect on risk/return tradeoff

Figure 65 – R&D success probability effect on risk/return tradeoff

Figure 65 shows the risk/return tradeoff for various success probabilities of the R&D process, ranging from 10% for the top line to 30% for the bottom line. We can see that increasing the probability of success increase the expected value of the intensive R&D firm (Firm 3), while decreasing the value of the two other firms. Accordingly, the function has become more convex.