Modelling the Satellite Internet Market
using Agent-Based Computational Economics

by

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Abstract

The satellite-based communication market is currently experiencing considerable transformation due to technological advancements, increased consumer demand, and the emergence of new competitors. The provision of internet connectivity via satellite has undergone significant growth from 19 million in 2010 to 43 million in 2020 [1], making it an area of critical interest. Understanding the long-term profitability of this industry through the analysis of existing market trends and hypothetical future scenarios is of great interest to operators, investors, and customers. Although trend following Equation-Based economic analysis is widely used within the satcom industry, it lacks the fidelity needed to consider specific logistical challenges inherent in this industry. Agent-based computational economics shows promise in analyzing these long-term market dynamics.

A novel agent-based model of the operators and consumers in the satellite communications market is proposed, developed, and tested. The Agent-Based Satellite Market model (ABSM) employs a ground-up approach to examine the behavior of satellite network operators as they compete for a heterogenous, globally distributed pool of customers.

The model underwent a historical calibration on the satellite phone market (1995 to 2005) using operators of Intelsat, Iridium, Thuraya and Globalstar along with the customer segments of residential, travel, business, and government. The ABSM produced a weighted mean absolute percentage error (WMAPE) of 12.4%. This falls into the good forecasting region and compares favorably with previous studies which fell within the same range (11% to 12%).

Several forecasts were produced for the satellite internet market. The datum forecast pegged to observed pricing saw a WMAPE of 10.4% and suggested present value of revenues to be \$11.5 B for SES, Intelsat \$14.4 B, OneWeb \$9.7 B, Starlink \$39.4 B, and

Kuiper \$14.2 B. Starlink, with their early market entrance and huge capacity, appears to be a winning combination. OneWeb performs the worst, possibly due to their late entrance and relatively low capacity.

The subsequent forecasts allowed the operator agents to select their own best pricing strategies through a range of different market conditions. When given the opportunity to develop and test new pricing strategies, Kuiper independently created a pricing strategy where they undercut the competition (\$50/year vs. \$600/year for an otherwise identical product) to stimulate demand and encourage customers already with an existing operator to switch to the lower-cost Kuiper service. Customers are typically resistant to changing operators due to high switching costs such as needing to purchase new equipment. However, we see evidence of this occurring with Kuiper's high portion of stolen customers (31% c.f. 21.4%), and a large drop in customers for their competitor Starlink in 2026 at the same time Kuiper enters the market. This is reminiscent of the strategy which the real-world satellite phone operator Thuraya engaged in when entering the satellite phone market relatively late in 2003. Examination of merger scenarios saw that an Intelsat-SES merger would result in an overall 10% loss in the present value of future revenue. Examination of a Starlink-SES merger found slight synergies (2% increase). Finally, rollout scenarios for a fiber internet substitute service were examined. SES with a mixture of consumers was least affected and even in the ten-times-datum scenario lost less than 10% of their future revenues. Kuiper, comprised of exclusively household-type customers, was most affected, losing more than 50% of their predicted revenues.

The ABSM model leads to several insights into the satellite-based communications market. The study emphasizes the importance of market segmentation, shows the development of competitive strategies such as price competition, and highlights the risks associated with ground-based fiber optic networks.

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Chapter 1

Introduction

This chapter introduces the thesis. To begin (1.1 Motivation on page 22) the state of the satellite internet market is reviewed. Next (1.2 General Objective on page 24) the general question of this thesis is indicated; we are trying to better understand what competitive strategies will prosper as the satellite internet market evolves. Then (1.3 Background on page 24) additional details on the satellite internet market is discussed, covering an introduction to telecommunications, the technical aspects of satellite-based internet, characteristics of the market, and potential modelling approaches. Subsequently (1.4 Specific Objective on page 35) the specific objective of the thesis is described; we will better understand the market by creating and testing a new agent-based tool known as the Agent-Based Satellite Market modelling tool (ABSM). Finally, the structure of the thesis is presented (1.4 Thesis outline on page 36) and chapter summarized (1.5 Chapter summary on page 37).

1.1 Motivation

One thousand two hundred kilometers northeast of Perth Australia, and by any measure in the middle of nowhere, a large grey box is placed onto the bulldust covered veranda of Prenti Downs cattle station. Opening it, the station manager finds a circular white disk, a tripod stand, some neatly coiled cables, and a Wi-Fi router. Turning on the power, the disk slowly pitches upwards, wanders like a confused sunflower, and stops. A ping on his phone lets him know that Prenti Dows is, for the first time, connected to the internet [2].

Satellite-based internet is already bringing real-time communication to a global market, stimulating growth [3], creating jobs [4], and connecting heretofore unconnected populations [5]. From 2020 to 2030 the satellite telecommunication industry's annual revenue is expected to grow from $2.9 to $18.6 billion [6]. Operators compete to supply internet connectivity to geographically distributed customers using on-orbit global satellite constellations (Figure 1). The industry is currently undergoing a significant shift. Starlink is providing a low-cost high-capacity internet service for residential users and some businesses facilitated by an unprecedentedly large constellation of next-generation satellites with Amazon's Project Kuiper not far behind [7]. Perhaps in response to this pressure, existing incumbents such as SES and Intelsat are considering the possibility of merging to better respond to these changes [8]. Understanding how investment, corporate strategy, and changing consumer habits affect an operator's long-term revenue is an important area for investigation.

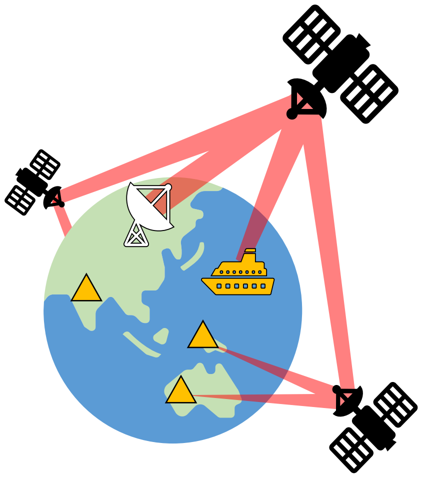


Figure 1: Satellite internet can connect populations which would not otherwise have internet availability such as mobile ocean platforms and households in remote regions. A gateway station (white) sends signals to operator satellites (black) which supply data connectivity (red) to geographically distributed customer terminals (orange).

This is not the first time that significant investment has been made in the space-based telecommunications sector. The Iridium constellation was a network of satellites in low Earth orbit that were used to provide voice and data coverage to satellite phones [9]. Developed by Motorola, the idea for the Iridium system was first proposed in 1987 and the first satellite was launched in 1997. The constellation was fully operational by the end of 1998, and the company's satellite phones became available to the public in 1999 [10]. Just as in today’s satellite-based internet services, the Iridium system was designed to provide global coverage, including in areas where terrestrial networks were unavailable or unreliable [9]. Despite being a technical success, Iridium struggled financially. Having spent approximately $5 billion on building and launching the constellation, they were unable to attract enough high-paying customers to cover their financial commitments and filed for bankruptcy in 1999 [11]. Although cash for operations was sufficient, debt servicing on these extreme loans is what ultimately killed the Iridium [12]. Rather than deorbiting the satellites and completely dismantling Iridium’s infrastructure the company was eventually acquired and by the early 2000s had become popular for remote and off-the-grid locations. Understanding the rise and fall of Iridium is an important component of strategic planning in the new age of satellite-based internet [13].

1.2 General Objective

Satellite-based internet is a rapidly evolving field with game-changing technological developments allowing providers to access market segments previously unreached. The satellite-communications market has undergone significant changes before, and success is never guaranteed. To understand this field one must explore and simulate the underpinning electromechanical and economic systems upon which it is built. The objective of this thesis is to answer the question of 'what competitive strategies will prosper for satellite-based internet providers from 2020 to 2040?' which is answered through the development of an agent-based model satellite market (ABSM) model. The competitive strategies explored are segment-specific pricing, mergers, and constellation capacity growth with additional exploration into the effect of fiber optic rollout on customers and revenue.

1.3 Background

Satellite internet technology is introduced with key industry-specific concepts reviewed. First an introduction to satellite telecommunications is provided, highlighting the benefits of satellite-based telecommunications as well as reviewing the historical shift from high-altitude one-way to low-altitude two-way connectivity. The key technologies underpinning modern satellite-based internet services are then discussed. The market is characterized, showing that it operates as a homogenous oligopoly with a limited number of operators selling a very similar product. Finally, the key modelling types of interest to this thesis (equation-based and agent-based) are introduced.

An introduction to satellite telecommunications

Satellite-based internet operators must reliably connect organizations and communities across the globe by exchanging digital data across internet devices using an integrated communications satellite constellation.

By the nature of global internet, consumers span all areas of government, business, and society. Internet connectivity allows these consumers to monitor their environment to make decisions, perform business operations, access digital entertainment, and connect with other users. The product is internet connectivity, sold in units of Megabits per second (Mbps) allocated to a certain user for a certain time.

There are three primary routes of digital data transfer of interest in this thesis, shown in Figure 2 as satellite (A), cell-tower (B), and wired (C). Typical availability and pricing are shown in Table 1.

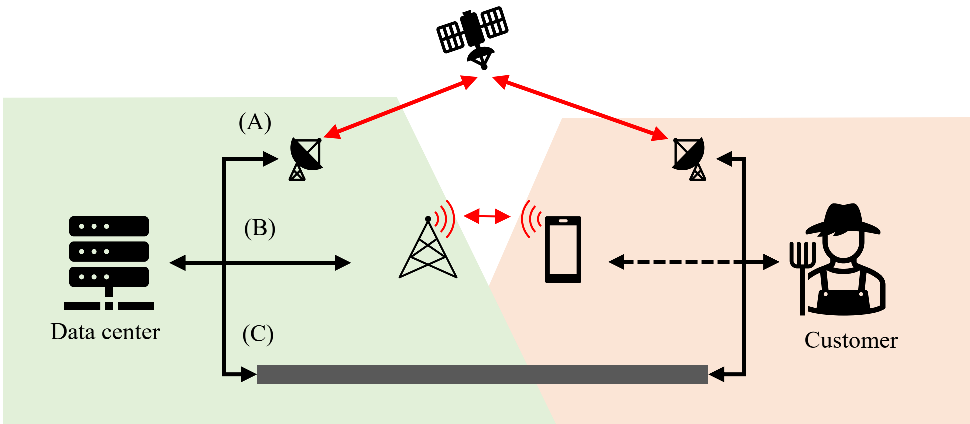


Figure 2: Bidirectional transfer of digital information between data centers and consumers using several routes. When the customer and data center are far apart or separated by impassable terrain then satellite networks (A) are ideal. As the distance reduces and terrain is easier to manage then mobile networks (B) and even direct connection using copper or fiber optic cable (C) become more appropriate.

Table 1: Key characteristics of the major information transfer routes. Fiber optic provides the fastest speeds for the lowest cost but is typically only available in urban areas. Satellites provide the greatest coverage but at significant cost and limited speeds.

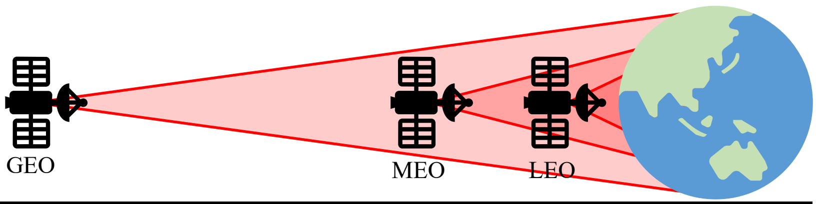
Internet type	**Satellite (old)**	**Satellite (new)**	**Cellphone 4G**	**Copper DSL**	**Fiber optic**
Availability	Global	Global	Rural	Rural	Urban
Download speed (Mbps)	50 Mbps	150 Mbps	150 Mbps	15 Mbps	400 Mbps
Price (USD)	\$200/month +\$800 terminal	\$110/month + \$600 terminal	\$75/month	\$75/month	\$30/month
Source	Viasat [14]	Starlink [15]	AT&T [16]	Verizon [17]	Xfinity [18]

Wired connections such as copper and fiber-optic are ideal for situations where customers and their data centers are close together. Copper cables are inexpensive and easy to install but have limitations in terms of data transmission speed. Fiber optic cables, on the other hand, use light signals to transmit data and can transmit large amounts of data over long distances at high speeds. They are more expensive and require specialized equipment for installation but provide faster and more reliable communication. Fiber optic connections can transmit more data and at faster speed and with higher reliability than any of the other types but are expensive to install. Since they can support so many simultaneous users once they are installed, per-unit cost can be extremely low if installed in regions with high customer population.

Cell-tower networks (B) use radio waves to wirelessly transmit signals across a wide area, typically up to 40 kilometers. Although more expensive than wired connections they provide users with the option to be mobile. Users can share this cell tower hub point without needing to have separate fixed connections. Cell networks are appropriate when there is a small distance between the user and the infrastructure required to connect them to a datacenter.

Satellite-based communications (A) rely on what are effectively free-flying cellphone towers (satellites with radio transmitters and receivers) hundreds of kilometers above the Earth's surface able to individually cover up to continent-sized regions. They work independently of the user's location but require line-of-sight to operate. A network of just three satellites can provide constant global coverage, although new constellations may use hundreds or thousands of low-altitude satellites to provide a higher speed connection with data rates and latency comparable to traditional ground-based networks. Since a single constellation can supply the entire planet satellite-based communications are often used as a stopgap to supply communities that do not yet have access to the other services.

The history of satellite communications could be considered a steady descent from unidirectional geostationary Earth orbit (GEO) to bidirectional low Earth orbit (LEO) services with a corresponding increase in data rate and uncertainty in usage characteristics [19], [20]. As shown in Figure 3, LEO is characterized by low latency but with only small coverage per satellite, while GEO has high latency with large coverage areas. Network latency is the time it takes for a round-trip transfer of data from the user to the internet, and back to the users. Since electromagnetic radiation ("light") has a finite speed (the "speed of light”) satellites located further away from the Earth result in networks of greater latency. Low latency is important for teleconferencing and gaming applications, but less essential for video streaming. Medium Earth Orbit (MEO) is correspondingly in the middle of this range.



Orbit	GEO	MEO	LEO
Altitude	35,786 km	10,000 km	500 km
Latency	238 ms	67 ms	3 ms
Relative field of view	Hemisphere	Continent	Country

Figure 3: Major orbits with typical parameters affecting satellite communications. As orbital altitude falls so does latency, resulting in a more desirable telecoms product. However, this comes at the expense of a smaller relative field of view thus requiring additional satellites to provide global network coverage.

Traditionally the role of satellite communication was for unidirectional broadcasting of video content such as direct-to-home television. In video broadcasting a fixed number of channels is broadcast constantly with no change in downlink data rate. Satellites operated primarily from GEO since the associated 238 ms round-trip light-speed delay does not negatively affect unidirectional broadcasting. GEO satellite appear to hang in the sky (in much the same way that bricks do not [21]) which means that users can have inexpensive fixed antennas which point directly at the satellite. These satellites cover a large area while remaining constantly in view for observers on the planet. Broadcasts from these satellites are inexpensive and reliable. After the launch of Intelsat I in 1969, with a data throughput equivalent to one television channel [22], [23], advancements in launch vehicle technology allowed for heavier payloads with hundreds of stations [24].

An early push toward bidirectional communications came in the 1990s with companies such as Iridium, Globalstar, Orbcomm, and Teledesic [13], [25]–[27], which focused on voice communications with limited broadband capacity. In a bidirectional system, data can be sent between users and terminals with the orbiting satellite as an intermediary. These networks employed large constellations of LEO satellites to reduce latency, though at the cost of requiring more satellites to cover the same area.

Despite this early enthusiasm, technological problems and wider build out of ground-based cellular networks limited the success of these early attempts [25]. Established in 1991, at the cost of $5 billion, Iridium was the first satellite-based phone network provider. Despite a strong technological foundation and robust, global coverage the company filed for bankruptcy in 1999 [28]. Iridium had overestimated customers' willingness to pay for the $3,295 satellite phone. With $7/minute airtime fees for satcom, customers instead chose more affordable alternatives (e.g., the 1996 Motorola StarTAC phone for $1000 and cell-tower-based service at $50/month with calls at $0.50/minute [29]). Additionally, Iridium underestimated the threat of substitute services. By the time their network was available, cell phone companies had improved and expanded the land-based cell-tower networks to the point where most consumers were satisfied with the cell-tower level of service. Iridium failed to identify the niche business segments of natural resources, aviation, and shipping which had a real need for the service. They also failed to advertise to lightly populated and remote regions that were impractical to reach with cell-tower coverage but ideally suited for satellite communications [13].

From 2010 to 2020, consumption has shifted from broadcast content towards on-demand streaming, resulting in a shrinking of the satcom broadcasting sector. In response, the satellite communications industry is moving toward bidirectional broadband internet coverage through digital communications payloads with multi-beam phased arrays. One such network is the O3b mPower constellation consisting of seven MEO satellites with a combined throughput of over 1 Tbps [30], [31]. As shown in Figure *3*, MEO provides these satellites with good coverage and acceptable latency.

With the now proven demand for satellite-based internet services, new commercial companies are entering the market. Exponential growth in the satcom industry driven by communications onboard planes, trains, automobiles, trucks, and Unmanned Arial Vehicles (UAVs) is predicted [32]–[36]. Since 2016, the Federal Communications

Commission (FCC) has received eleven applications from commercial companies for new high-throughput non-geostationary satellites [37], specifically low latency LEO constellations, such as from Telesat [38], OneWeb [39], and Starlink [40]. Due to the small individual coverage area of each satellite, these networks may eventually contain up to 30,000 total satellites [40].

The next few decades of the industry are uncertain. Some established players, such as SES and ViaSat, are expected to launch dedicated broadband satellites [41], [42], while others, Globalstar and Iridium, have made no public statements about a shift in strategy. Since 2016, one major player, Amazon, has entered, while two others, LeoSat and OneWeb, have filed for bankruptcy, which serves to emphasize the uncertainty of operations in this field.

The modern satellite-based internet industry from a technical perspective

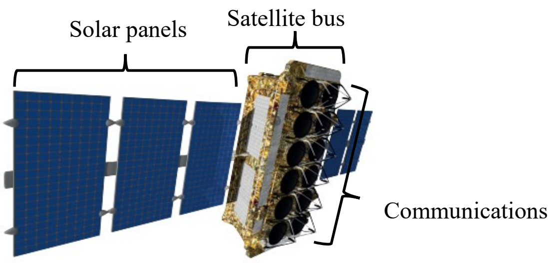


Figure 4: SES O3b satellite with key components indicated [43]. The communications payload is comprised of several independently actuated antennas which receive signals from gateway stations and then relay them to user terminals. Many user terminals can be connected to each of the antennas simultaneously by using different transmission frequencies. This payload is supported by the satellite bus with power provided by solar panels.

Figure 5: Gateway station in Australia for connecting the internet to the satellite [43]. These large antennas are directly connected to the backbone of the internet.

Figure 6: User terminal for connecting the customer to the satellite [44]. Note the dual antennas required for continuous communication.

To understand the market environment of satellite-based internet providers a preliminary appreciation of the underlying engineering is important. Key components of the system with a typical satellite (Figure 4), gateway (Figure 5), and user terminals (Figure 6) are illustrated. The communications array is comprised of twelve Ka-band antennas each with a throughput of 800 Mbps in each direction (1600 Mbps up and down). Two are for connecting to gateways and ten are for linking with user terminals. Note that many user terminals can be simultaneously connected to a single antenna on the communications array. The flow of information is from the gateway to the satellite communications array to the user terminals, and then back from the user terminal to the communications array to the gateway.

Information transfer from the gateway to the satellite, from the satellite to the user terminal, from the user terminal to the satellite, and from the satellite to the gateway are facilitated using the electromagnetic spectrum. Typically microwave Ku-band (12 to 18 GHz) Ka-band (26.4 to 40 GHz) are used. Use of this spectrum is limited and must be negotiated between satellite operators and the countries where they operate. In the U.S. frequency allocation is managed by the FCC. The transmitter produces this electromagnetic signal which propagates through both the atmosphere and the vacuum of space. As it does so some of this energy is lost through beam spreading and interactions with the atmosphere, meaning that only a fraction of the original energy is obtained by the receiver. To ensure that the signal is communicated efficiently the transmitter can increase the power of the signal while the shape (including the use of electronics-based phased arrays) of both the transmitter and receiver can be used to collect more of the incoming electromagnetic waves and thereby increase the 'gain' of that antenna. The onboard satellite bus interprets the received signal, boosts the power, and then retransmits it using the appropriate antenna toward the intended target.

Gateway stations are often very large (~10 m diameter) with high gain antennas to increase the signal that can be communicated. Satellites must be launched into orbit at significant cost so have limited mass available. Therefore, satellites have relatively small (<0.5 m diameter) antennas with limited power (1500 Watts total from solar panels and rechargeable batteries). User terminals could be as large and power intensive as gateways, but since users typically are unwilling to dedicate the space (e.g., on a plane or ship), power, and cost required will instead opt for smaller terminals (typically 1-5 meters in diameter).

In satellite communications, useful data rate is tied signal power. A signal with more power can be more reliably transmitted and received; allowing for more signal-per-second to be transmitted. The shape and type of the receiving and transmitting antennas can increase the gain of the link; effectively 'scooping up' more power to increase the reliability of a given link. Free space loss is a measure of how much the power of a wave decreases as it travels through free space (i.e., a vacuum or the atmosphere). The loss is due to the expansion of the wavefront as it travels and the inherent loss of energy occurring during propagation.

Characteristics of the market

Satellite-based internet providers operate at the intersection of industry (B2B), consumers (B2C), and government (B2G). At any given time, a satellite might be allowing a shipping business to monitor the status of their ripening bananas during transport across the ocean, connecting a remote Australian farm station manager to his family in the city via a video-call, or giving a live-feed from a government drone providing humanitarian surveillance in a disaster zone. These groups do business in very different ways.

B2B transactions occur when the operator sells services to a business. They may be the end-user of the internet data but may also be a distributor that on-sells to other businesses or individual consumers. Businesses typically have many terminals across a large geographic area. This segment makes large purchases and demands high reliability of service – and has the tools to ensure they get what was promised. A common B2B contract is a service level agreement (SLA) where a service (provision of internet, intranet, or other data connection) with defined performance characteristics (guaranteed minimum data rate and percentage uptime) is agreed upon. These contracts are negotiated on a case-by-case basis.

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In B2C transactions the satellite operator sells directly to consumers. These consumers often operate with a single terminal. They expect lower cost services but in return have lower service reliability expectations. A common B2C product is broadband. According to the FCC [45], broadband is defined as internet connection with a minimum of 25 Mbps download and 3 Mbps upload speeds. It is typically provided as a "best effort" service where although a customer may nominally pay for 300 Mbps download speed, at any given time they may only have 150 Mbps. Broadband connections are often oversubscribed, such that if a connection has the capacity to transfer 1 Tbps, 100 Tbps might be sold with the assumption that not everyone using the service will be demanding connectivity at the same time. Due to the large number of consumer customers, B2C products are highly commodified, perhaps as a broadband connection with a promised (but seldom delivered) speed of 100 Mbps, 200 Mbps, or 300 Mbps for $30, $40, and $50/month respectively. For example, in August 2022 SpaceX's Starlink lost a $900 million bid for rural broadband subsidies after failing to meet the promised 100 Mbps download and 20 Mbps upload speeds; instead only achieving 90 Mbps download and 9 Mbps upload [46]. B2C transactions may occur directly between the operator and consumer (e.g., Starlink) or through an intermediary Internet Service Provider (ISP) who packages together many different customers (e.g., Intelsat selling to HughesNet ISP selling to a house in rural Texas).

B2G transactions are when the operator sells services to the government. Contracts may have unique characteristics and security requirements. For example, a government agency that needs to establish internet connectivity in a remote area may contract with a satellite internet service provider to install and maintain a satellite internet network or else services for military or research use. Often the process of this transaction would involve the government agency putting out a bid request for satellite internet services to which various providers would respond with a proposal that outlines their solution to meet the agency's needs. This proposal would include details on the cost, scope of work, and timeline for delivering and maintaining the satellite internet network. Just as in B2B, B2G contracts are maintained through an SLA which outlines the agreed payment schedules and service quality characteristics that must be maintained.

In an oligopoly each firm is so large that its actions can affect market conditions [47]. An extreme form of this is a homogenous commodity oligopoly, one where firms have very similar products and must compete on price rather than by the quality of their product. In an oligopoly, competing firms are constantly aware of their rival’s actions and can respond appropriately. If one operator were to reduce their price then they would instantly dominate the market, prompting their competitors to match (or exceed) this reduction and regain market share. This leaves neither with a net benefit and dissuades price-based competition. A price-setter is an operator able to take advantage of technological and market share scale benefits to obtain the lowest per-unit cost. If firms compete on price, then it is the price setter which can sell the product for the lowest price while still making a profit; thus, allowing them to dictate the price at which the commodity is sold. Collusion between operators is one way to maximize profits for all firms but comes at the expense of customer wellbeing and the risk of government prosecution. Collusion is illegal in many countries, including the US, but this does not always guarantee that such actions do not occur. For example, the Organization of Petroleum Exporting Countries (OPEC) is a well-known international cartel operating in the oil production market [48]. In 2013 premium ice cream manufacturers Ben and Jerry’s and Haagen-Dazs were accused of product collusion where they agreed not to compete with certain products [49].

Although there are more than thirty satellite-based internet providers globally [50], not all of these supply all markets. For example, in the U.S. (the largest region by customer share with a quarter of global revenue [51]) only HughesNet, ViaSat, and Starlink have any meaningful market share. This status quo is maintained by very high barriers to entry, such as filing for spectrum allocation with the FCC and needing to launch a large satellite network. Satellite networks operate using different frequencies and architecture. Since purchasing new equipment is an expensive and time-consuming process customers avoid this, meaning that consumers exhibit high stickiness and loyalty to their chosen operator. By the nature of global satellite internet there are very extreme economies of scale; a satellite operator who does not use maximum capacity throughout the orbit is wasting much potential revenue. Combined these indicate that the satellite-based internet industry acts as an oligopoly. Despite some speed and latency differences between operators, ultimately the internet connection product which they offer is the same. This suggests that the satellite-based internet industry is a homogenous oligopoly.

Modelling the market

Although there are various analytical and experimental methods by which to examine any market, the one most interesting to this research is agent-based modelling (ABM). Bonabeau [52] describes ABM as a computational approach often used in the modelling of complex systems, including financial markets. The approach models individual agents and their behaviors in a market, allowing for the simulation of market dynamics and the emergence of macro-level phenomena. A comparison of ABM against traditional equation-based modelling was conducted by [53] and summarized by Table 2. Agent-based modelling is ideal for the complex, heterogenous, and spatially dependent world of satellite internet.

Table 2: Comparison between agent and equation-based modelling. Equation-based modelling captures results from the top-down while agent-based explores behaviors the bottom up. Adapted from [53].

Type	Equation-based modelling	Agent-based modelling
Overview	Overall outputs of the system are directly captured by systems of equations.	Simulates the micro-level behavior of individual agents. Emergence from many agents gives the overall behavior of the system.
Heterogeneity	System is considered in its entirety. Heterogeneity is not possible or very challenging to incorporate.	Agents can have diverse decisions, characteristics, and preferences.
Spatial resolution	Representation of physical space is either not possible or significantly lacking in granularity.	Topological characteristics can be considered.
Ideal application	Best for modelling large (trillions of atoms) physical systems and those with a high degree of homogeneity.	Appropriate to model real-world human systems.
Validation	Only the final output can be used for validation.	Individual agent behavior of real systems can be observed directly and incorporated into the ABM. The final output can also be compared with real-world data.

1.4 Specific Objective

The objective of this thesis is to develop an agent-based computational economic model of the satellite internet industry, that is the ABSM, calibrate the model against historical case studies, and provide a projection of potential scenarios in the future of the market.

As summarized in Table 3 the model should be able to answer a range of questions appropriate to the market but does have several limitations.

Table 3: Key questions that this model should and should not be able to answer.

Questions the model should be able to answer	Questions that are out of scope for this model
When a set of operators use certain strategies within an assumed economic environment what revenue will those operators obtain? Which competitive strategies consistently perform will under a range of conditions?	What are the strategies that operators will use? Which operators will succeed? Where should the reader invest their money?

1.4 Thesis outline

A market model is a mathematical representation of the interactions which comprise the economic environment within which a business operates. These models are used to inform strategic business decisions such as expanding into a new market or adjusting their product offerings. They are often used to explore what-if scenarios to test economic policy or competitive decisions to see how these affect system objectives of net income, market share, and customers serviced. The chapter two Literature Review on page 39 of this thesis explores existing market models and their application to the satellite-based internet market. While often useful, these models rely on simplifying assumptions which diminish the believability of their results.

One promising, yet underdeveloped, market modelling approach is agent-based computational economics which used a bottom-up approach to simulate market interactions. Because it seeks to simulate all the entities within a market, agent-based economics can overcome many of the shortcomings of these past approaches. However, until recently, the computing resources required to implement such an approach has proved an intractable challenge. Chapters three (Model Assumptions on 53) and four (Model Implementation on page 69) are devoted to the development of the ABSM which seeks to overcome the shortcomings of other modelling approaches while taking advantage of modern computational capabilities. Chapter three covers the assumptions which underlie the ABSM and then chapter four describes how these were implemented, demonstrates a generic satellite market model through which input parameters are tested on a progressively more complete implementation, and conducts model benchmarking for execution time.

Chapter five Historical Calibration on the Satellite Phone Market 1995-2005 on page 93 calibrates the ABSM by comparing its forecasts against historical data and through the consideration of the rise and fall of satellite phones.

Chapter six Satellite Internet Forecast on page 129 used the ABSM to forecast trends in satellite industry using data derived from publicly available sources. The chapter presents forecasts of datum, optimized, two-phase, merger event, and extreme substitute rollout scenarios.

Finally, the thesis concludes in chapter seven Conclusion on page 157 with a discussion of future directions for agent-based market modelling as a tool for business, with directions for further theoretical and empirical research.

1.5 Chapter summary and conclusions

Satellite communications have a long history and are expected to see significant future growth. Traditional equation-based modelling approaches are ill equipped for modelling the industry, but equation-based modelling shows promise. This thesis uses a custom agent-based tool to interrogate the market.

Chapter 2

Literature Review

This chapter provides a review of industrial and academic literature applicable to this thesis. To begin (2.1 Market modelling of satellite networks on page 40), we see how the existing literature on satellite-based internet networks lacks accuracy and realism. Next (2.2 Satellite market segmentation on page 42), we consider how market segmentation allows for a deeper understanding of customer characteristics, preferences, and willingness-to-pay for different satellite-based internet products. Subsequently (2.3 General market modelling of operators on page 43), a broader view of market modelling emphasizes the importance of competitive analysis and its integration into marketing strategy, with a theoretical basis encouraging the development of analytical models for competition. Then (2.4 Market modelling of customer behavior on page 45) assess the importance of customer-focused study for product adoption of new technologies. Next (2.5 Agent based modelling on page 48), we consider the role of agent based modelling in providing more comprehensive market models. Finally (2.6 Chapter summary and conclusions on page 51), we assess how agent based modelling works in the best-case scenario, what was learned through this literature review to best setup our own model for success, and what gaps exist within the literature which this thesis will work toward closing.

2.1 Market modelling of satellite networks

Within the literature, models to study these satellite networks are very simplistic. The models typically assume a homogenous distribution of demand comprised of a single customer class and neglecting to incorporate the effects of competition [54]–[56]. The effect of this versus the reality of the situation is shown in Figure 7. Effectively, they assume that revenue is directly proportional to the capacity of the network and that there is some omnipotent consumer of the internet which will purchase a firm’s entire capacity at a fixed price regardless of where that capacity is located. Clearly this is untrue; satellites passing over oceans use very little of their total capacity, while those over cities may be overwhelmed with demand. As high-capacity mega-constellations from Starlink, OneWeb, Telesat, and Amazon come online, it is likely that the market will be flooded with supply in the coming decade, with significant implications for price. The assumption that demand can increase indefinitely to match capacity is a central uncertainty in predicting future revenues. If multiple suppliers exist within a market, then their behavior and revenue will differ from if they were operating as a monopoly.

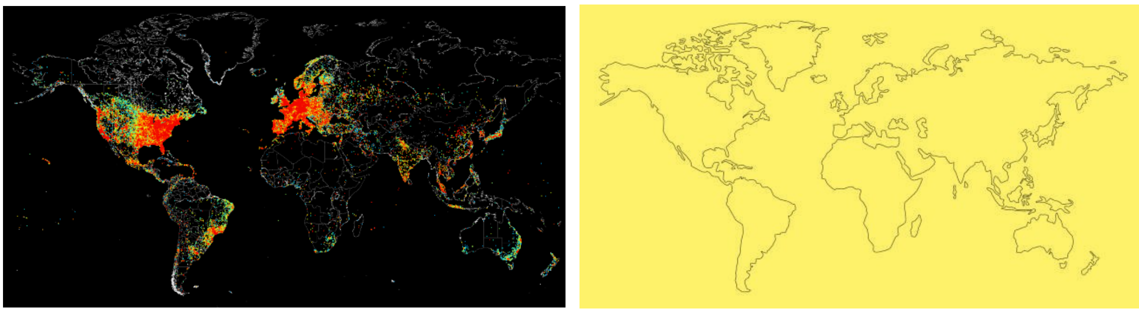

Figure 7: Real-world satellite-based internet user distribution (L) as compared with the homogenous distribution assumed within the literature (R). Clearly the literature is missing some fidelity by not taking into account real-world heterogeneities; in reality very few people are trying to access the internet from the Indian ocean!

There have been no specific studies as to whether these assumptions are appropriate in the context of satellite internet, although similar problems were discussed by Winsberg in his book “Simulations, Models, and Theories in the Science of Computer Simulation” [57] and from these we may perform our own assessment and draw our own recommendations.

Winsberg explores the concepts of verification, validation, and the similarities and differences between simulations and experiments. Using a case study of climate modelling Winsberg identifies three sources of uncertainty: structural model uncertainty, parameter uncertainty, and data uncertainty.

Winsberg described structural model uncertainty as that when developing a simulation model, researchers make choices about which variables and factors to include, how to represent their interactions, and what mathematical equations or algorithms to use. These decisions can have a significant impact on the behavior and outcomes of the simulation. However, due to the complexity of real-world systems, it is often difficult to determine the best or most accurate structural choices for a model. By comparing literature assumptions [54]–[56] to the real world we can use Winsberg's framework to deduce that structural model uncertainty is significant in these studies and therefore their conclusions may not correctly reflect reality. In this thesis we must therefore reduce structural model uncertainty by making out own model include the real-world system complexities.

Parameter uncertainty refers to uncertainty associated with the values of parameters in a model. Parameters are the variables that define the characteristics or behavior of the model, such as coefficients, constants, or other factors that influence the model's outcomes. In contrast, data uncertainty refers to uncertainty associated with the quality, accuracy, and reliability of the data used in the modeling process. Data uncertainty arises due to limitations in data collection methods, measurement errors, missing or incomplete data, or sampling variability. In the case of these literature studies [54]–[56] we see authors assuming certain parameters which are only order-of-magnitude accurate with little regard to the true data. Again, Winsberg would say this means their conclusions do not reflect reality. For our model we must seek to refine knowledge of the parameters and accuracy of the data. According to his recommendations, parameter uncertainty will be addressed through sensitivity analysis and parameter estimation techniques. Data uncertainty will be mitigated through data validation, data quality assessment, and statistical techniques (e.g., confidence intervals).

There is precedent for more sophisticated modelling of satellite constellation revenues. Guerster [58] considers capacity allocation with geographically heterogenous customer distribution. Guerster provides an algebraic model for the power budget of a satellite network, validated against industrial data. Major satellite-based internet customer segments are identified although their purchasing characteristics are not used for revenue estimation. Guerster is also only concerned with only a single operator rather than the entire market. Considered through Winsberg's framework [57] Guester shows good parameter and data estimation techniques and a more realistic structural model than typically seen in the literature. However, it is still limited by its small scope.

In their 2021 paper [48], Ogutu and Oughton develop a supply-side engineering system model to estimate the revenue of satellite-based internet networks, studying the networks of three different competitors. Only a single class of residential customers paying a fixed price for a single level of service is considered and the authors only consider each network in isolation, without accounting for competition with terrestrial operators. Customer distribution is modelled by regional population density. The model is used to determine the average bandwidth users will experience in the region although is not an input into the revenue calculation. Again considered through Winsberg's framework [57], the paper shows excellent improvements to structural modelling, parameters, and data reliability. However, it is still somewhat limited in scope.

2.2 Satellite market segmentation

One method of improving model structure, parameters, and data reliability is to more deeply analyze the customers who comprise the model. Operators themselves also engage in a similar practice known as market segmentation where similar customers are grouped into segments. This has been well studied in the case of satellite internet markets.

Market segmentation is the process of dividing a market into broadly similar groups who can be targeted with similar product offerings and is an important feature of academic research and business practice [59], [60]. These segments have different uses for satellite-based internet and have correspondingly different willingness-to-pay for different internet products. Segmentation of the satellite-based internet market has been proposed by the ITU [61], NSR [62], [63], Euroconsult [64], and Grand View Research [65]. Critical categories are residential broadband; cruise ships; oil and gas; airlines; backhauling or trunking; and government. Residential broadband addresses a single terminal consumer to connect their house with the internet especially in remote regions with limited or no wired internet and can be sold to directly or through an ISP who bundles together multiple households. Cruise ships are characterized by large crews and passenger count demanding access to the internet from a mobile moving platform. Oil and gas are fixed offshore customers where satellite communication is the only option. Airlines are even more mobile, providing connectivity to the passengers onboard a commercial aircraft. Backhauling and trunking connect a subnetwork to the broader internet or to supplement existing connections during temporary demand spikes. Government is the broadest segment with aspects of all users described since the terminals can range from small sizes on UAVs to larger terminals on a remote base. Unique contracting and security requirements make this a separate group.

2.3 General market modelling of operators

Outside the field of satellite-based internet networks, academic literature on industrial modelling is more advanced. Henderson [66] observes that a business' success depends on how its management conducts competitive analysis and takes on these results into their marketing strategy. Hanssens et al. [67] infer that this analysis should being their highest priority, directing all other operations of the business. Porter [68] implores managers to understand what is driving competition, what decisions competitors are likely to make, and how the industry will evolve over time in order to best determine how the business should act. This theoretical basis has encouraged the development of analytical models for competition.

Schmalensee [69] examines competitive behavior in monopolies, oligopolies, and pure competition. He examines how firm size allows them to exercise cartel-like behavior to control market prices and prevent new entrants becoming profitable. This provides a foundation for understanding how oligopolies such as a satellite-based internet operate to reduce competition. Schmalensee relies on simplified market dynamics where operator profitability is described by combinations of linear equations. Customer behavior is not modelled beyond a basic elasticity function.

Dutta and King [70] provide an outline as to how to develop competitive market modelling approaches from the perspective of operators in the market. Although they demonstrate the use of the model in a hypothetical two-firm market with only the levers of price and product quantity, although they indicate that such an approach could be extrapolated for any system. As summarized in Figure 8, the method works by iteratively testing strategies accepting adjustments only when such a strategy improves outcomes to the firm. Dutta and King only consider the model as a ‘mind tool’ for decision makers to consider how their competitors may behave, however the general approach could be considered a form of linear optimization as could be implemented by a computer program.

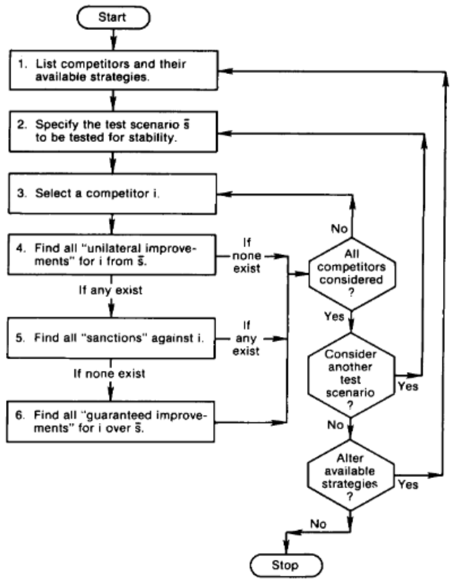

Figure 8: Scenario exploration flow chart as proposed in [70]. This technique allows for many different operator strategies to be assessed with a game-theory-type approach.

Lise and Hobbs [71] describe a recursive dynamic simulation of the European gas market to predict how growth in demand combined with significant investment from both incumbent operators and new market entrants affects the revenue of different operators. Several sub-models are combined to explore the interaction of five suppliers and six customer classes under three different scenarios.

2.4 Market modelling of customer behavior

Another branch of literature focusses on how customers react to new products; keeping operator behavior fixed and instead focusing on customer choice. Customer adoption of a new technology, such as satellite internet, is of primary interest when constructing a market model.

The theory of adoption of new products is discussed at length by Rogers [72], developed in 1962 and which has since been adopted into the economics literature often depicted with an adoption curve similar to that shown in Figure 9. Rogers defines a new technology as one that is new or novel to the organization or individual using it, not that it is necessarily a recent innovation. Rogers proposes that all new technologies follow an adoption curve where first a small group of innovators will adopt the technology, followed by subsequently larger groups of early adopters and an early majority. As the technology reaches saturation the rate of adoption slows with a late majority adopting it followed by a very late small group of laggards. Adoption rate can be modelled as a normal distribution. Rogers describes how characteristics of the product (such as relative advantage), communication, surrounding social systems, and time all influence how likely it is for a given individual to adopt a technology.

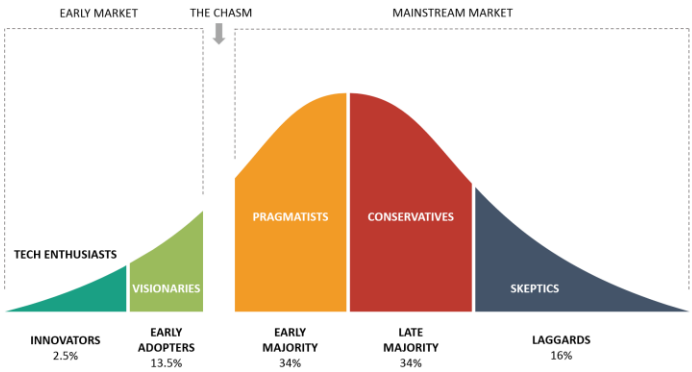

Figure 9: A typical example of the adoption curve, as shown in Moor's "Crossing the Chasm" [73]. Innovators and early adopters are the first to adopt a product and businesses often struggle to 'cross the chasm' to mainstream adoption by the subsequent (and more numerous) groups.

Bass' 1969 model [74] today provides the most frequently cited methodology for implementing Rogers' factors of adoption. His paper describes a mathematical derivation for the factors influencing adoption which he demonstrated and compares with historical data for several consumer goods. As shown in Figure 10 although the precise sales figures cannot be predicted from year-to-year, the general trend follows the model well.

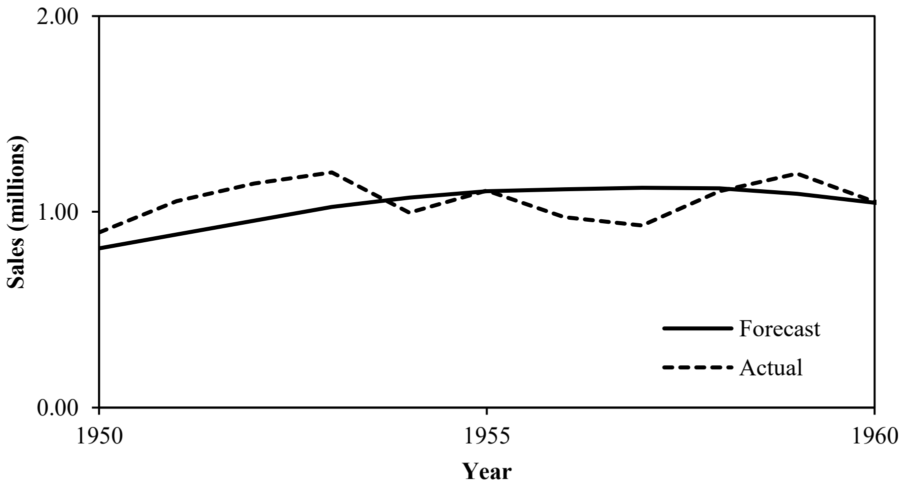

Figure 10: Forecast and actual sales for home freezers as shown in [74] using adoption time. The two show a close resemblance suggesting that it is theoretically possible to mathematically model the adoption of consumer goods.

Throughout this thesis we will be assessing models using the Weighted Mean Absolute Percentage Error (WMAPE) which is one of the most common performance indicators to measure forecast accuracy. It is calculated using

$$WMAPE = \frac{1}{n} \cdot \frac{\sum_{t=1}^{n} |A_t - F_t|}{\sum_{t=1}^{n} |A_t|}$$

Where n is the number of forecasted points, A_t is the historical value observed at time t and F_t is the forecasted value for this time. In his 1982 guide to industrial forecasting analysis, Lewis [75] describes a WMAPE of less than 10% as “highly accurate forecasting”, 10% to 20% as “good forecasting”, 20% to 50% as “reasonable forecasting”, and worst than 50% as “weak and inaccurate forecasting”. A typical weather forecast falls in the “good forecasting” range [76]. In this case Bass’ home freezer study shows a WMAPE of 9.1% putting it within the “highly accurate forecasting” range.

With this strong start, today Bass’ 1969 model [74] provides the most frequently cited methodology for implementing Rogers’ factors of adoption. His paper describes a mathematical derivation for the factors influencing adoption which he demonstrated and compares with historical data for several consumer goods. As shown in Figure 10 although the precise sales figures cannot be predicted from year-to-year, the general trend follows the model well.

Bass’ final derivation for the sales over the time interval t_i to t_{i+1}, S_{t_i} is given by

$$S_{t_i} = \left(M - X_{t_{i-1}}\right)[F(t_i) - F(t_{i-1})] \div [1 - F(t_{i-1})]$$

where $M - X_{t_{i-1}}$ is the number of individuals who have not yet adopted the product and $F(t)$ is the probability that a given individual has adopted the product by time t. $F(t)$ is given by

$$F(t) = \left[1 - e^{-(p+q)\cdot t}\right] / [1 + \left(\frac{q}{p}\right) \cdot e^{-(p+q)\cdot t}]$$

where q and p represent what Bass terms the coefficients of innovation and imitation respectively. Innovators (p) independently adopt a product based on its perceived benefits while imitators (q) make decisions based on the actions of their peers. The parameters are found through regression analysis of historical data. Bass used the model to predict future trends for color television sales, fitting his function to existing data and then extrapolating forward.

Jain and Rao [77] build upon the Bass model by incorporating the influence of price. Price is assumed to have a multiplicative effect on adoption rate equivalent to improving the product characteristics described by Rogers [72]. In its simplified form this new relationship is

$$S_{t_i} = \left(M - X_{t_{i-1}}\right) \cdot P(\eta) \cdot [F(t_i) - F(t_{i-1})] \div [1 - F(t_{i-1})]$$

where $P(\eta)$ incorporates the effects of price. As shown in Figure 11, with this formulation the team were able to closely estimate the adoption of various home goods. Their air conditioner results shown has a WMAPE of 7.4% (18% lower than Bass' 9.1%, although care should be taken to consider that the two were modelling different products) placing it in the "highly accurate forecasting" category [75].

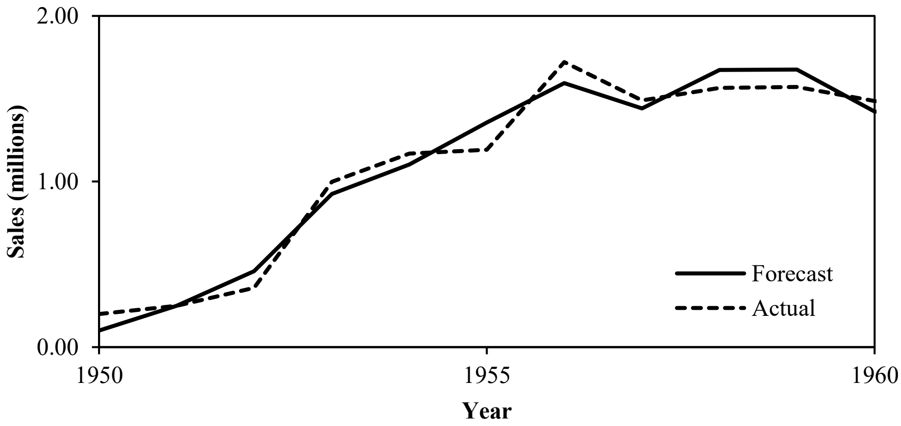

Figure 11: Forecast and actual sales for air conditioners as shown in [77] using price in addition to adoption time. The two show even closer resemblance than the Bass model (Figure 10), qualitatively indicating that the inclusion of price helps to improve model accuracy.

2.5 Agent based modelling

So far, all these studies have focused on the actions of operators and customers independently with the actions of the other considered as fixed or else with a simple relationship of linear elasticity. While this is useful in testing out new economic theories it neglects feedback mechanisms between operators and customers. Recent developments in the field of agent-based modelling may provide one avenue in which such feedback can be incorporated.

A critical work utilizing ABM is Epstein and Axtell's 1996 "Growing Artificial Societies"[1] [78]. The pair use ABM to simulate the emergence of social phenomena such as wealth inequality and segregation. The authors developed a model of artificial societies in which agents interacted based on certain rules, and the results showed that patterns of segregation and inequality could arise even in societies where individual agents did not have discriminatory tendencies.

One of the early pioneers in ABM for financial markets is Leigh Tesfatsion, who developed a computational model of the electricity market in the late 1990s. In the years that followed, ABM was increasingly applied to financial markets, with a focus on simulating the interactions between traders, and the resulting price formation and market dynamics. In [79] Tesfatsion describes such models as being comprised of heterogenous agents with interactions based on internalized social norms, behavioral rules, and data acquired from experiences in world. Tesfatsion compares ABM to equation-based modelling (EBM). EBMs often experience difficulties in detecting and describing direct relationships between agents and system behavior whereas ABM uses these relationships to build such behavior from the bottom up. ABMs allow for heterogenous decisions, characteristics, and preferences suitable for economic models.

One of the challenges in ABM is the parameterization of agent behavior. Kumar [69] developed a model of a financial market in which agents used deep reinforcement learning algorithms to learn trading strategies based on historical market data. The resulting model

[1] This work helped inspire the Shalmaneser Artificial Intelligence (AI) in John Brunner's 1968 sci-fi novel "Stand on Zanzibar" which in turn inspired the Rehoboam AI in season three of HBO’s Westworld. Rehoboam was created to assist in advertising and market modelling – a key focus of this research and the name of the final code model. To paraphrase [172], *with this thesis at long last, we have created the Torment Nexus from the classic sci-fi series Don't Create The Torment Nexus.*

was able to reproduce many of the behaviors observed in financial markets, including volatility clustering and long-term memory in price dynamics.

Bennett et al's paper [80] described an in-house CENKI space economic simulator that a ABM framework for in-space products and service analysis. The simulator focusses on business-to-business transactions such as the acquiring of a competitor or purchasing of additional satellite infrastructure. Five agents representing launch providers, satellite manufacturers, and satellite operators are simulated, and their actions and relative profitability compared to historic data. The study demonstrates the modeling and predictive capability of the agent-based approach to capture sales and acquisition behaviors in historical telecommunications satellite provider data. The scenario does not consider the user-side of the market and significantly restricts the size of the industry. The model was tested against the historical revenues of Intelsat acquiring a competitor in the year 2005. As shown in Figure 12, with this formulation the team were able to closely estimate the adoption of various home goods. With a MAPE of 11.7% the technique displays characteristics of "good forecasting" [75].

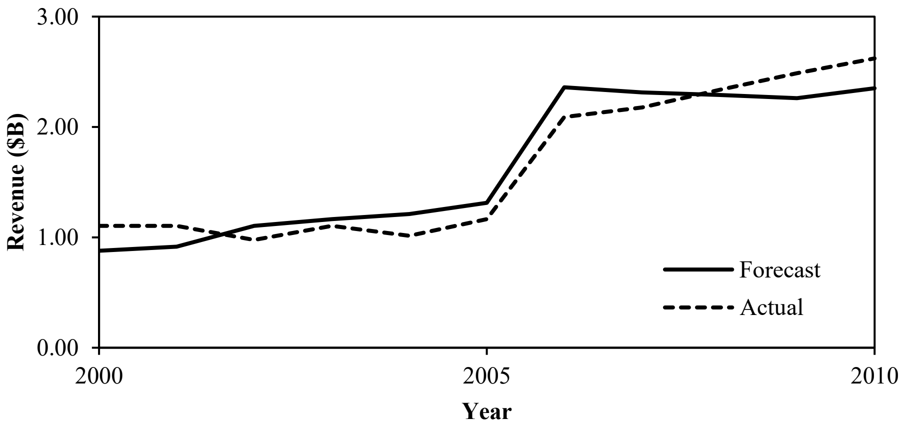

Figure 12: Forecast and actual revenue for Intelsat from 2000 to 2010 as they acquire an competitor in 2005 as shown in [80]. The plots show close similarity indicating the accuracy of the model and usefulness of the technique.

In their 2021 Master's Thesis "Agent-based model of broadband adoption in unserved and underserved areas" [53], Agarwal describes the development of and ABM to predict internet adoption behavior. They create a small <1000 agent model where consumers chose to either keep their existing low-bandwidth service or else upgrade to a new service with higher-bandwidth but increased cost. Customer agents are initialized with heterogenous preferences for internet speed, monthly costs, data caps, and reliability. Agents are clustered and are influenced by the adoption decisions of their neighbors. Agarwal then uses his model to assess which of five potential internet plans should be offered to a community in Patton Missouri. The study is limited to residential consumers and does not consider satellite-based internet offerings. Customers are only able to decide between two operators, which fails to account for the competitive realities of the situation. Operator responses and behavior are also not incorporated. Unfortunately, model validation is extremely limited with Agarwal only using a single comparison for fiber adoption in the 274-household region of Perry Missouri. Agarwal predicts a penetration of 69% as compared with the actual penetration of 62%; a WMAP (if such a term can be used with only one datapoint) of 11.3% in the "good forecasting" region [75].

2.6 Chapter summary and conclusions

The existing literature on satellite network modeling has limitations in capturing the complexities of the satellite-based internet market. The assumptions of homogeneous demand distribution, neglecting competition, and revenue proportionality to capacity do not reflect the reality of the market. Structural model uncertainty, parameter uncertainty, and data uncertainty are identified as sources of uncertainty in these models. To improve the modeling of satellite networks, it is essential to consider real-world complexities, refine parameter estimation, and enhance data reliability. Market segmentation analysis can provide insights into customer behavior and willingness-to-pay, contributing to better model structure, parameters, and data. Studies that have made advancements in structural modeling, parameters, and data reliability are highlighted, although they are still limited in scope. Overall, there is a need for more sophisticated and comprehensive models that capture the complexities of the satellite-based internet market. Improved modeling techniques and a deeper understanding of market dynamics can provide more accurate predictions and inform strategic decision-making for operators in this evolving industry.

In the best-case ABM is shown to produce good results with low WMAP (<10%). It can generate new strategies and independently replicate existing ones. This makes it an important tool for predicting future system states and emergent behaviors. However, there is still a need to perform rigorous validation against historical data to make these results believable.

This literature review has also highlighted the best ways to set up ABM for success. The model should begin by taking a broad and realistic view of the system being considered; physical realities of satellite-internet provision such as how satellites work, and supply data is essential. Some location-based considerations such as population centers and vacant zones ais essential. It is also useful to consider the complexities of customer agents, treating them as many individuals belonging to several segments rather than as a single homogeneous mass. Customers have different adoption times and can influence each other to buy or not buy a product. The model should be verifiable with significant existing data from which to compare.

Finally, we see a clear gap in the literature which motivates this thesis: the absence of comprehensive models that consider the dynamic interaction between satellite-based internet operators and customers in a competitive market environment. Existing studies have separately focused on operator behavior and customer adoption, but there is a pressing need for integrated models that capture the feedback mechanisms between operators and customers. Additionally, we observe that there has been limited consideration of market segmentation analysis within existing literature. To bridge these gaps, our research proposes the utilization of ABM techniques to simulate the complex dynamics of satellite-based internet markets. By integrating market segmentation analysis into the modeling framework, our research aims to provide a more accurate representation of the diverse customer base and their distinct demands. Through this analysis we aim to contribute valuable insights into the dynamics of satellite internet markets and offer a more holistic understanding of this evolving industry.

Chapter 3

Model Assumptions

This chapter begins the methodologies, results, and discussion components of this thesis. As a reminder, Chapter 3 (this one) explores the model assumptions which underpin the ABSM. Chapter 4 Model Implementation on page 69 describes how these assumptions were converted into a usable model and demonstrates its general applicability by sweeping through different input ranges using a generic satellite communications market model in which key components of the model are successively activated. The model is benchmarked, and code optimized to improve execution speed. Chapter 5 Historical Calibration on the Satellite Phone Market 1995-2005 on page 93 validates the model with historical data. Finally, Chapter 6 Satellite Internet Forecast on page 129 applies the model to the modern problem of satellite internet and presents forecasts of datum, optimized, two-phase, merger event, and extreme substitute rollout scenarios.

A generic market model was developed which brings together operators and consumers through the purchase of products. By adjusting the agent-based assumptions, this market model can be applied equally to the cases of satellite-based phone connection for validation and satellite-based internet connection for use in forecasting. The model relies on several key assumptions with are discussed in detail within this chapter. These assumptions are divided into system (page 54), operator (page 55), distribution (page 59), customer (page 62), and substitute services assumptions (page 66). Finally, (3.6 Chapter summary and conclusions on page 67) we discuss the limitations of these assumptions.

3.1 System assumptions

System assumptions dictate the broad scope of the model; where is the system boundary and what is inside it?

1. The market is comprised of operators who supply a product or service to customers using a distribution mechanism.

This is a fundamental feature of how markets work. Stigler and Sherwin [81] explain that markets facilitate the exchange of goods and services between buyers (customers) and sellers (satellite operators). Markets pricing incorporates the costs associated with producing and distributing the item in addition to some additional profit for the seller. The actions of many buyers and many sellers help to establish this price by deciding whether to buy or sell the product. Yang et al. [82], construct a distribution mechanism based on decentralized energy generation units for their model of the renewable energy market.

2. The market simulated is the entire Earth and the region being simulated is a sphere of resolution 180 x 360.

This simulation region was selected to represent the Earth using equirectangular projection with 1° x 1° divisions. This provides 64,800 (180 x 360) cells corresponding to a dimension of around 100 km x 100 km. Customer agents use this high-resolution scale for geographic distribution for determination of properties and the rollout of substitute services which may 'remove' customers from a given cell as they switch to this substitute. However, operators and their satellite-based distribution mechanism only see the amalgamated 10° x 10° regions (1100 km x 1100 km) to better even-out this demand. While this may seem large, a typical satellite's field of view is 1,500 km. A satellite would be able to allocate more capacity to one region than another if both are within its field of view, validating the use of this assumption. Long [83] employs a similar assumption with 15° x 15° regions (1700 km x 1700 km) in their satellite traffic prediction model.

3.2 Operator assumptions

Operator assumptions consider the intents and activities of the operator agents; what do they which to achieve and what actions can they take to achieve them?

3. Operators seek to maximize their own net present value.

Net Present Value (NPV) is a financial metric commonly used in decision making that calculates the difference between the present value of cash inflows and the present value of cash outflows. The present value of a cash flow considers the impact of alternative investments which an agent could have made rather than the one under consideration. For example, spending $100 today for a return of $110 is a good decision if the alternative would be buying a government bond with a 5% return (worth $105 in one year) but a poor decision if the alternative is investing in a different project with a 25% return (worth $125 in one year). The rate at which a decision maker uses to compare cash flows over time is known as the discount rate. If the NPV is positive, the investment is considered profitable and is likely to be accepted. If the NPV is negative, the investment is not considered profitable and is likely to be rejected. Operators seeking to maximize the NPV of the projects they undertake is an underlying assumption of the economic modelling of rational agents. Acheampong et al. [84] and Menabde et al. [85] NPV-centric decision making to the context of resource extraction. Batyshnikov et al. [86] apply the concept of NPV when assessing different strategies used by multimedia services when seeking to engage in developing differentiated service offerings.

4. Operators do not become bankrupt; however they can merge with all the assets and customers of one operator being transferred to the other.

This is a surprising assumption, but one which has real-world precedent. One would expect that if an operator were unprofitable for more than a certain number of months, they would go bankrupt and be forced to sell their assets to a competitor. For example, the Iridium constellation opened to users in November 1998, was unprofitable for nine months, and then declared bankruptcy in August 1999. Globalstar lasted slightly longer but still declared bankruptcy after 22 months of insufficient revenues. However, modern satellite operators appear to be able to survive considerably longer. It took 26 months from November 2020 to January 2023 for Starlink to become profitable [87] but is today going strong. During discussions with engineers from Iridium and Globalstar, it became evident that the root cause of their bankruptcy was not simply a lack of profitability. Rather, the primary factor contributing to their financial struggles was the sustainability of their high capital expenditure (CAPEX) operations. It was discovered that the viability of these operations relied more on the availability of cheap liquidity than on the traditional metrics of profit and loss. This insight sheds light on the intricate relationship between financial stability and the ability to secure affordable funding for such ventures. By recognizing the critical role of accessible and inexpensive capital, we gain a deeper understanding of the challenges faced by companies in capital-intensive industries, where the cost of infrastructure and operational expenses can greatly impact their overall financial health and longevity. Predicting the boom-and-bust cycle of investment is outside the scope of this thesis, leading to the simplifying assumption that operators do not become bankrupt.

5. Satellite operators cannot purchase or use each other's networks without a merger.

Although buying and selling a competitor's satellites is technically feasible, discussions with one operator determined that this was very unlikely to occur. What would occur is that one operator would entirely acquire another operator's assets. This behavior has been excluded from the analysis.

6. Operators can choose to launch (or not launch) additional capacity.

In the real-world the FCC receives applications to reserve spectrum and orbital slots for use by operators These filings are famously excessive with operators reserving far more capacity than they could ever reasonably use [88]. The operator does not need to immediately use this reserved capacity but will typically need to launch half of it within a decade to keep the reservation. This is an example of an engineering option; the right (but not obligation) to exercise an action at a future date. In December 2022 the FCC approved 7,500 of Starlink's planned 42,000 satellite Gen2 constellation [89].

We assume that operators have reserved a significant amount of capacity and will choose to launch or not launch additional satellites to meet observed customer demand. Strategies may be as simple as 'if we make revenue of greater $3B per year then launch 100 additional satellites else do nothing'. The optimizer can develop and test strategies independently or can be given known strategies of major operators.

A time delay between deciding to do an action and the action being implemented is based on the time to build and launch a rocket and its payload.

7. Operators can only sell one product per customer segment and do not execute perfect market segmentation.

As described by Wilkinson [90], perfect market segmentation would involve each customer in the market having their own custom-designed product and pricing so as to extract the most possible revenue from that customer. As noted by Guerster et al. [91], this perfect segmentation is close to how satellite-based internet market currently operate where each customer is treated separately with prices and service characteristics decided through negotiation. Looking at historical cases, Iridium started out with a similarly fine segmentation, but soon moved to a single product offering regardless of customer segment [92]. New operators such as Starlink already use this simpler form of segmentation and as satellite internet becomes more prevalent, we assume that this will be the dominant form.

8. Operators allocate some capacity every time they sell a product; operators do not have infinite capacity and must select which customers they want to sell to. This is different for each customer segment based on that segment's use characteristics and willingness to accept service loss. This is known as an overbooking factor. By selling to one customer today this results in some opportunity loss where tomorrow they may not be able to sell to a different customer as there is not enough available capacity in the region.

Guerster et al. [93] describe overbooking factors extensively in their paper. Historically, service level agreements have been used to ensure that contracted capacity for major customers was consistently available, with strict penalties for any failure to meet the agreed targets. Third parties also monitor service quality for residential customers and in August 2022, the FCC withdrew $885.5 million in subsidies for the Starlink constellation due to its failure to meet the agreed service speeds [94]. To guarantee compliance the operator could consider selling only the amount of capacity which they have available. This would represent an overbooking factor of one. Since not all consumers use all of their allocated capacity all of the time, a booking limit based on the customer's expected use case is commonly employed [93].

9. Operators do not collude to fix prices.

The satellite-based internet operates as an oligopoly. As described by Friedman [47] such market structures will often have competitors collude to fix prices and extract unduly high rents. Predicting if, when, and how these competitors collude is outside of the scope of this thesis and instead we will assume that government observers have the resources to spot and prevent such collusion before it impacts the market.

10. Some operators are unable to supply certain segments.

This assumption is based on observations of the current satellite internet market. The physical characteristics of customer constellations may prevent them from selling to certain customer segments. Similarly, certain operators may decide not to service a given segment. For example, Starlink terminals are much smaller than those of SES. As a result, Starlink is unable to provide the data rates or reliability demanded by a customer multiplexed or fast-moving customers such as a cruise ship or airplane, but SES would be able to. However, for these same reasons, SES may decide not to sell to residential customers while Starlink would.

11. Operators can decide to exit a market even if they are physically able to supply it.

Each operator is controlled by a separate agent using a modified form of a genetic algorithm to identify the best price at which to sell each product. A genetic algorithm is an optimization approach inspired by the process of natural selection. It works by generating a population of potential solutions which for this case are operator pricing policies and evolving them over multiple generations. Each strategy is evaluated with those producing the greatest NPV kept and allowed to evolve. Some of these strategies may involve leaving a segment or leaving a segment in one location while keeping it somewhere else such as supplying residential broadband only to Australian customers.

3.3 Distribution mechanism assumptions

Distribution assumptions describe how operators supply the customer demand; how does the simulation consider the role of physical assets (satellites) within the market?

12. The distribution mechanism is made of many independent hubs which each service only a limited region. In the case of satellite-based internet, a ‘hub’ is a single satellite while the entire distribution mechanism would be the network of satellites.

This is a fundamental feature of satellite-based communications. This concept of hubs has been employed by Li et al. [95] in the context of energy generation.

13. Each of these hubs is limited by the amount of capacity they can deliver; the entire capacity of the distribution mechanism is divided evenly across the entire region.

This means that if (say) the total capacity is 100 Mbps and the total surface is 100 km^2 then each km^2 could receive a maximum of 1.0 Mbps. If 0.5 Mbps is demanded by the customers of a particular km^2 then they can all purchase the service. On the other hand, if 1.5 Mbps are demanded, then only 1.0 Mbps can be supplied with 0.5 Mbps of capacity remaining unfulfilled. Li et al. [95] use a similar concept for energy distribution where each hub of their heat distribution network is modelled with a finite heating capacity which must be allocated to their network of geographically distributed customers.

14. The distribution hubs are at a steady state; they can’t store capacity from one region to deliver it to the next.

Although it is possible for satellites to store energy from one region to distribute it in another, such a sharing arrangement is outside the scope of this thesis. Li et al. [95] again use this assumption.

15. Constellations are comprised of identical hubs with no difference between the capabilities of each hub.

Modelling individual satellites is outside of the scope of this thesis.

16. Not all the capacity can be utilized to its full extent and as such different constellation configurations have a different efficiency.

In some configurations, hub points are positioned to provide redundant service to a region and as such waste some capacity. Let's consider the case of a global satellite constellation (Figure 13) where each satellite can provide 10Mbps capacity to each km^2 region. In (A) the Perth region (blue) has three satellites in view so could use aa 30 Mbps capacity. However, a little while later in (B) this same region sees only one satellite and therefore can only draw 10 Mbps capacity. If the operator were to sell Perth 30 Mbps of capacity as suggested in (A) then at time (B) 20 Mbps of demand would be unfulfilled and the customers would demand a refund on their service. Thus, the operator must only sell the minimum capacity available of 10 Mbps. Applying this to the entire world we get the figure shown in (C). Because of the overlapping regions sometimes there may be 30 Mbps of capacity available when only 10 Mbps was sold. This results in a 20 Mbps inefficiency.

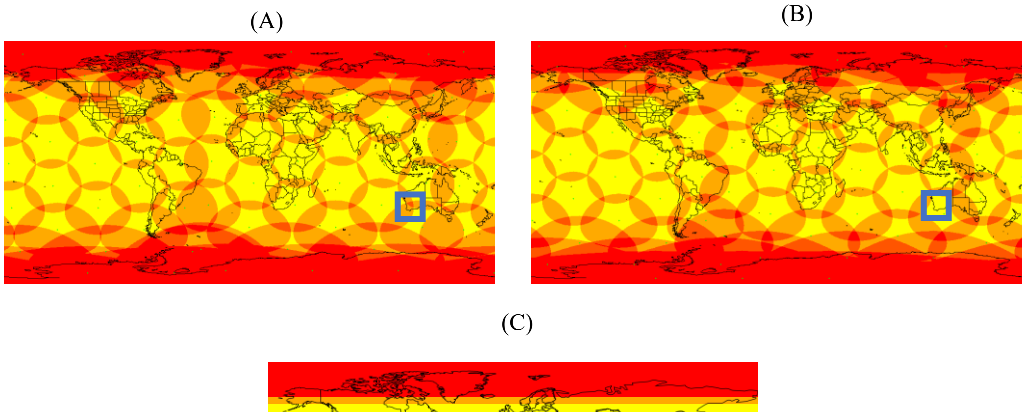

Figure 13: Iridium satellite coverage where yellow represents a single satellite in view, orange two satellites, and red three (or more). (A) is the map at one time, (B) at a different time, and (C) the minimum satellites in view at any time. Perth is indicated with a blue box. An operator assessing how many Perthlings should be allowed to purchase the service must do so by only considering the available capacity in (C). Sold as (A) with three satellites in-view there would be three times too many customers and the network would be unable to reliably supply service during coverage states such as (B) when only a single satellite is in view.

3.4 Customer assumptions

Customer assumptions consider what are the goals for each customer agent and what actions do they take to realize those goals.

17. Customers make decisions according to the theory of planned behavior.

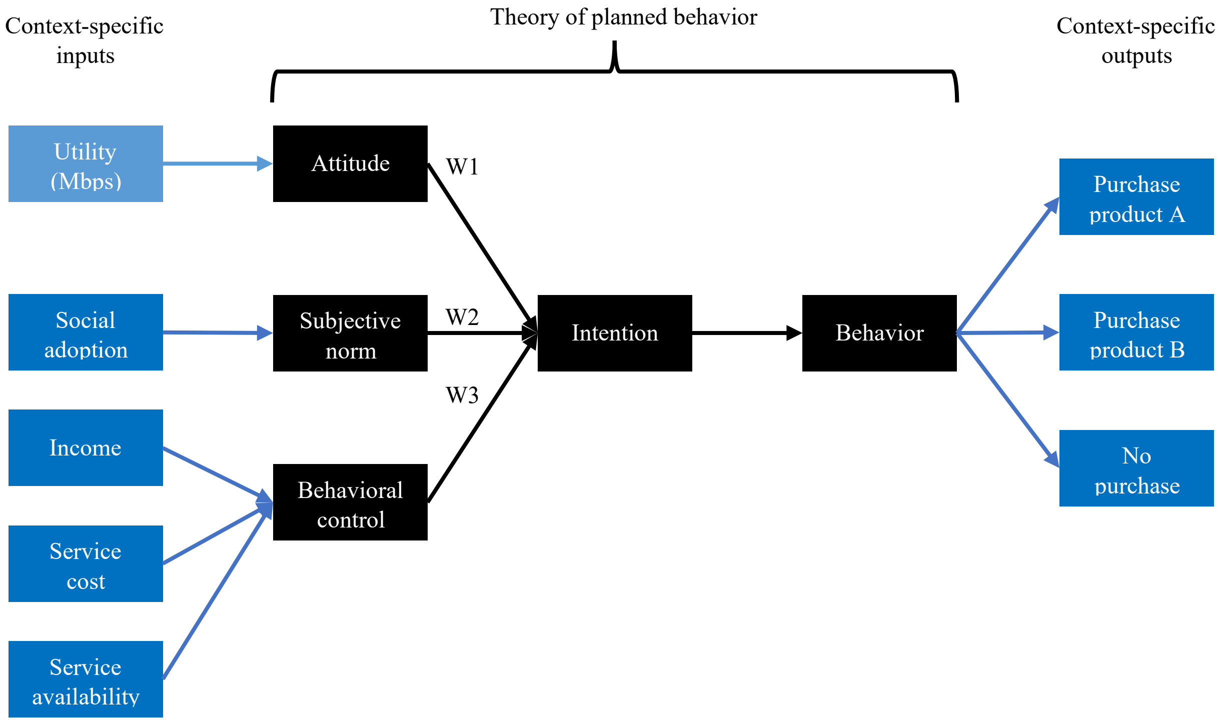

Figure 14: Broadband adoption model as used in this thesis and adapted from [53]. Customers have attitudes, subjective norms, and behavioral controls which influence their intentions and lead to certain behaviors. Different agents weigh each factor differently (W1 to W3) which can lead to otherwise identical agents making very different decisions. An agent that values high-speed connection highly (an attitude with a high W1 weighting) may purchase product A if it has the desired high-speed characteristics. A different agent might value what their peers are doing and be influenced by social adoption within their network (subjective norm with high W2) leading to them purchasing the highly adopted product B. Finally, an agent who has very little disposable income may ultimately make no internet purchase as they are limited by behavioral controls (W3) which prevents them from purchasing the high-cost products A and B.

The theory of planned behavior, shown graphically in Figure 14, states that the intention to perform a behavior, such as purchasing a given internet product, is attributed to the belief constructs of attitude, subjective norms, and perceived behavioral control [96]. In Agarwal's 2021 thesis on agent-based model of broadband adoption in unserved and underserved areas [53] interpreted this that customers would chose to purchase broadband by assessing the product's quality (specifically speed in Mbps), price, and how many of their neighbors had also purchased the service. Agarwal inferred that customers would all preferentially purchase the higher Mbps service and suggested that operators would tend to sell services of this higher quality. As such we assume quality is static between operators, fixing it at the optimal value of 100 Mbps determined in the thesis.

18. Customers are geographically distributed according to their real-world distributions. This distribution does not change significantly over time in terms of shape.

Customer geography is a key feature of satellite communications. Real customer distributions using point-based customer distributions were used extensively by Luis et al. [97] for satellite-based internet power allocation. A simple continent-scale customer distribution was used by Long [83] to tackle the beam-routing problem.

Customers are assumed to mostly follow the same geographic distribution over time. For example, a city with people is unlikely to move over the course of a decade but may grow in population from one million to one-and-a-half million residents. In that same decade the city may go from having no fiber optic internet to having fiber-optic internet.

19. Customers can be divided into segments with similar behaviors and similar product demand characteristics. This defines bounds for their belief constructs as in the theory of planned behavior.

Segmentation of the satellite-based internet market has been conducted by several researchers. Initial segmentation was conducted by the ITU [61] into fixed and mobile services with mobile users further divided into land, maritime, and aeronautical. Guerster et. al. [93] conducted 60 interviews with existing satellite internet customers to expand this segmentation using basis of type of business, customer mobility, and terminal usage. Segments identified were private jets, private boats, residential broadband, airlines, cargo ships, cruise ships, small-medium business, energy, backhauling, trunking, government, and service-providers.

20. Customers take cues from their peers with respect to purchasing a product. This informs their subjective norm belief construct.

As described in [96] and applied by [53], consumers make decisions partially informed by the actions of those in their network. In this case the customer's network is defined geographically as those occupying the same 1° x 1° region. Rather than explicitly modelling direct connections between individual customers we instead consider the problem probabilistically with the higher the portion of a given cell who purchase a product the more likely it is for their undecided peers to join them in this decision.

21. Customer segments exhibit price elasticity defined by a willingness to pay equation. This informs their behavioral control belief construct.

The willingness to pay equation is a measure of market elasticity used to estimate what percentage of a customer segment is willing to purchase the product at a given price. Economic theory states that as the price for a product increases demand for that product will fall with the coefficient of price elasticity measures the sensitivity of consumers change in prices.

The approximated willingness to pay equations used for each customer group will be shown in the relevant sections and based on the most reliable data. This is fitted using the equation

$$WTP = e^{X \cdot price}$$

where X is some constant characteristic of the market. If we have data that 50% of the customer segment would be willing to purchase a product for \$100 then this would give

$$WTP = e^{X \cdot price}$$

$$50\% = e^{X \cdot \$100}$$

$$\therefore X = -6.93 \times 10^{-3}.$$

Thus, using the modified WTP equation of

$$WTP = e^{-6.93\times10^{-3}\cdot price}$$

we see that a price of \$200 would result in only 25% of the population willing to purchase the product. Using the definition of elasticity as the marginal change in quantity over the marginal change in price we have

$$elasticity = \frac{\delta\ quantity}{\delta\ price} = \frac{\delta}{\delta\ price} \cdot WTP = \frac{\delta}{\delta\ price} \cdot e^{-6.93\times10^{-3}\cdot price}$$

$$= -6.93 \times 10^{-3} \cdot e^{-6.93\times10^{-3}\cdot price}$$

which shown graphically in Figure 15.

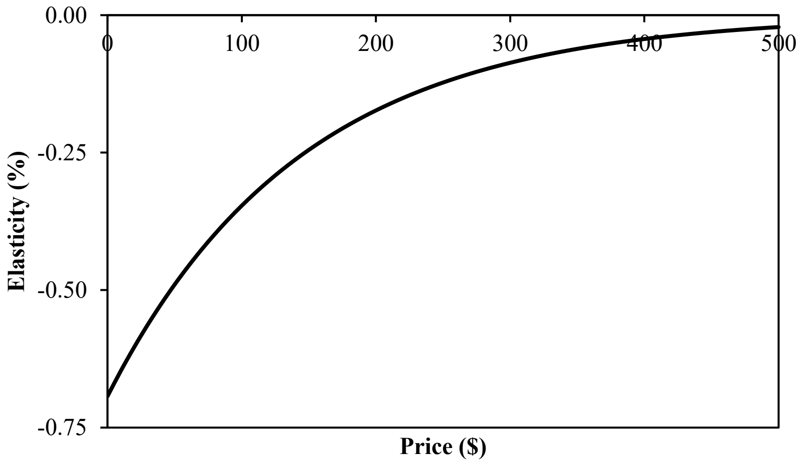

Figure 15: Elasticity using the WTP derivation. Customers show very elastic behavior at lower prices which becomes more inelastic as prices grow. In all cases increasing the price reduces the number of customers willing to pay it (negative elasticity). At low prices with have many customers who only somewhat need the service, but as price grows only the most dedicated customers who truly need it remain, which is how elasticity changes with price.

In the literature price elasticity is typically taken from within a short range of prices and is thus presented as a constant – equivalent to a linear WTP equation. Wan et al. [98] highlight the flaws of this approach by use the context of electricity market modelling. Fitting data using an exponential rather than linear elasticity distribution improved fit by a factor of two in the near-range (\$0-\$75) and even better in the extremes (>\$75). While this doesn't definitively show that exponential models are better at modelling market dynamics than linear ones, it does suggest that exponential models can better fit the historical data by better accounting for extreme observations. As such price sensitivity will be modelled by an exponential distribution throughout this thesis.

Zhu et al. [99] present a meta-analysis of 103 articles on the price elasticity of residential electricity demand; a field which has been researched significantly with much available data, thus providing a 'gold standard' with which to compare. Their general insights into the effect of time, and country development level are used to help interpolate data as required. For example, in their analysis they found that mean price elasticity was -0.220 for developed countries and -0.273 for developing countries, showing how those in developing countries are more price sensitive. This is incorporated into the model.

Viriend [100] describes customers as rational agents which behave by selecting products that satisfy their needs for a price less than or equal to their maximum willingness-to-pay (WTP). Breidert et al. [101] underline the importance of using willingness-to-pay as a tool for making pricing strategies and demonstrate the use of these statistics for use in making market forecasts. Through an extensive literature review, Breidert et al. [85] identify market data, experiments, and surveys to be the three most useful techniques for obtaining a WTP relationship. Historical market data produces the most valid, verifiable results but is limited in its ability to predict the pricing of new products. Experiments where the price of certain products are intentionally varies overcome this limitation but are expensive to implement and are less verifiable. Direct surveys provide the most cost effective and flexible way to obtain WTP data but are the least verifiable of the approaches.

3.5 Substitute product and service assumptions

Assumptions about the substitutes consider how customers might purchase from adjacent industries (e.g., fiber rather than satellite internet) and how this influences the decisions of other agents.

22. If available customers will transfer to a substitute service with a certain probability.

The growth of substitute services as a serious threat to operator profitability is well documented. Porter [68] describes the impact of substitute services in his seminal book on Competitive Strategy. In the case of satellite phones, the rollout of phone towers took away customers who would otherwise have used the service [102]. Similarly, a customer who was paying for satellite internet in 2020 but in 2025 may connect to a less expensive, higher speed, and more reliable fiber-optic internet line may now move to the fibred service and cancel their satellite-internet subscription. Hecht [103] believes that physics-based limitations make it unlikely that satellite-based internet can ever beat fiber with respect to cost, reliability, and speed; increasing the validity of this assumption.

23. This substitute service may change its distribution with respect to both shape and size.

A key feature of ground-based communications is that they have only a small area of influence. The area of influence grows over time as the network is expanded.

3.6 Chapter summary and conclusions

This chapter establishes the fundamental assumptions of the market model, encompassing the system, operator, distribution mechanism, and customer aspects. These assumptions provide the foundation for simulating the dynamics of the market and understanding the interactions between operators and consumers. The chapter highlights the complexities and limitations associated with each set of assumptions, setting the stage for further analysis and exploration in subsequent chapters.

Among the assumptions discussed, perhaps the least realistic assumption is that operators do not become bankrupt. While the assumption is based on the observation that modern satellite operators have been able to survive longer periods of financial struggle, it overlooks the inherent risk and uncertainty associated with business operations. In reality, operators, especially in competitive markets such as satellite internet, can face financial challenges that may lead to bankruptcy if they cannot sustain profitability or secure affordable funding for their ventures. The assumption of operators not becoming bankrupt simplifies the model and disregards the potential consequences of financial instability in the market. Closely tied to this issue there is no mechanism to estimate the costs of doing business and therefore operators are revenue-maximizing agents rather than profit-maximizing. This means that the simulated operators will typically choose behaviors such as expanding the constellation or selling to as many customers as possible while in reality the costs of performing such actions may often outweigh revenue increases. At the very least, a one-off sale (i.e., without ongoing subscription revenue) of an internet terminal for \$10 that costs \$100 to make while increasing revenue will be actively harmful to income.

The model also fails to account for some operational realities of real satellite operators. We assume that satellite operations are not affected by atmospheric conditions or space weather. In reality, atmospheric conditions such as temperature, humidity, and atmospheric pressure can impact satellite communication links, leading to signal attenuation and interference. Factors like rain, fog, and atmospheric turbulence can degrade the quality and reliability of satellite communications. Additionally, space weather events like solar flares, coronal mass ejections, and geomagnetic storms can generate intense radiation, charged particles, and magnetic disturbances, causing disruptions, power outages, communication blackouts, and potential damage to satellite components. Ignoring the influence of these environmental factors in the model assumes an idealized scenario where satellites operate unaffected by external conditions, whereas in practice, they are crucial considerations in satellite system design, operation, and risk management.

Despite these drawbacks, the assumptions provide a sturdy foundation from which to build the model. Sensitivity analysis of the key assumptions (5.4 Sensitivity analysis on page 122) will be used to assess their validity.

Chapter 4

Model Implementation

This chapter describes how the model was implemented and details initial validation using a generic satellite communications market. The model is then benchmarked and optimized for speed of execution. The chapter continues the methodologies, results, and discussion components of this thesis. First (4.1 Model breakdown on page 70) the implementation of the model is discussed in detail. We then (4.2 Generic satellite communication study on page 74 and it's subsequent sections 4.2.1 to 4.2.6) detail a generic satellite market model which is used to progressively test the effect of price, elasticity, capacity, and substitute products on progressively more complete implementations of this model. Finally (4.10 Chapter summary and conclusions on page 92) we summarize the chapter and provide key takeaways.

4.1 Model breakdown

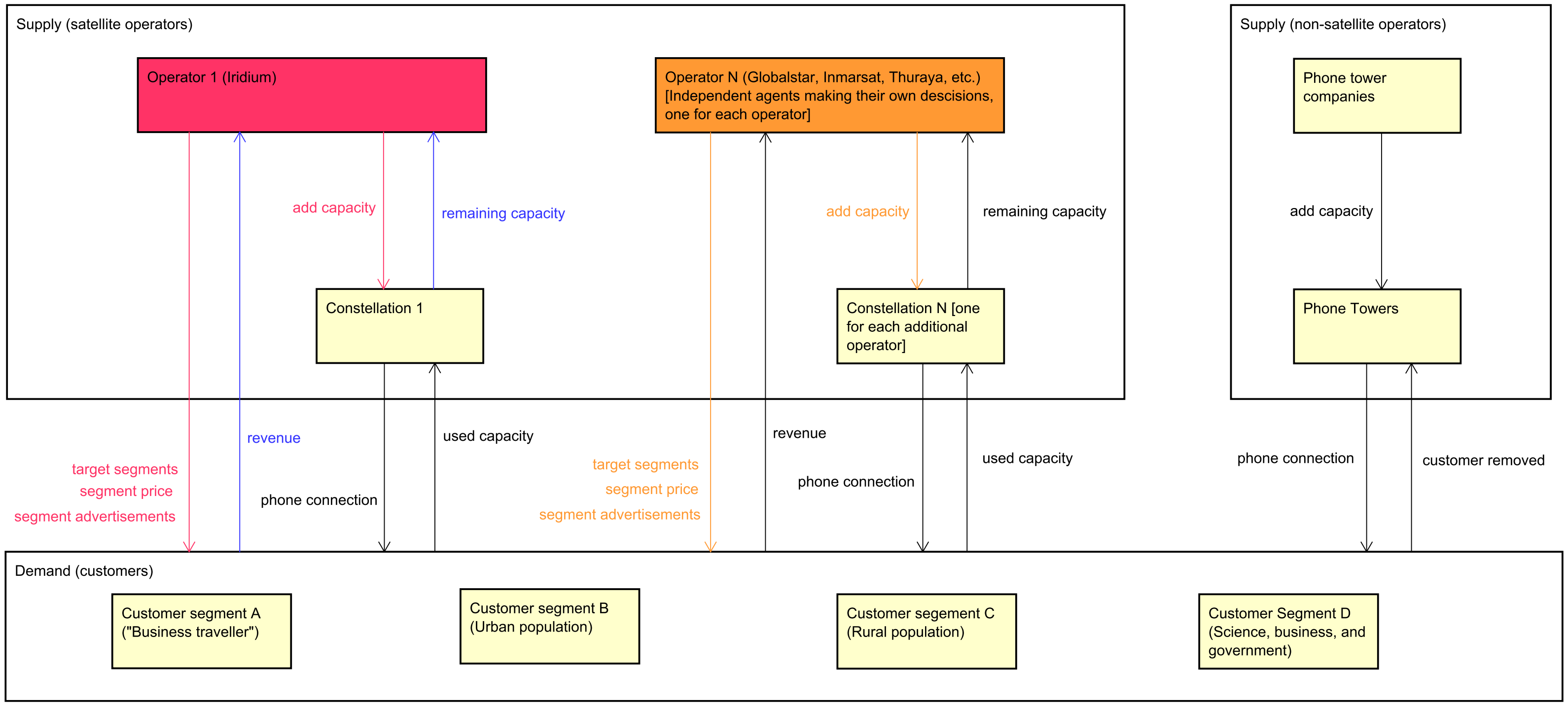

Figure 16: Generic market model control structure diagram. Shown for the satellite-phone configuration. Supply is at the top of the chart with satellite-based operators in the left and non-satellite operators on the right. At the bottom is demand with customers of varying segments.

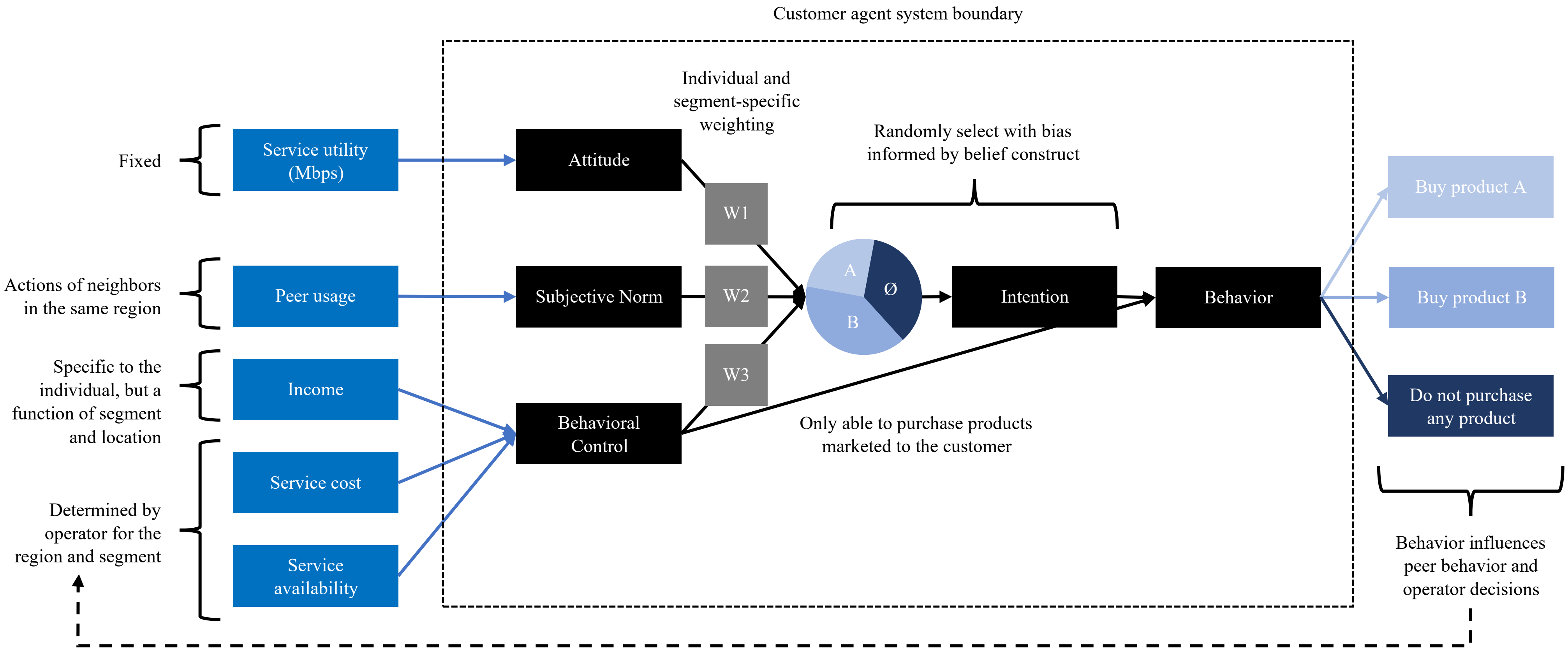

Figure 17: Generic customer agent decision process. From left to right; market properties like service speed, peer adoption, and service cost combine with agent-specific characteristics such as income. Individual agents perceive this through attitudes, subjective norms, and behavioral controls. Different customer agents weigh these factors differently which leads to them forming (weight-based) intentions leading to behaviors such as buying or not buying certain products. The influence of customer choices on operators and the customer's peers is shown by the dotted arrow learning back to the start.

Numerous tools are available for conducting agent-based modelling research, including widely recognized platforms such as Swarm [104], MASON [105], and FAME [106]. However, these existing tools were found to be inadequate in controlling the context-specific assumptions necessary for studying satellite markets. To overcome this limitation, a bespoke Agent-Based Satellite Market model (ABSM) was developed from scratch to address the operational challenges unique to this domain. The ABSM was implemented using a custom-written Julia script, chosen for its combination of high-level language readability akin to Python and the performance advantages reminiscent of lower-level C-type languages [107]. This customized solver offered enhanced control over the heterogeneous customer segments and facilitated the efficient implementation of location-based supply and demand distribution. While a detailed analysis of the code falls beyond the scope of this thesis, this section provides a high-level overview of the key components comprising the model.

The assumptions were used to produce a control structure diagram as illustrated in Figure 16. Note that in this implementation there are four operators with operators 2 to 4 combined into the Operator N category to improve legibility of the diagram.

In the upper half of the chart represents supply. It is made of both industry (left) and non-industry (right) operators. Industry operators (i.e., competitors) are modelled as independent agents and can compete, while the non-industry operators (i.e., substitutes) are not independent agents but instead follow a pre-determined growth pattern.

As described in the previous assumptions, industry operators have the goal of maximizing their own NPV. They can perform actions (in red) such as changing who they sell to, the price which they sell it, and whether to exercise the option of adding more capacity. They make decisions by responding to feedback (blue).

Non-industry operators and their substitute products are modelled as a single entity. They are not considered to be rational agents, but instead just rollout capacity regardless of what else is happening. When they do, they 'steal' some portion of the customer as defined by where the customers live and where the phone towers are being built.

The lower half of the chart is demand. It is comprised of many different customer segments. These customer segments comprise many independent customers with their own willingness-to-pay characteristics. They are modelled as independent agents making decisions according to the theory of planned behavior (Figure 17).

Customer segments are defined by size, location, and willingness-to-pay characteristics. Size is how many customers are in that segment. It can grow or shrink over time; for example, a residential household segment will grow as more people are born or move to an area. Location is where people are located. There must be some free capacity in these regions to supply customers in that segment. Finally, willingness-to-pay is a function which determines for a given price what percentage of the population will buy the product or service. For example, at $100/year 50% of residential customers might be willing to purchase internet connection, but at $500/year only 10% may be willing.

Customers choose which operator to apply to by considering these factors, weighting them by their own specific belief construct characteristic to the segment and individual, and then (with bias) randomly select to purchase a service from one of the operators, use a substitute service, or remain unconnected.

Operators and customers are linked together by targeted segments, segment price, segment advertisement, and revenue. Service provided and used capacity monitor the capacity which remains and ensures that the operator does not sell capacity that does not exist. Segment price and regions services are optimized using a genetic algorithm. In this implementation, operators may choose to exit a segment. As customers are matched with operators, they provide a certain amount of revenue to that operator. These operator agents independently optimize their product and price offerings to maximize revenue.

4.2 Generic satellite communication study

The ABSM was subjected to rigorous testing by employing a diverse set of input values, followed by a qualitative analysis of the results to assess their overall consistency. It is important to note that the emphasis of this chapter lies on the implementation of ABSM rather than the specific outcomes generated. Consequently, generic inputs were utilized to simulate the operations of a typical satellite communications operator. Therefore, the obtained results should be interpreted cautiously, considering that they primarily serve the purpose of detecting any glaring issues with the model and identifying potential areas for refinement. The conducted tests and their respective outcomes are meticulously described and accompanied by insightful comments for further elucidation.

Studies started with only a single operator and single customer segment with gradually more operators and segments added over time. The scenarios assessed are:

4.2.1 Effect of changing price with a single operator and single customer segment
4.2.2 Effect of changing elasticity with a single operator and single customer segment
4.2.3 Effect of changing capacity with a single operator and single customer segment
4.2.4 Effect of changing capacity with a single operator and multiple customer segments
4.2.5 Effect of changing capacity with a multiple operators and multiple customer segments
4.2.6 Effect of substitute products with a multiple operators and multiple customer segments

4.2.1 Effect of changing price with a single operator and single customer segment

The effect of price on revenue underpins both economics and this model. In this validation case, only a single operator and single customer segment is being modelled (Figure 18). The operator is based loosely on the Iridium constellation and the customer segment is a residential consumer. The simulation considers only a single allocation period, notionally designated as the year 2000. Willingness to pay is set to $WTP = e^{-8.0\times10^{-3}\cdot price}$ and individual customer agents are randomly assigned an individual maximum price according to the distribution.

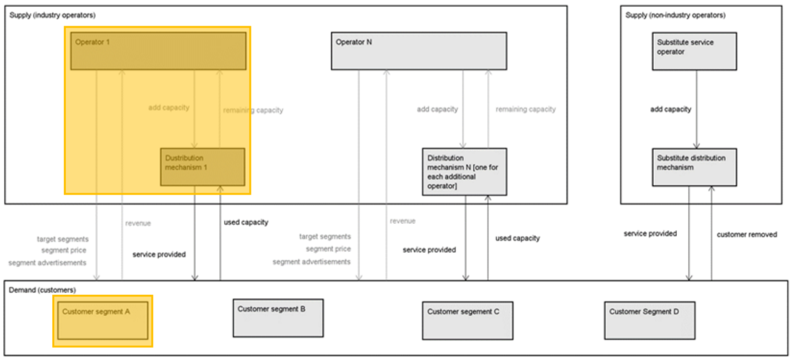

Figure 18: Market model control structure diagram with activated components highlighted. A single operator and single customer segment are being modelled.

The operator changes the price being charged for the subscription from \$0 to \$1000 in units of \$1. The effect of this on income, number of customers purchasing the product, and number of customers who would have purchased the product but were unable to due to there being insufficient capacity are recorded.

We begin by considering the heterogenous (‘real world’) distributions shown by the solid lines in each of the proceeding figures. Figure 19 shows how changing price affects annual revenue of the operator. Figure 20 shows how price affects the number of subscriptions which are fulfilled and Figure 21 the number of subscriptions which were possible but left unfulfilled due to constellation capacity restraints in their specific region. Starting from zero, as price increases the revenue increases until reaching a maximum of \$274,000 with a price of \$469/year. At this point 584 people have subscriptions with 1660 people who would have purchased a subscription but there was insufficient capacity available in their region to meet this request. Since the constellation can supply at maximum 10,000 customers and the market size is 100,000 the rejected subscriber graph closely resembles the willingness to pay distribution of the segment. As price increases, less and less of this population can afford the subscription and therefore the number that applied but were rejected falls. The number of rejected subscribers is greater than the number of accepted subscribers until a price of $594 and by $897 there are few enough applicants that everyone who could afford the subscription is able to purchase one.

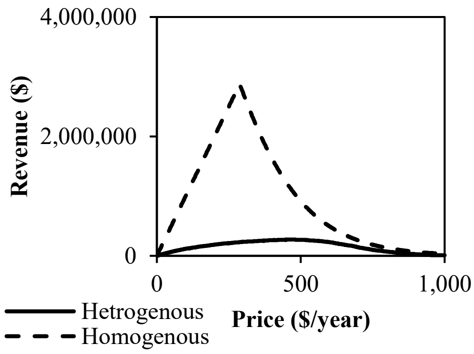

Figure 19: Effect of price on revenue. Increasing price increases revenue until there are not enough customers who are willing to pay and revenue falls.

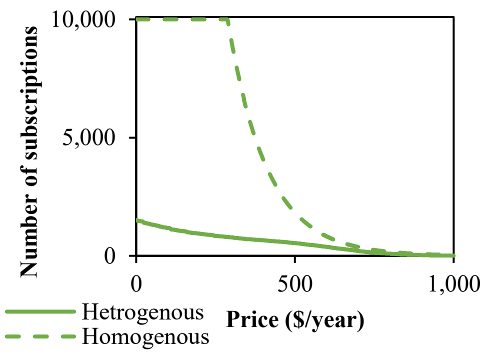

Figure 20: Effect of price on the number of subscriptions. In the homogenous distribution the constellation is fully utilized at low price points.

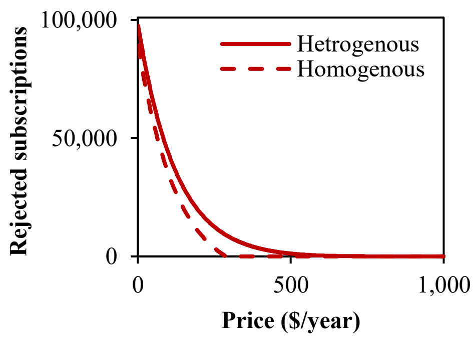

Figure 21: Effect of price on the number of rejected subscriptions. For both, many customers are rejected. The market is in a state of demand far outstripping supply.

The graphs are not smooth. This is because of the heterogenous population and capacity distributions whereby certain regions are at or below capacity at different price points. To illustrate this effect the experiment has been repeated for homogenous constellation and capacity distributions with the results plotted with dotted lines on the corresponding graphs.

When capacity and demand are homogenously distributed graphs are smooth and more closely match traditional economic theory.

Considering just the homogenous distributions (dotted lines), in Figure 19 revenue increases linearly until a maximum of \$2,170,000 at a price of \$346 with 6280 customers being supplied with service and none being rejected (i.e., due to the constellation having insufficient capacity). Not by coincidence, this is the lowest price at which there are no customers being rejected. Worded another way; \$346 is where the constellation capacity and customer demand meet exactly. Figure 20 is linear prior to this amount with the constellation always at full capacity (10,000 subscriptions) followed by the number decreasing according to the exponential willingness to pay distribution detailed previously. There are fewer rejected customers (Figure 21) by virtue of these customers being spread homogenously.

These results are as expected, which support the hypothesis that the model has been correctly implemented according to described assumptions.

4.2.2 Effect of changing elasticity with a single operator and single customer segment

The curved graphs of the previous tests are expected because of the exponential willingness to pay equation. However, they may at first appear confusing to those accustomed to linear elasticity functions. This test compares several types of willingness to pay equations to assess and explain their implementation. It uses the same formulation as before with elasticity the only change.

Three linear equations with low, medium, and high elasticity were generated. All were made to match that 50% could purchase the subscription for a price of \$100/year. The equations used are:

$$\mathrm{WTP}_{\mathrm{exponential}} = \mathrm{e}^{-6.93\times 10^{-3}\cdot \mathrm{price}}$$

$$\mathrm{WTP}_{\mathrm{linearLowElasticity}} = -2.5\times 10^{-3}\cdot \mathrm{price} + 0.75$$

$$\mathrm{WTP}_{\mathrm{linearMediumElasticity}} = -5 \times 10^{-3} \cdot \mathrm{price} + 1.00$$

$$\mathrm{WTP}_{\mathrm{linearHighElasticity}} = -10 \times 10^{-3} \cdot \mathrm{price} + 1.50$$

which are bounded by $0\% \leq WTP \leq 100\%$. The resulting plots are shown in Figure 22. As before, the price being charged by the operator is varied from \$0 to \$1000.

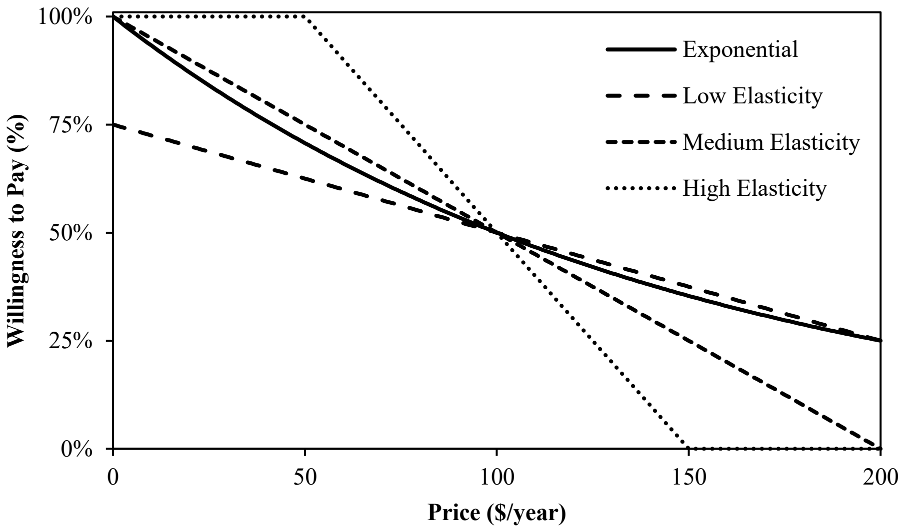

Figure 22: WTP distributions used to populate customer agents. The exponential distribution is similar to low elasticity line at prices below \$100 and similar to the medium elasticity line at prices above \$100.

Considering the effect of price on revenue (Figure 23), each willingness-to-pay function produces a different optimal price. The exponential function has a maximum revenue of \$349,000 at a \$561/year subscription price, low elasticity linear of \$232,000 at \$245/year, medium \$165,000 at \$163/year, and high \$136,000 at \$119/year. As is consistent with the economic theory; lower elasticity means that the operator can charge higher prices for the same product to generate greater income. This is supported in Figure 24 where customers with lower elasticity have higher number of customers for longer and a shallower curve. Figure 25 almost exactly matches the Figure 22 plot of price vs willingness to pay curve.

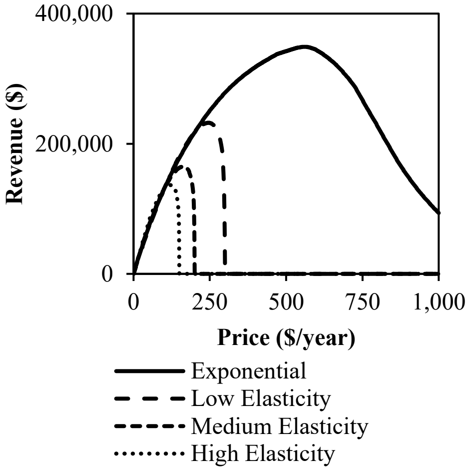

Figure 23: Effect of price on revenue. Similar at low price the different elasticities diverge considerably as prices increase. Note how linear elasticities experience sharp drop-offs while the exponential is more gradual.

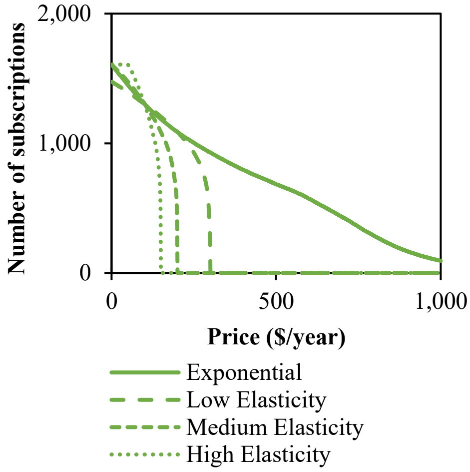

Figure 24: Effect of price on number of subscriptions. Counterintuitively the relationship is almost linear for the exponential distribution with more sudden drop-offs for the other groups.

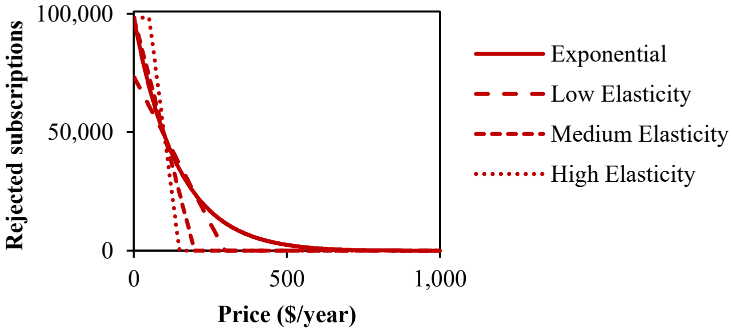

Figure 25: Effect of price on rejected subscriptions. There is much greater demand than supply.

Comparing the linear and exponential curves both produce useful results. The steep decline as price approaches the willingness-to-pay of 0% in the linear elasticity functions appears to be unrealistic as we typically expect a more gradual loss in revenue if price increases. Thus, the exponential willingness-to-pay function will be used throughout further analysis.

4.2.3 Effect of changing capacity with a single operator and single customer segment

One of the major design levers available to operators is the capacity of their constellations. This test assesses how changing capacity affects key parameters. The standard single operator, single customer scenario was reimplemented with the only modification being the change in capacity of the constellation. Rather than manually varying prices in this scenario we allow the operator to select the best possible price using the previously described genetic algorithm with a goal of maximizing revenue. Constellation capacity is varied from 0 to 100,000 simultaneous connections in units of 1000. As should be expected, at 10,000 units of capacity the optimal price leading to maximum revenue exactly matches that predicted previously in the price change test, with a price of $469/year producing a revenue of $274,000.

As shown in Figure 26 as capacity increases so does revenue. There are diminishing returns, but capacity always increases revenue. This is expected; in a worst-case scenario the operator would just repeat their original pricing from the previous level of capacity which can at worst match the original income. Figure 27 shows price generally decreasing as capacity grows. This makes sense; at an initial low capacity we would expect the operator to sell that capacity for as high a value as possible. Figure 29 indicates that initially there are very few rejected customers; consistent with this being a very high price which few can afford. As capacity increases price falls and there are more people who receive subscriptions (Figure 28) and at the same time more who could have received a subscription but were unable to do so due to limited capacity.

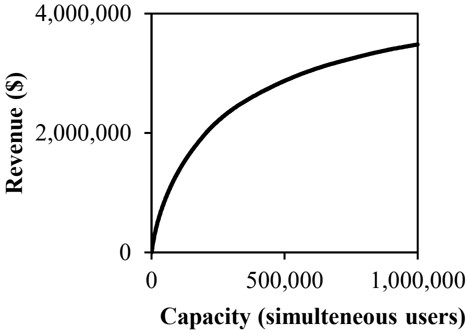

Figure 26: Effect of capacity on revenue. As available capacity increases so does revenue; but at a diminishing rate. There are less available customers to sell to as capacity increases to meet this demand and those new customers have a lower willingness to pay.

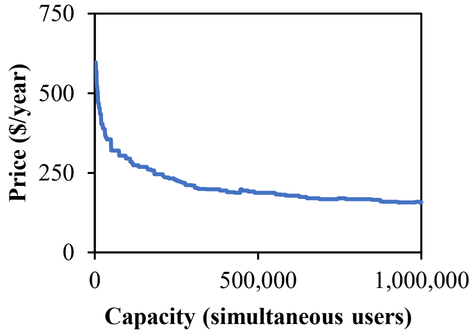

Figure 27: Effect of capacity on price. At low capacity the operator can sell high to just a few customers, but as capacity increases there are fewer customers at this price point and price must reduce.

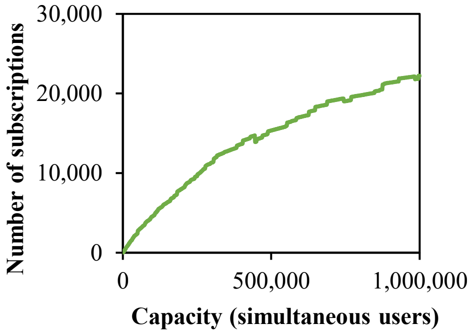

Figure 28: Effect of capacity on the number of subscriptions. Capacity and number of subscriptions are almost linear; as capacity increases we want to proportionally increase the number of subscriptions.

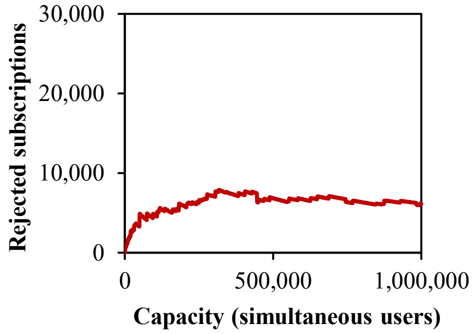

Figure 29: Effect of capacity on the number of rejected subscriptions. The number of rejected subscriptions is relatively constant. This suggests that there is some optimal rejection level to ensure maximum revenue.

It is surprising that these trends do not hold throughout, and indeed at some points prices rise (and the number of subscriptions fall) although with revenue increasing throughout. An instance of this is moving from 445,000 to 446,000 units of capacity where price rises from \$189 to \$198 with subscriptions falling from 14,727 to 13,909. Revenue increased from \$2,756,693 to \$2,761,771. The test was repeated with smaller divisions (Figure 30) which still revealed this behavior; suggesting that it was not at the optimizer was incorrect, but that this is the actual behavior that should be observed.

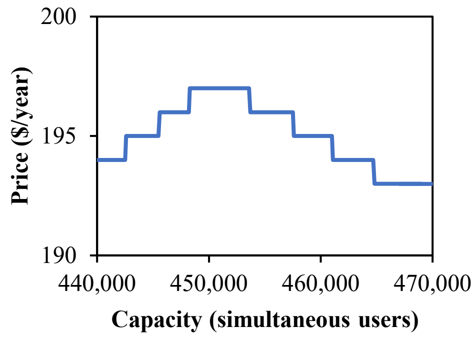

Figure 30: Zoomed-in view of the effect of capacity on price, plotted from 440,000 to 470,000 units in step sizes of 100 units. Depending on the heterogenous customer characteristics at times (as shown here) it may be beneficial for the operator to either increase or decrease subscription price as capacity grows. That is; it is not a constantly decreasing relationship.

One explanation for this could be due to the presence of a small number of high-density (cities) and large number of low-density regions (rural and unpopulated areas). When there is a small amount of per km^2 capacity the optimizer sets prices low so that there are always people to buy capacity from every cell. In other words, since low-density regions will have numerically few high-paying customers prices need to be low to get customers. However, when capacity increases it is possible to get more revenue by rising prices and selling just to the high-density regions (with numerically greater high-paying customers) which counteracts the losses from other regions where there are numerically fewer high-paying customers.

A simple Excel model can be constructed to replicate this effect. Assume that there are 1000 cells each with a certain number of households. Five of these cells are cities with an average population of 1801 and 995 of these are rural regions with an average population of a single household. 1% of households have a high willingness-to-pay ($100 for internet), 9% medium ($50) and 90% low ($7). On average the cities have 18 high, 180 medium, and 1801 low willingness-to-pay households, while the rural cells average just a single low willingness-to-pay household. Note that setting price to 'medium' will allow both high and low willingness-to-pay households purchase the subscription at the 'medium' cost. Low willingness-to-pay households will not purchase the service. We increase the capacity of each cell in increments of five households, starting from 5 and finishing at 25.

Strategies of setting price to high, medium, or low are compared in Table 4. Again, we see the same effect where a price starts low, rises, then falls back down.

Table 4: Pricing strategy comparison by setting prices to high, medium, or low. The best (green) and worst (red) strategies are highlighted at each capacity.

Capacity per region	Number of households sold to by setting price…			Revenue by setting price…		
	High	Medium	Low	High	Medium	Low
5 households	35	125	1020	$3,495	$6,225	$7,140
10 households	60	150	1045	$5,995	$7,475	$7,315
15 households	85	175	1070	$8,495	$8,725	$7,490
20 households	100	200	1095	$10,000	$9,975	$7,665
25 households	100	225	1120	$10,000	$11,225	$7,840

4.2.4 Effect of changing capacity with a single operator and multiple customer segments

This test considers how different customer segments affect the simulation. This is an essential part of how an operator conducts market segmentation. A new scenario was constructed with three customer segments and a single operator (Figure 31). Segments use a range of geographic distributions and preferences. The first is a business segment characterized by high WTP but low segment size, the next urban customers with medium WTP and medium size, and the final rural customers with many customers of low WTP.

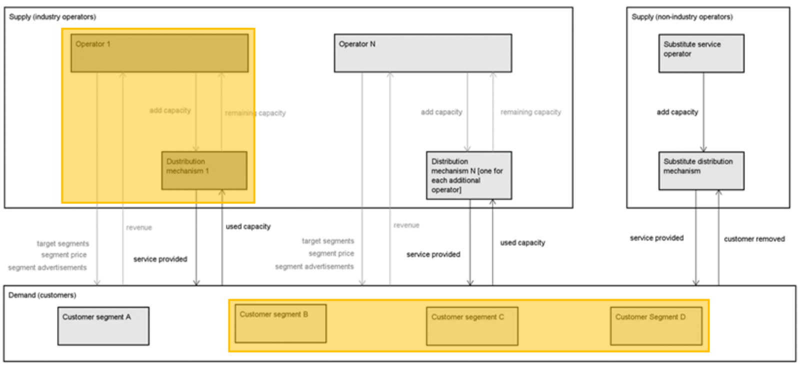

Figure 31: Market model control structure diagram with activated components highlighted. A single operator and three customer segments are being modelled.

Constellation capacity varies from 0 to 100,000 simultaneous users in units of 1,000. The optimizer selects the best price for each segment so that the best possible revenue can be obtained for the entire constellation. At times this could mean reducing the amount of capacity allocated to one segment to maximize revenues from a different one.

To better show key features in the low-capacity region the test was repeated from 0 to 10,000 simultaneous users in units of 100. To better show key features in the low-capacity region the test was repeated from 0 to 10,000 simultaneous users in units of 100. Results are shown in Figure 32 to Figure 34.

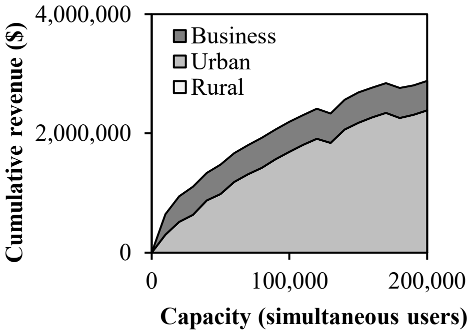

Figure 32: Effect of capacity on revenue. Contribution from each segment is stacked. Increasing capacity tends to increase the revenue from each segment in proportion.

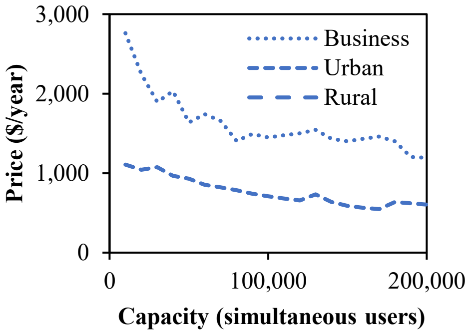

Figure 33: Effect of capacity on subscription price for each segment. Note that the optimizer has decreed that rural customers are not sold to, therefore do not appear on the chart. As capacity increases price falls.

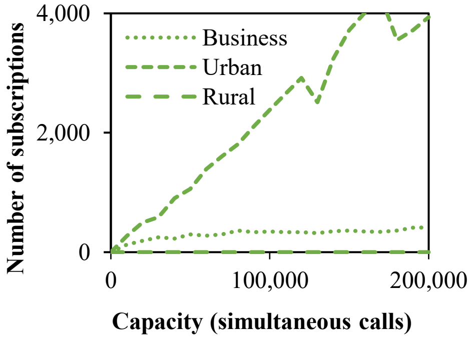

Figure 34: Effect of capacity on the number of subscriptions for each segment. Business customers are the most profitable, but as most are already supplied with little capacity any gains in capacity must be made by increasing sales to the urban segment.

As before, increasing capacity increases the number of subscriptions while also reducing the cost of these subscriptions. However, now there are multiple segments we see how the operator preferences different customer segments. Initially only the high-value business segment is sold to as the operator can best maximize revenue by selling just to this class. As capacity increases prices need to fall to ensure that this extra capacity is being used most effectively. Eventually it falls to the point where it is beneficial to sell to the urban segment as well. The low WTP rural segment does not appear over the ranges covered.

An interesting observation is that there are more urban customers being sold to than business customers despite business being a clear preference. This is because there are many more of the urban customers and they spread over a much wider geographic region. Therefore, it is possible to sell to many of these urban customers without losing any capacity in the business-focused regions. This emergent phenomenon is not observable in equation-based modelling since it lacks the location dimension.

4.2.5 Effect of changing capacity with a multiple operators and multiple customer segments

This test considers how different customer segments affect the simulation. An additional three operators loosely based on Globalstar, Inmarsat, and Thuraya were incorporated into the simulation (Figure 35). These operators have a range of capacities and coverage areas. For the moment flexibility options have been reduced to observe the direct implications of the model.

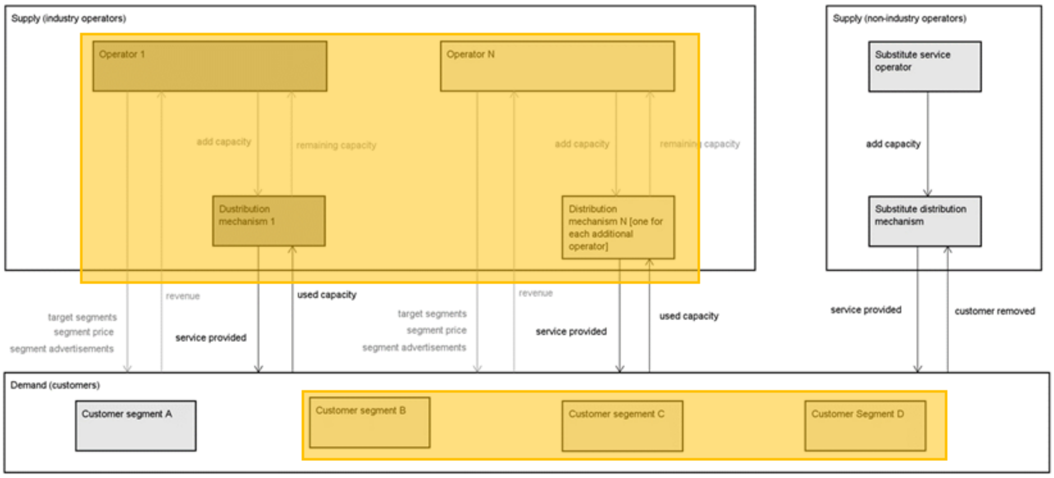

Figure 35: Market model control structure diagram with activated components highlighted. Four operators and three customer segments are being modelled.

As in the previous tests, capacity of each constellation was varied independently with the effect on each operator's revenue and pricing structure observed. A small selection of results where we observe how the growth of Globalstar affects the properties of Iridium are shown. Revenue, price, and number of subscriptions are shown in Figure 36 to Figure 38.

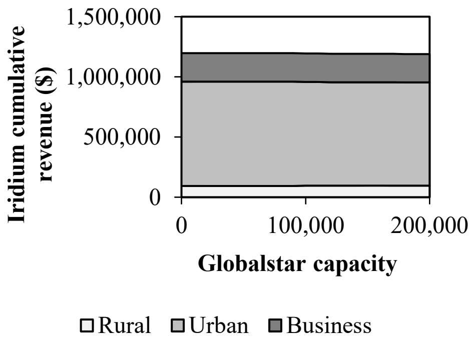

Figure 36: Effect of Globalstar capacity on Iridium revenue. Contribution from each segment is stacked. Increasing Globalstar capacity has little effect on the decisions made by customers purchasing Iridium products.

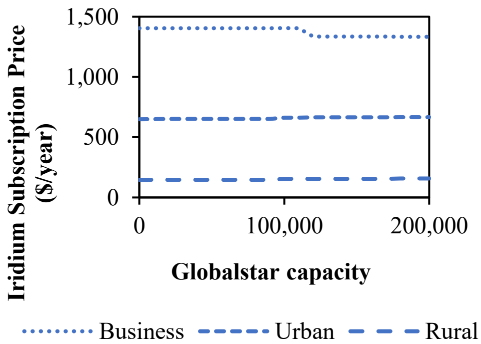

Figure 37: Effect of Globalstar capacity on subscription price charged by Iridium for each segment. There is a slight drop in price as Iridium must compete with Globalstar.

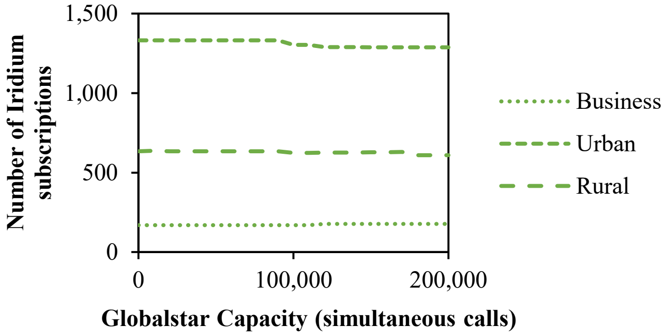

Figure 38: Effect of Globalstar capacity on the number of Iridium subscriptions for each segment. As capacity increases for Globalstar there is a slight drop in the number of Iridium subscriptions as users switch to the Globalstar service.

With this relatively small model, it appears that the growth of a single operator has only a small effect on its competition and the wider market. This is likely caused by the fact that there is an excess of demand such that a little extra supply does very little to modify the wider market. This would perhaps be less true if the market instead was in a state of greater equilibrium. A reader could infer that the input variables to this test make its results irrelevant, and while it is certainly true that these results should not be taken as investment advice, it is clear to observe how the growth of one operator forces its competition to lose subscriptions, lower prices, and ultimately lose revenue. Most importantly, the results show that the model with multiple operators can run successfully to produce results.

4.2.6 Effect of substitute products with a multiple operators and multiple customer segments

This test considers the effect of adding a non-industry competitor which removes some of the customers over the course of the ten-year simulation. All operators and segments were incorporated into the simulation (Figure 39) and this is the most complete of the general validation tests. The non-industry substitute follows the general structure and penetration of mobile towers in the year 2020.

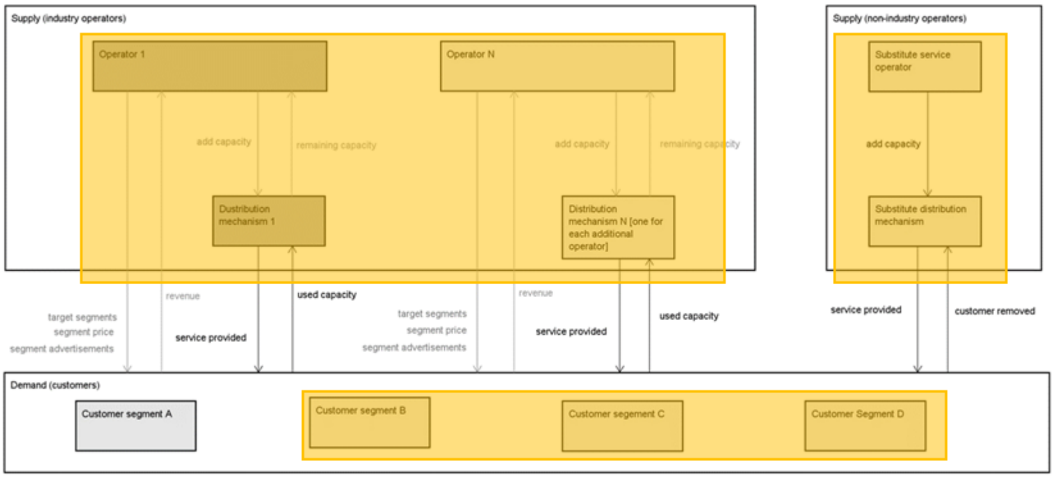

Figure 39: Market model control structure diagram with activated components highlighted. Four operators and three customer segments are being modelled.

Over a ten-year period the roll out of a substitute service was conducted, starting at 0% and then finishing at some new percentage with results plotted in Figure 40 to Figure 42. As is expected, this substitute service causes income to fall.

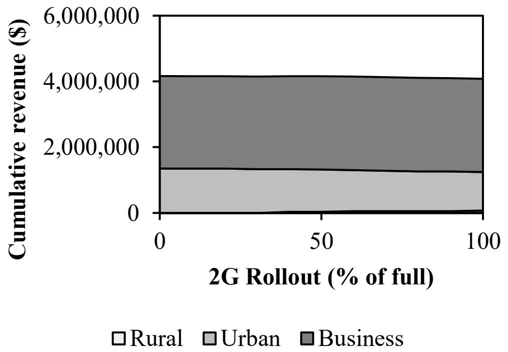

Figure 40: Effect of substitute rollout on Iridium revenue. Contribution from each segment is stacked. Revenue decreases as rollout grows.

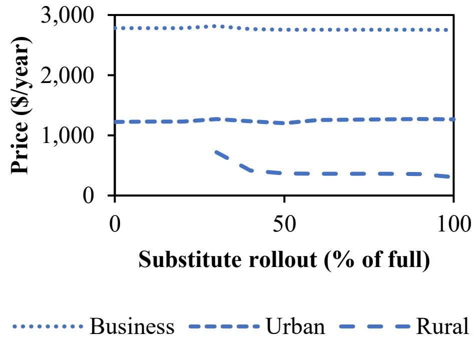

Figure 41: Effect of substitute rollout on subscription price charged by Iridium for each segment. Iridium does not supply the rural segment until 30% rollout is reached and thus does not appear on the chart. This is not a plotting error; the operator is choosing not to supply this segment until it becomes financially beneficial to do so.

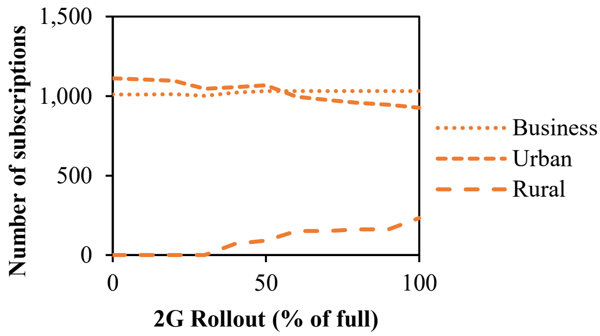

Figure 42: Effect of substitute rollout on the number of Iridium subscriptions for each segment. As 2G rollout increases the operator must shift their strategy to segments less impacted by this rollout; specifically rural segments far from cities.

This test provides a compelling case study in the importance of behavioral and location-based segmentation. Urban customers closely clustered around regions of greatest rollout experience the most atrophy. Price increases slightly, perhaps to extract the most revenue from a gradually diminishing segment. On the other hand, business customers are largely unaffected. This segment heavily features mobile users such as airlines and cruise ships that are poorly suited for land-based substitute services. This could be considered a safe bet for operators apprehensive about the rollout of substitute services.

Another emergent property of the system is that, in the face of substitute service growth, operators seek out new customer segments. Rural customers grow from being entirely ignored to a progressively more important segment. Rural regions experience only minimal substitute penetration making them strongholds for satellite-based connectivity. Price charged to the rural segment drops as a method to incentivize these users adopting satellite-based services.

4.9 Model benchmarking and optimization

The ABSM is executed for the historical satellite-phone and future satellite-internet forecasts.

For the year 2040 in the satellite internet model there are some 19,662,445 agents each with slightly different goals and interactions. The model was set up to run for three days before the computer executing it crashed and the results were lost. Later estimates indicated that it would have taken 144 days to complete. Understandably, this execution time problem has discouraged agent-based modelling from being applied to full-scale problems. As previously discussed, the next largest model of its type is Ankit et al.'s 2021 ABM for predicting the adoption or non-adoption of broadband within a single postcode which uses just 1000 agents [53].

As this is a research thesis and not a code review the specifics of how the model was implemented and optimized fall outside of its scope. In brief however, it was found that the original code would re-calculate peer influence effects for every step of the calculation. Using a temporary matrix which would be updated with every new allocation turned this into a slightly more complex but significantly faster method of performing the calculation. The code was also distributed across eight parallel CPU cores. This linearized problem complexity and provided a 4,500 times speedup; taking just 46 minutes to run.

An additional approach to reduce calculation time was to combine similar customers into groups. As shown in Figure 43, reducing the number of agents by performing this grouping improved precision but generally did not affect accuracy. Although the 10,000-agent model is slightly bumpier than the 100,000 and 1,000,000-agent iterations, all follow the same basic pattern. Considering the 1,000,000-agent model as ground truth WMAPE was 2.8% and 0.91% for the 10,000 and 100,000 agent models respectively. As shown in Figure 44 and Figure 45 reducing model size improved execution time significantly making this a useful strategy. Testing model iteration (original and optimized) with a varying number of agents shows how the original model increased calculation time exponentially with size while the optimized was able to linearize this complexity.

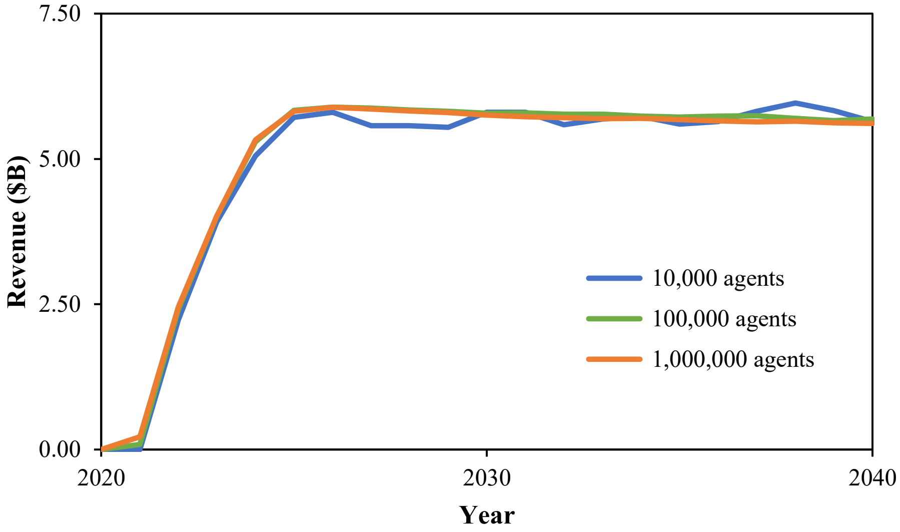

Figure 43: Starlink revenue results with varying numbers of agents. All plots generally show the same structure and are equally accurate, although the more bumpy nature of the lower-fidelity models (especially 10,000 agents) suggests that these have lower precision.

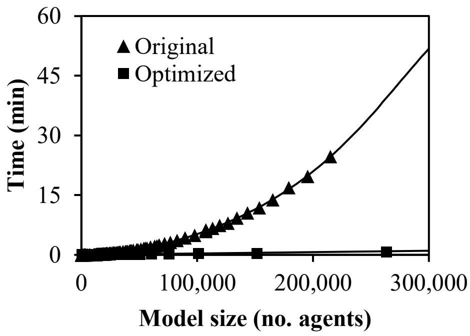

Figure 44: Model size vs. calculation time. Shown at full scale to show the exponential slope of the original unoptimized model.

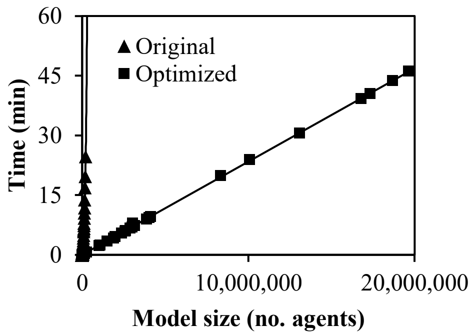

Figure 45: Model size vs. calculation time. Enlarged to show key features of the optimized model.

When speed of execution was required such as when running the genetic algorithm, residential consumers were combined into groups of 250 with business, government, and travel into groups of 100. Thus, the model has 74,000 household agents, 1200 business agents, 9500 government agents, and 1000 travel agents with 85,700 independent customer agents in total. When this speed was not required then the full model of all 20 million agents was used.

4.10 Chapter summary and conclusions

This chapter has laid the foundation for further exploration of satellite markets using the ABSM model. The insights gained from the initial validation will inform subsequent analyses of more specific market scenarios and facilitate the evaluation of various strategies and policies.

The chapter began with a detailed breakdown of the model, including a control structure diagram illustrating the components of the model. The supply side is represented by industry operators and non-industry operators, while the demand side consisted of various customer segments. Operators aim to maximize their own net present value (NPV). Customers made decisions according to the theory of planned behavior, considering factors such as service speed, peer adoption, and service cost.

The implementation of the model was followed by the validation using a generic satellite communications market. A series of tests were conducted to examine the effects of price, elasticity, capacity, and substitute products on revenue, number of subscriptions, and rejected subscriptions. The tests started with a single operator and customer segment and gradually introduced more operators and segments.

The results of the tests demonstrated the behavior of the model under different scenarios. For example, the effect of changing price showed that revenue increased until reaching a maximum, while the number of subscriptions and rejected subscriptions varied based on the willingness to pay and capacity. The effect of changing elasticity highlighted how different elasticity functions affected optimal prices and revenue. The effect of changing capacity demonstrated that revenue increased with capacity, but with diminishing returns.

Overall, the initial validation of the ABSM model using a generic satellite communications market provided valuable insights into the model's behavior and confirmed its alignment with economic theories. The results supported the hypothesis that the model was correctly implemented according to the described assumptions.

Chapter 5

Historical Calibration on the Satellite Phone Market 1995-2005

This chapter describes the selection, implementation, and analysis of a historical test case through which to compare forecasts and actuals. It continues the methodologies, results, and discussion components of this thesis. Due to the lack of historical data for the case of satellite-based internet connection, validating the market model is inherently challenging. Therefore, we want to be able to perform a forecast using the ABSM and compare it to actual historical data. First (5.1 Historical calibration case study identification on page 94), several historical cases were considered for their applicability to the model with the case of satellite phone connection ultimately selected. Next (5.2 Setup of the satellite phone market model on page 98), input parameters and context-specific assumptions for the satellite phone market model are established. Subsequently (5.3 on page 116) the model is executed with direct replication of real-world operator activities with forecasts contrasted against actuals. Then (5.4 Sensitivity analysis on page 122) these results undergo sensitivity analysis to test for the robustness of the solution. The influence of customer size, subscription prices charged, the rollout of substitutes, and operator capacity, along with customer-specific weightings of attitudes, societal norms, and controls are assessed. This gives a near-complete exploration of the input space. Finally (5.5 Chapter summary and conclusions on page 127) we summarize the results to make an assessment on the use of the ABSM for predicting modern satellite internet.

5.1 Historical calibration case study identification

Identifying a relevant case study through which to calibrate the model is an essential step in calibrating the model. We wish to pick an industry and context which matches the modern era of satellite internet as closely as possible. The industries considered are fast food restaurants, car yards, TV advertising, and satellite-phone connection.

We begin by reviewing the satellite internet industry [108], [109]. Operators provide internet connectivity through satellites, providing users with different levels of service based on their needs. Satellite internet providers like SES, Starlink, Amazon Kuiper, and others operate in this global industry, catering to multiple customer segments including households and businesses. The customer distribution tends to cluster in areas where terrestrial connectivity is limited or unavailable. The supply distribution relies on satellites positioned in orbit, covering a specific radius of effect. The industry incurs mostly fixed costs associated with satellite deployment, maintenance, and ground station operations. Customers will typically purchase the product as part of a multi-year subscription and industry timelines are many years long. Fiber optic internet is a key substitute service offering an alternative means of accessing the internet but only if the physical cables have been installed to the user's property.

Fast food restaurants [110], [111] provide quick-service meals to customers. They are known for their convenience, affordability, and standardized menu offerings. As with satellite internet, a few major operators, such as popular chains McDonald's, Burger King, and KFC, compete for dominance. Unlike satellite internet where the product is highly standardized these chains compete on more than just price and instead offer differing types of food and levels of quality. Fast food restaurants could be considered a differentiated oligopoly as opposed to the homogeneous oligopoly of satellite internet [47]. Both industries have substitutes where in the fast-food industry an option could include making food at home, while in comparison, the satellite internet industry faces substitutes in the form of alternative communication technologies such as cellular networks and fiber optic. Home-prepared meals are always an option for fast food customers whereas fiber optic and cellular networks only spread slowly over long periods of time. The frequency of consumption also differs between the two industries. Fast food restaurants typically serve customers multiple times per day, as individuals may visit them for each meal. In contrast, satellite internet subscribers may go years between changing providers or renewing their subscription.

Incorporating fast food restaurants into the ABSM presents certain challenges. From a mechanical standpoint, it is possible to model restaurant densities by treating them as geostationary satellites with known locations and assigning a radius of effect to each. This would involve transforming the global 180 x 360 map into a rectangular region with equivalent dimensions. However, the mobility of customer agents poses a significant challenge in assigning them to specific restaurant locations. Just because someone does not have access to fast food near their residence does not mean they won't become a customer when traveling or when at their workplace. Unlike satellite internet, where users require service at their physical location, fast food customers' preferences and choices can vary greatly, with a greater emphasis on the specific food offerings (e.g., burgers vs. noodles) rather than factors like consumer loyalty or peer influence.

Car yards [112], [113] sell new and used cars to customers. Car yards can be considered as a less suitable analog for satellite-based internet due to their differing product and customer dynamics. While both industries cater to consumers, car yards primarily focus on physical products (cars), whereas satellite-based internet provides a digital service. For the operator, car yards costs have a high degree of per-unit expenses while satellite internet is mostly fixed. In terms of distribution, car yards typically require physical visits to the dealership for test drives and negotiations, while satellite-based internet is accessible remotely. However, they can still be considered to operate with node-model where car purchasers visit a yard which services a district and internet users access their data via a node satellite which services their region. In both industries customers have long-term partnerships with the operator; for internet this is a multi-year ongoing subscription while cars are purchased and then kept for several years. Depending on specific financing options it is also possible that owning a car could be considered akin to a subscription service where the customer makes repeated payments over an extended period.

While car yards could be modelled as geostationary satellites with overlapping regions of influence, again high customer mobility as compared to this region makes modelling them challenging. The differentiated nature of the market also makes consumer decisions hard to model.

TV advertising [114], [115], involves promoting products or services through television commercials, operates in the advertising industry. In this case we wish to assess the business-to-business transactions involved when a TV network sells one of these slots to another business within which that business may advertise a product. This has a very short sale period where a customer may purchase multiple slots each hour. This differs considerably from the multi-year contracts typical of satellite internet. How they are similar is that the TV network only has a finite amount of capacity (minutes of advertising) and they must make significant investments to generate more (launching a new channel with new programming). Capacity is perishable and if not used in each period becomes useful. A satellite can (say) support 100 Mbps in total. If only 60 Mbps are being used at a certain time, then 40 Mbps are being wasted. Similarly, a TV network can sell (say) 10 adverts an hour. If only six are sold, then there are four advert slots that go to waste.

Advertising slots are a relatively homogenous product, making them suitable for consideration using the decision theory approach. However, the distribution mechanism is significantly different. Where in satellite internet the distribution of capacity is important, advertising slots have no direct bearing to real-world geography and therefore TV advertising would not be suitable for testing the location-based aspects of the model. Note that while obviously the TV stations themselves have a zone of influence equivalent to their distribution region, this only affects the value of the TV slot (e.g., larger region of coverage with a high-value demographic would be more valuable to a business purchasing and advertising slot). Therefore, while there are certain similarities ultimately TV slot advertising is not a suitable analogue to satellite-internet.

Finally is satellite-phone connection [25]. This allows users to make calls and access data services using satellite networks, is the best analog for satellite-based internet. The underlying infrastructure and principles of signal transmission through satellites are shared between satellite-phone connections and satellite-based internet. Therefore, the suitability of satellite-phone connection as an analog for satellite-based internet is high. Both industries cater to consumers' need for remote connectivity, especially in areas without reliable terrestrial infrastructure. Both technologies rely on satellites for communication and data transmission. Both act in heterogenous oligopolies with a limited number of operators providing very similar services. Both experience a gradual rollout of substitute services with cell towers of fiber internet. The primary difference lies in the specific service provided, with satellite-phone connections focusing on voice calls and data access for individual devices, while satellite-based internet offers broader internet connectivity to users.

Using the ABSM with the satellite-phone rather than satellite-internet industry is trivial. We have very similar segments with very similar distributions. The mechanism for delivery capacity (orbiting satellites) is identical as well with certain regions being able to support simultaneous users. The unit of capacity is slightly different with phone networks being rated by number of simultaneous calls and satellite internet the total Mbps throughput, but this is a simple matter of changing the units. Substitute service rollout is also very similar with the substitute (phone towers or fiber) starting in cities and growing outwards.

The technological similarities and reliance on satellite infrastructure make satellite-phone connections the closest analog to satellite-based internet. From this analysis it may be concluded that the satellite-phone connection industry is best suited for subsequent analysis. The industry is very closely related to the modern satellite-internet industry under consideration. The historical nature of this industry makes data readily available.

5.2 Setup of the satellite phone market model

The previously described ABSM was set up to represent the historical conditions of satellite-based phone service as they existed between 1995 and 2005. Critical components of the model as well as the historical real-world data which will be compared are presented in the following sections. Operators, customers, and substitute services

5.2.1 Operators

This model considers four satellite operators representing the largest operators by weighted average market share over the 1995-2005 period. Thus, we consider operators that had a large and sustained market influence over the entire simulation, not just at their peak or at the simulation's end. These are Inmarsat (52%), Iridium (26%), Thuraya (10%), and Globalstar (7%) which combined represent 95% of the total market for this period [116].

Inmarsat

Inmarsat was founded in 1979 under the directive of the United Nations to establish and operate a satellite communications network for the maritime community [117]. It was privatized in 1998. Four satellites in geostationary orbit provide global coverage (Figure 46). As such there are some regions which can be covered by more than one satellite: increasing the capacity of those regions. Information on the Inmarsat-2 and Inmarsat-3 satellite buses was not available, but a 10x improvement is assumed for each subsequent generation. Capacity is shown in Figure 47 and simplified as

$$capacity_{inmarsat} = \begin{cases} 4500; & year < 1996 \\ (year - 1996) \cdot 26235 + 4500; & 1996 \leq year \leq 1998 \\ 56970; & 1998 \leq year \end{cases}$$

which is plotted on the same figure. Historical revenues and customer statistics were reconstructed by shareholder reports and news documents of the time [117]–[119]. They as summarized in Figure 48 and Figure 49.

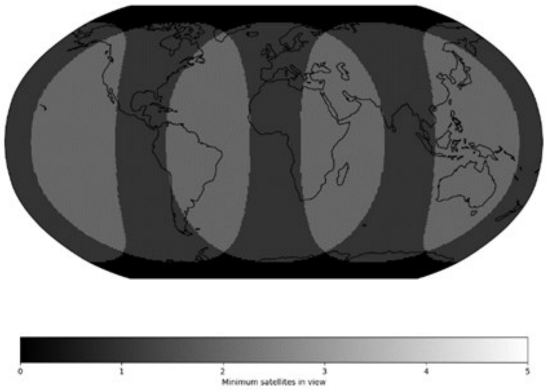

Figure 46: Inmarsat satellite coverage map. As this is a GEO network certain regions are constantly in view of multiple satellites; resulting in effectively double the available capacity.

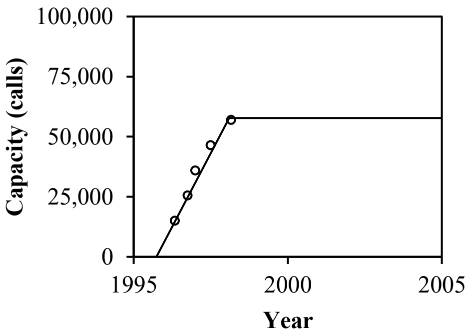

Figure 47: Inmarsat total system capacity. Launched capacity is given with the open circles with the equation-fit results given by the line. Reconstructed from launch statistics [120].

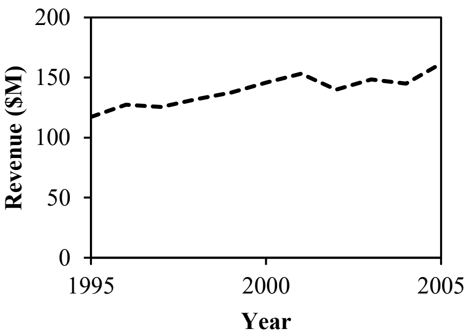

Figure 48: Inmarsat revenue for satellite phone service only. Note that this includes non-phone subscribers. Reconstructed from shareholder reports and news documents [117]–[119]. In USD for the year 2000.

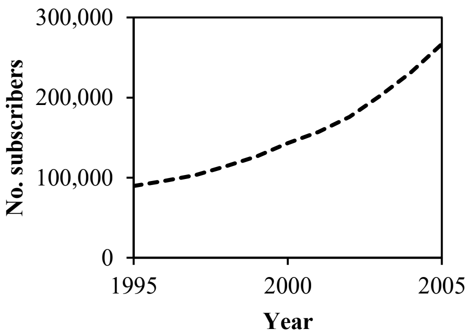

Figure 49: Inmarsat subscription figures. The operator shows steady growth. Note that this includes non-phone subscribers. Reconstructed from shareholder reports and news documents [117]–[119].

Iridium

Conceived in 1987 and developed by Motorola from 1993, the Iridium constellation became operational in 1998. At the time, it was the largest satellite constellation ever launched. While successful from an engineering standpoint, Iridium filed for bankruptcy in 1998 due to lower than expected service uptake [25]. Iridium was originally planned as a constellation of 77 satellites (reminiscent of the atomic structure of the element Iridium) although the final constellation used 66 satellites in a Walker star configuration with 6 orbits of 11 satellites each. The minimum number of satellites viewable at any point is provided in Figure 50. Each satellite had a capacity of 1100 concurrent phone calls, giving a total capacity of 72,600 simultaneous calls. Not all users were expected to be using the full capacity at all times and is was expected to be more than sufficient for the predicted three million users [9]. Total capacity of the system was generated by plotting satellite launches over time and is shown in Figure 51 by plotting satellite launches over time. It has been simplified as

$$capacity_{iridium} = \begin{cases} 0; & year < 1997 \\ (year - 1997) \cdot 65772; & 1997 \leq year < 1998 \\ (year - 1998) \cdot 1707 + 65772; & 1998 \leq year < 2002 \\ 72600; & 2002 \leq year \end{cases}$$

and plotted on the same figure. Historical revenues and customer statistics were reconstructed by shareholder reports and news documents of the time [121]–[124]. They are summarized in Figure 52 and Figure 53. According to their press releases Iridium had hoped to change each customer \$3,000/year however analysis of their financial documents and dividing the total revenue by the total number of customers reveals they were only receiving an average of \$770/year. In this case a customer represents a single handset, so that if there was (say) a mine site which purchased ten handsets this would count as ten customers.

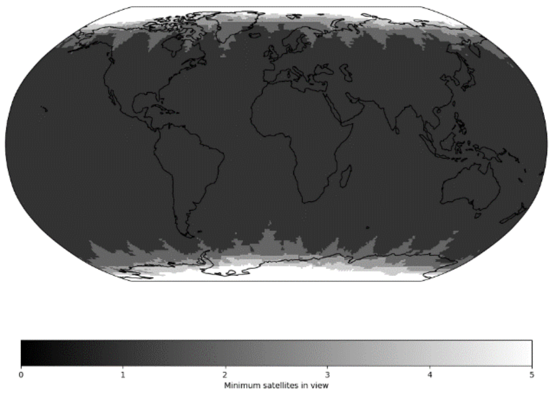

Figure 50: Iridium satellite coverage map. As the constellation uses multiple satellites in polar orbits there is more permanent capacity at the poles and less around the equator.

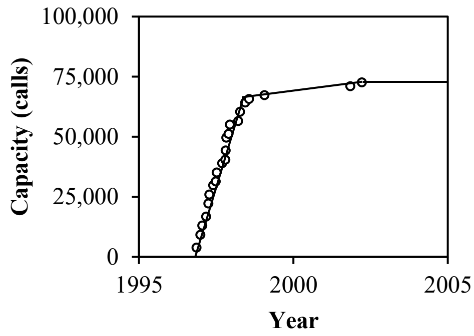

Figure 51: Iridium total system capacity. Launched capacity is given with the open circles with the equation-fit results given by the line. Note that since the constellation required all 66 satellites to become active the model assumes that customers are unable to buy this capacity until the full constellation has been launched. Reconstructed from [123].

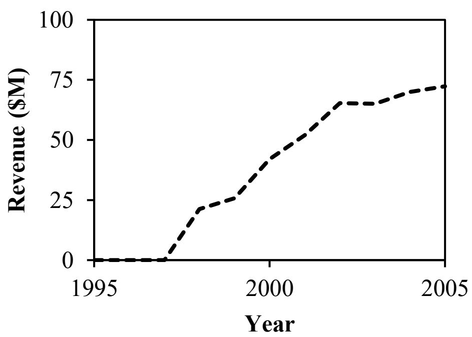

Figure 52: Reconstructed Iridium revenue. Reconstructed from shareholder reports and news documents [121]–[124]. In USD for the year 2000.

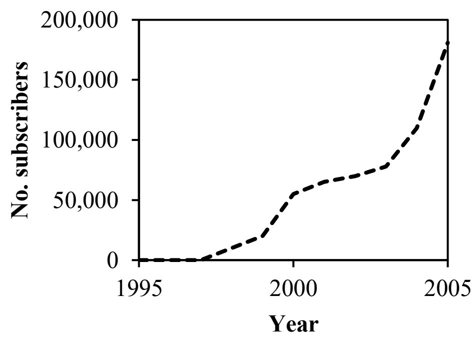

Figure 53: Reconstructed Iridium subscription figures. Reconstructed from shareholder reports and news documents [121]–[124].

Thuraya

Thuraya is a regional mobile satellite service provider based in the United Arab Emirates which (over the 1995-2005 period) provided phone connectivity through a single high-throughput satellite in geostationary orbit (Figure 54). Thuraya was founded in 1997 with its satellite launched in 2003 [125]. The satellite can provide 13,750 simultaneous phone calls. Capacity is shown in Figure 55 and summarized by the equation

$$capacity_{thuraya} = \begin{cases} 0; & year < 2003 \\ 13750; & 2003 \leq year \end{cases}$$

which is plotted on the same figure. Historical revenues and customer statistics were reconstructed by shareholder reports and news documents of the time [126]–[128]. They as summarized in Figure 56 and Figure 57.

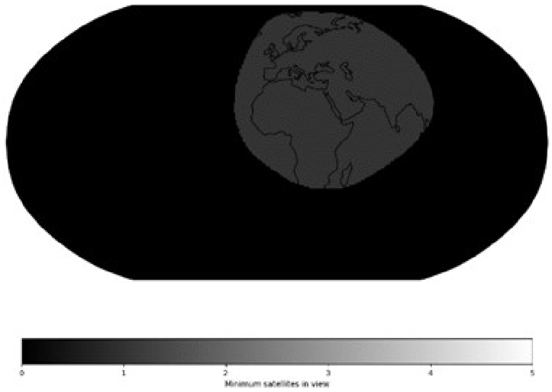

Figure 54: Thuraya satellite coverage map. As a single GEO satellite over the middle east capacity is circular and centered over the sub satellite point.

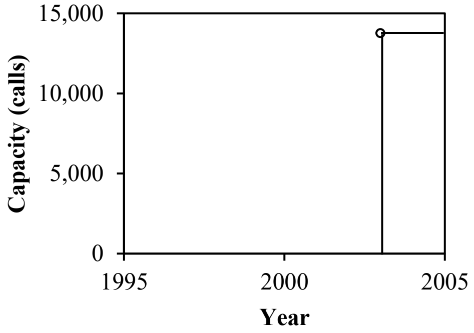

Figure 55: Thuraya total system capacity. Launched capacity is given with the open circles with the equation-fit results given by the line. Reconstructed from [127]. All capacity is available after launch of the single satellite.

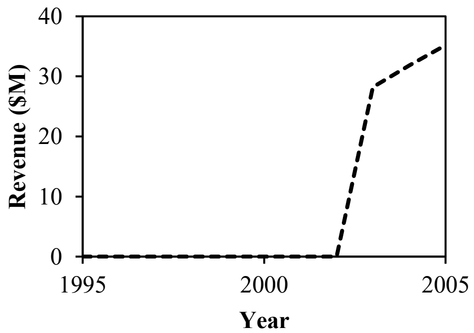

Figure 56: Reconstructed Thuraya revenue. Reconstructed from shareholder reports and news documents [126]–[128]. In USD for the year 2000.

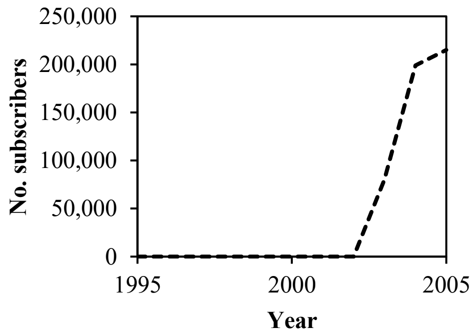

Figure 57: Reconstructed Thuraya subscription figures. Reconstructed from shareholder reports and news documents [126]–[128].

Globalstar

Globalstar was created in 1991 as a partnership between Loral Corporation and Qualcomm with the support of Alcatel, AirToutch, Deutsche Aerospace, Hyundai, and Vodafone. It began commercial service in 1999. It uses 40 satellites to provide both internet and telephone connection (Figure 58). Globalstar satellites are simple ‘bent pipe’ systems which do not use intrasatellite links but must instead directly connect to gateway terminals. The system has a total capacity of 2,400,000 calls. Plotting satellite launches (Figure 59) gives total capacity of the system over time [129], simplified using the equation

$$capacity_{globalstar} = \begin{cases} 0; & year < 1998 \\ (year - 1998) \cdot 1200000; & 1998 \leq year \leq 2000 \\ 2400000; & 2000 \leq year \end{cases}$$

also plotted on the graph. Historical revenues and customer statistics were reconstructed from shareholder reports and news documents of the time [130]–[132]. They as summarized in Figure 60 and Figure 61.

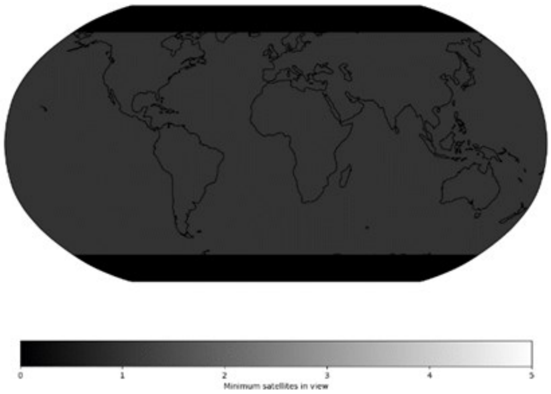

Figure 58: Globalstar satellite coverage map. The constellation uses inclined circular orbits with even spread across most of the Earth but no polar capacity.

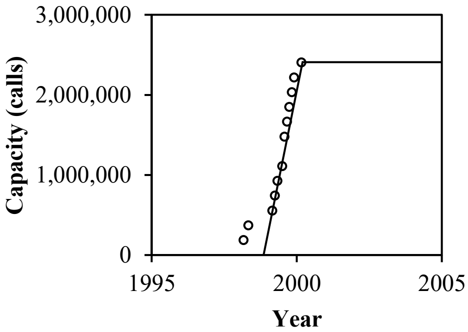

Figure 59: Globalstar total system capacity. Launched capacity is given with the open circles with the equation-fit results given by the line. Reconstructed from [129].

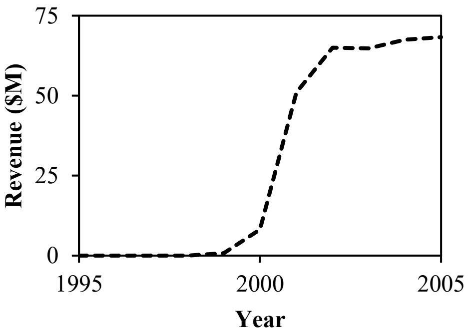

Figure 60: Reconstructed Globalstar revenue. Reconstructed from shareholder reports and news documents [130]–[132]. In USD for the year 2000.

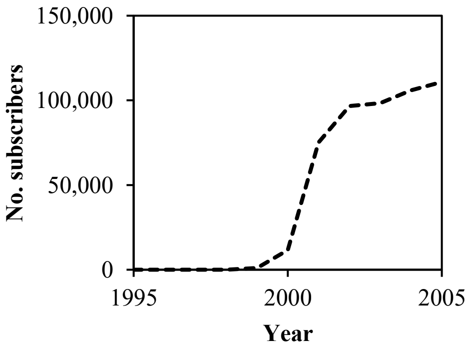

Figure 61: Reconstructed Globalstar subscription figures. Reconstructed from shareholder reports and news documents [130]–[132].

5.2.2 Customers

Several segments are identified and simulated in this analysis. The primary segments were identified by Guerster et al. [133] with their findings presented in Figure 62. Rather than including all the segments, they have been grouped into the four major categories of households, travel, industry, and government.

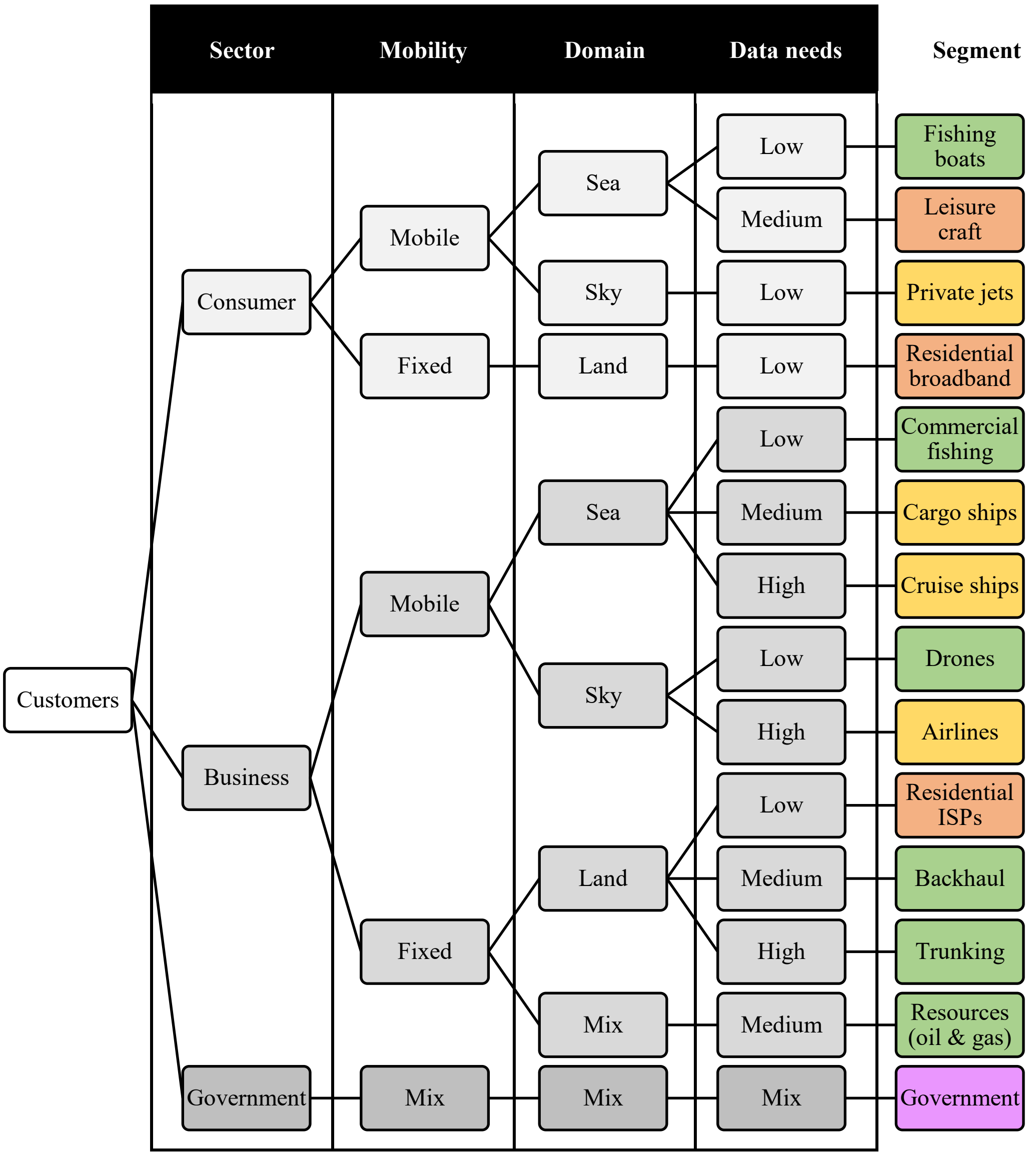

Figure 62: Full customer segmentation as presented in [133] with simplified segments used in this analysis identified as households (orange), travel (yellow), business (green), and government (purple). Consumers are segmented based on their general sector (B2C, B2B, and B2G), their relative mobility, what domain they operate in, and their data needs. This not only identifies the consumers but also characterizes what sort of products they demand and how difficult it is to supply them.

Households

The household market was created by combining individual residences with a larger business which may group multiple households together to purchase and sell capacity as a single block (the equivalent of an internet service provider for satellite internet). Since this larger provider is merely grouping together lots of residential consumers it is assumed that the behaviors of this larger segment are just the summation of the behaviors of the individual consumers and thus can be treated equivalently. Residential customers address single phone users using the service to place calls from regions of limited connectivity. This could include users engaged in outdoor remote adventure activities as well as those needing it for more routine uses of connecting with friends and family. Due to this segment's low mobility and low usage rate a suitably high overbooking factor of ten was selected.

Globally, the average household size is 4.9 persons [134]. If we assume that this number holds true across the world (a simplification) and that each household would purchase at most one satellite phone, then it is trivial to convert the world population into potential household customers. From 1995 to 2005 the world population grew at an average rate of 1.32% per year, starting at 5.744 billion and finishing at 6.542 billion. Of these, however, we are only interested in those not living within major cities as these will effectively always have alternate forms of communication. This translates to a household segment size of

$$segmentSize_{households} = 1.62 \times 10^5 \cdot year - 3.12 \times 10^8$$

distributed according to world rural population density using the plot shown in Figure 63.

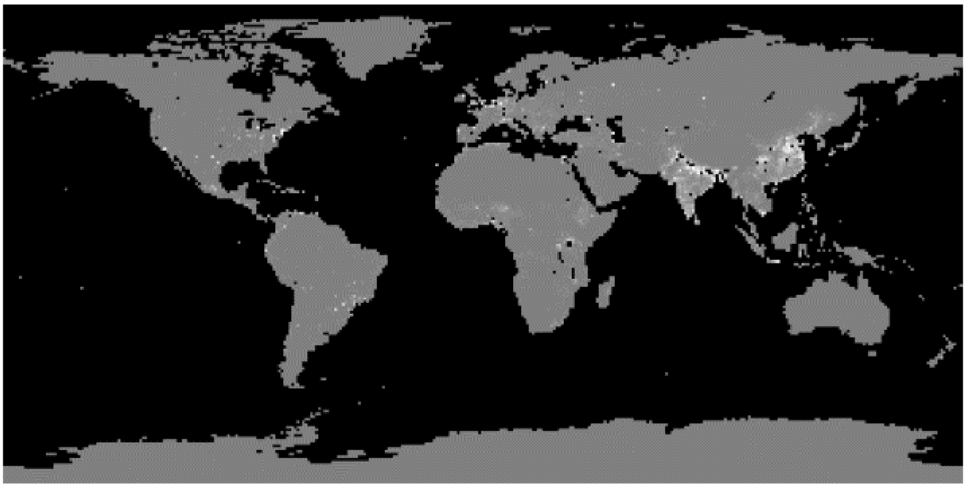

Figure 63: World rural population density distribution in the year 2000. Adapted from [135].

WTP is based on individual income for each customer agent. From 1981 to 2008 US households spent an average of 2.3% of income on telephones and telephone services with remarkable consistency [136]. This suggests that a household that makes \$100/year would be willing to spend \$2.50/year on the satellite telephone service while one that earns \$100,000 would be willing to spend \$2,500/year. Hellebrandt et al. [137] provides a location-based breakdown of household income. By using these location-based values as average income, assuming income follows the same exponential distribution as before, and that the 2.3% figure holds then we see WTP is given by

$$WTP_{households} = e^{\left(\frac{\ln(0.5)}{income \cdot 2.3\%}\right) \cdot price}.$$

As a reminder, WTP is defined within the codebase as the proportion of households who are willing to purchase the product at a given price which is why price is an input to the equation. For example, in a region where the income is \$50,000/year and the price for the product is \$1000/year we can calculate

$$WTP_{exampleA} = e^{\left(\frac{ln(0.5)}{\$100{,}000/year \cdot 2.3\%}\right) \cdot \$1000/year} = 54.7\%,$$

or that just over half the population would be willing to purchase the service. If instead the price of the product was just \$500 then we would calculate

$$WTP_{exampleB} = e^{\left(\frac{ln(0.5)}{\$100{,}000/year \cdot 2.3\%}\right) \cdot \$500/year} = 73.9\%,$$

or that almost three quarters of the population would be willing to purchase the service.

When the agents are initialized, this equation is effectively being used in reverse to assign a fixed maximum price they are willing to pay for the service. All else equal, the lower the offer price relative to that maximum willingness to pay price the more likely they will select that product. Note that they will never purchase a product more expensive than this maximum willingness to pay.

Characteristics for the subjective norm decision influence are informed by adoption rate statistics from Ritchie et al. [138]. They tracked the adoption of various technologies from flushing toilets to desktop computers to assess how fast consumers were willing to move to a new technology. Their results closely mirror the normal distribution described by Rogers [72]. Note that the Ritchie et al. [138] study does not account for differences in relative income, only the location of the individual deciding to adopt the product. Region-level statistics for the adoption of mobile phones is shown in Figure 64.

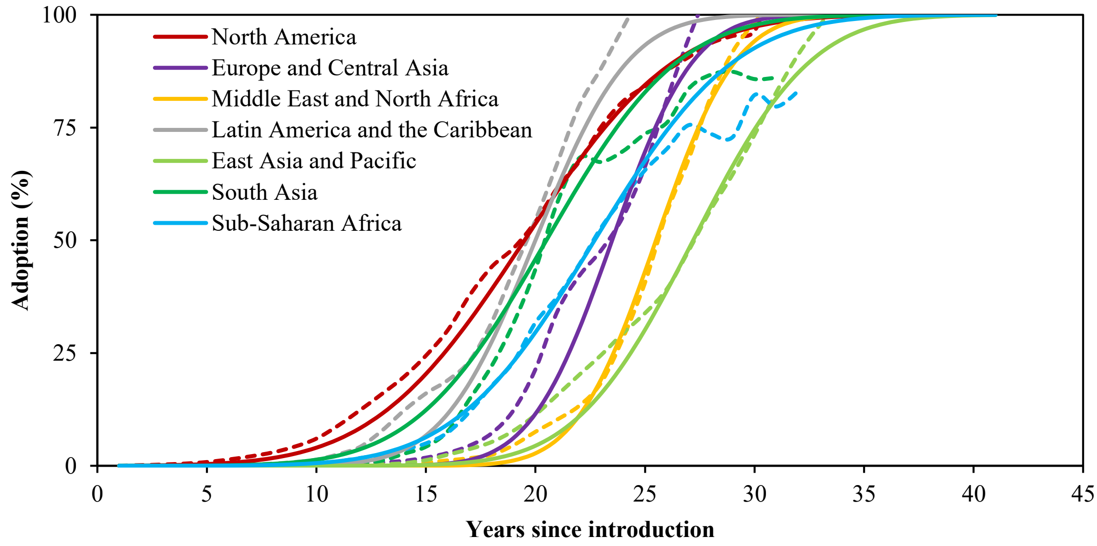

Figure 64: Region-dependent adoption rate for the mobile phone, showing historic (dashed) and fitted (solid) data.

From the Ritchie et al. [138] study we see that North American customers are among the first to receive the new technology and the innovator group become quick to adopt it, but it takes some time to become put into major use. American innovators take 11 years, early adopters 17 years, early majority 23 years, late majority 28, and laggards at 34 years. This is characterized by the normal distribution

$$adoption_{NorthAmerica} = N(19.5, 5.43^2) \text{ years.}$$

In contrast, the Middle East and North Africa take some time for the service to reach the early adopters but then take off very quickly. Middle East innovators take 18 years, early adopters 23 years, early majority 26 years, late majority 29, and laggards at just 28. This is characterized by the normal distribution

$$adoption_{MiddleEast} = N(25.5, 2.87^2) \text{ years.}$$

These region-level statistics were used to initialize the decision rate norm. A low standard deviation implies that customers are highly influenced by their peers; when your neighbor gets a satellite phone so will you. On the other hand, a high standard deviation implies that the customers are more individualistic and instead will only switch services when they see a clear personal benefit. A low mean adoption time implies that the group can quickly appreciate the benefits of the new technology while a low one means the opposite. All segments use the same location-based adoption rate statistics as a starting point. The household segment employs no scaling to adoption rate since the Ritchie et al. [138] database was directly constructed from this same segment.

Irani et al's empirical studies on internet adoption using the theory of planned behavior [139] [149] provide weightings for the importance of each factor on the decision to adopt. From this study attitude (i.e., quality of service) was weighted at 0.307, peer influence at 0.360, and price at 0.331.

The final factor to consider for residential household consumers is the substitution rate. We assume that if given the option, 99% of these consumers would purchase a cellphone type service. The 1% who do not represent those who regularly engage in travel-type activities which intentionally go 'off the grid'. What this means is that if the cellphone service is available to a customer who is currently using a satellite phone, then there is a 99% chance, they will switch from the satellite service to the cell phone service. If the customer is not currently using a satellite phone, then (for 99% of these unallocated customers) we are effectively taking away their decision to purchase a satellite phone and replace it with the option to buy a cellphone instead. This model is not concerned with whether a given individual buys a cellphone, only that they do not buy a satellite phone.

Travel

The travel segment is comprised of those users using the sky and ocean to transport or access passengers and cargo. Airlines services provide connectivity to the passengers and crew onboard a commercial aircraft, however since many satellite phones are unable to penetrate the hull (especially during the early era of lower-powered satellite telecommunications) this was only a minor segment and has been disregarded for this analysis. Private boats and cargo ships often can use this connectivity to update the mainland on the status of their shipment and to connect the crew to friends and family. Cruise ships have similar characteristics but with significant passenger count demanding this phone connectivity.

Due to the high mobility of this segment an appropriately high amount of capacity must be reserved for each customer. Because the user can move between locations each of those locations must have some reserved capacity in the case that that user moves between them; for example, a ship crossing from the Indian Ocean to the Pacific which is being covered by a different satellite. This will be modelled with an overbooking factor of 1; that is each time we sell one unit of capacity to a user in a region, a full unit must be reserved. This assumes that multiple users will not be in the same region demanding the same service or that if such an event occurs then not everyone will be demanding this service at the same time. In the case of highly mobile travel customers which still occasionally cluster around shipping lanes and major ports, this makes an overbooking factor of one appropriately conservative.

Segment size is based on the world's merchant fleet from [140], [141]. Assuming each vessel purchases only a single phone then

$$size_{travel} = 676 \cdot year - 1.27 \cdot 10^6.$$

Winebrake [142] reports fleet travel for the year 2000 (Figure 65), acting as our template for customer distribution.

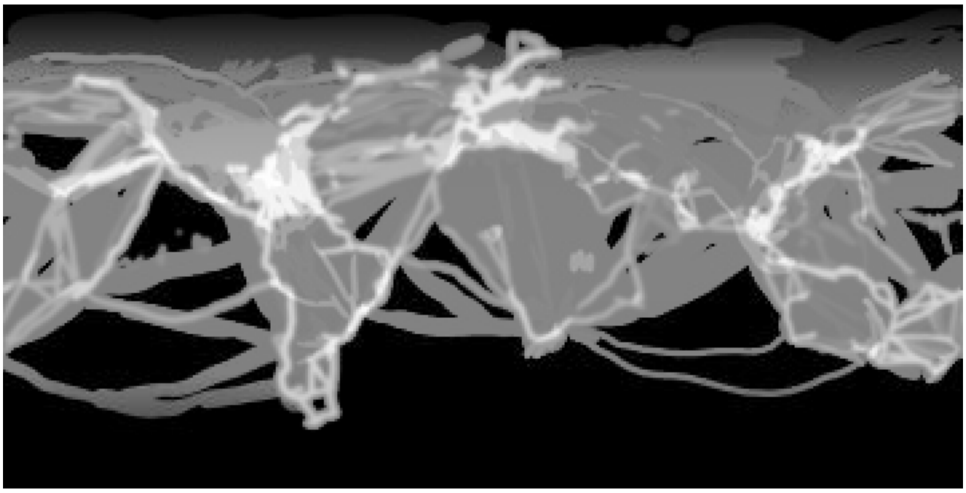

Figure 65: Flight paths and shipping traffic density distribution.

Willingness to pay statistics were inferred by examining company reports. If we consider the 2003 Maersk financial report [143] we see a net revenue of $12.82 billion for their directly-shipping-related activities, at which point they had 57 ships. This corresponds to a revenue of $225 million per ship. This could be considered near the top of the willingness-to-pay curve. If we assume that maritime operators are willing to spend a similar fraction of income as residential users (2.3%) this would suggest that operators would be willing to pay up to $5 million per ship for their communications needs. We would expect that, as a portion of total expenditure, businesses will actually spend far less than an household on their communications. Thus, we assume of this, only 1% might end up going toward the phone connection with the rest going into other communications technology (such as charts and navigational equipment) as well as other context-specific applications. This gives a final annual cost of $50,000 per ship. Closer to the bottom we have smaller vessels for fishing and transport. In the EU, GPD per worker in the maritime industry was 1.7x that of that of their non-maritime equivalent. In the year 2000 GDP per worker in the EU was $75,664 which implies that a maritime worker had an annual income of $128,628. Assuming the average number of crew per ship is 10, if 2.3% of this were spent on phone service for the vessel then the lowest operators would be paying is $29,584. In this analysis we will continue with the location-based price modification; assuming a WTP given by

$$WTP_{travel} = e^{\left(\frac{\ln(0.5)}{income}\right) \cdot price}$$

which implies that the cost for connectivity is roughly the same cost as an individual crew member. Obviously some of these travel customers will spend much more which is accounted for by the exponential nature of the WTP distribution.

As described by Papadimitriou et al. [144], the maritime industry has long been an adopter of new technologies especially those which rely on space segments. As such the travel segments modify the initial adoption rate statistics to account for users, on average, adopting space-based technologies twice as fast as their land-based counterparts. Similarly, they have a very low substitution rate of 5%. This represents that this highly mobile segment is unlikely to switch to ground-based mobile phone towers even if these become available.

Business

The business segment covers a large range of industries that use phone coverage to fulfill consumer demand and conduct operations. For those requiring remote phone connection the major group is resource extraction (of oil, gas, minerals, and fish) which tend to stay within a limited area that is predictable by considering where these resources are most tightly clustered. Industry users are often large and require reliable service, thus disincentivizing operators to overbook. As such an overbooking factor of one (no overbooking) will be used.

The size of this segment is estimated by taking the total number of offshore rigs and remote mining operations and then assuming that each wish to purchase an average of five phones per worksite. Although this does not encompass all users of the technology it is assumed that this is a good-enough approximation. Using satellite-imagery, Maus et al. [145] provide an estimate of 44,929 distinct mining operations for the year 2022. The National Institute for Occupational Safety and Health [146] uses employment records to assess the number of mines in operation from 1983 to 2021. Statista provides a global distribution of offshore rigs [147] and places the number of rigs in 2018 at 1,332. Combining all these together and accounting for five phones per operations region this gives a size of

$$size_{business} = 5.65 \times 10^2 \cdot year - 1.03 \times 10^6.$$

Maus et al. [145] provide a comprehensive dataset of mining areas while oil and gas platforms were mapped by the Colorado School of Mines [148]. These charts were used as a basis for our own distribution Figure 66.

Figure 66: Business distribution.

Willingness to pay statistics were inferred by examining company reports. Considering the 2001 BHP Billiton report [149], a mining operator with significant remote operations, they experience a net cash flow from mining operations of \$4.09 billion across forty sites. If we continue with our five-phones-per-site value from before and the 2.3% on communications of which 10% is phones this suggests the willingness-to-pay per connection is on the order of \$230,000. Smaller operations would have a similar purchasing power to that of their workers. The average number of workers on a smaller mine site is seven [150]. In 2001 the US GDP per worker in the mining industry was \$285,000 [151]. Keeping the 2.3% value this would suggest that this lower segment of operators would be willing to pay \$9,170 per connection. Using these results as a guide and continuing with location-based price modification gives

$$WTP_{business} = e^{\left(\frac{\ln(0.5)}{3 \cdot income}\right) \cdot price}.$$

Businesses show a range of attitudes towards new technology with some being early to adopt while others lag using tried and tested techniques. With this uncertainty the adoption rate statistics will not be modified from the initial datum. As these customers are largely immobile a high substitution rate of 75% will be used.

Government

The final segment being considered is government. Government is a very broad user segment with aspects of the other three. This includes military users who may employ commercial satellites to achieve connectivity when operating in foreign operations. The segment is often characterized by unique contracting structures and security requirements [152]. Like industry, government customers are demanding and an overbooking factor of one (no overbooking) will be used. The size of this segment is hard to analysis. Globally, 21.3% of workers are employed in the government sector [153]. The armed forces in both combat and peace operations may need one satellite phone per squadron, while other segments such as administrative staff and public-school teachers need no such resource. According to Brock [154], segments that do need this resource (defense, international relations, and environment) comprise just of 4.65% of government employees. Of these a single phone can be used by multiple users, and we will assume a 1:100 ratio of phones to employees. Assuming that these statistics hold true for the segment and using population size from [155] then total segment size is given by

$$size_{government} = 7.77 \times 10^3 \cdot year - 1.49 \times 10^7.$$

This sector has a significant range during engagement with domestic (e.g., environmental monitoring), foreign (e.g., aid), and transport-related (e.g., navy sailing across the ocean) activities. Distribution will therefore be comprised of population and maritime traffic distributions (Figure 67).

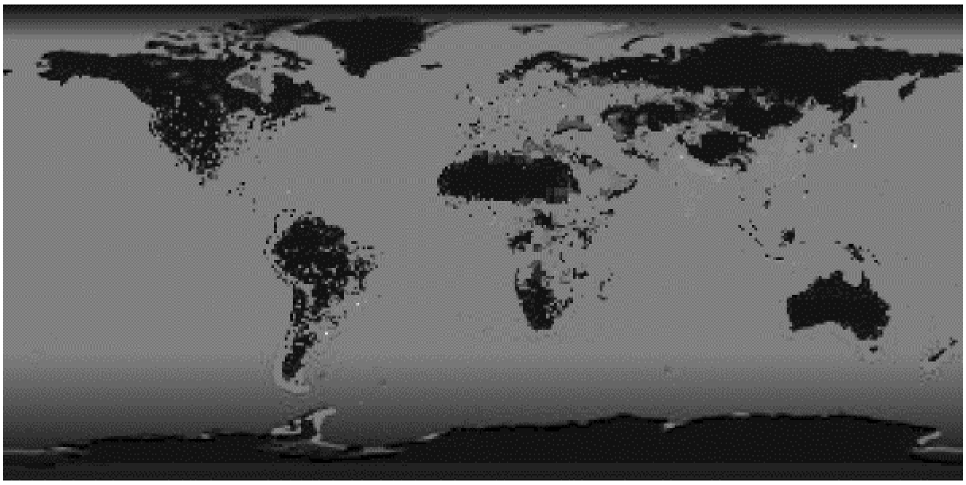

Figure 67: Government distribution.

Government budgets follow a different demand structure than for residential or business consumers. Depending on the country, department, and time of year governments may be either very frugal or very wasteful (“use it or lose it”) with their spending [156]. Government-specific studies in India [157] and the US [158] where government communications procurement costs are contrasted with commercial procurement suggest a rate of roughly double industry cost is appropriate. Furthermore, by assuming that government discretionary spending follows a distribution similar to their GDP per capita (a reasonable assumption) we can suggest a WTP curve of

$$WTP_{government} = e^{\left(\frac{\ln(0.5)}{2\cdot income}\right)\cdot price}.$$

Governments are slow to adopt new technology, taking longer to recognize its potential benefit and longer to assess the technology for security vulnerabilities [159]. Time to adopt has been doubled from that of the datum. This segment used a mixture of mobile and non-mobile solutions. Even in cases where cell towers could be utilized, such as when government workers are present in another nation’s territory, use of the foreign cell service may be undesirable. A 25% substitution rate will be used. As before, this implies that if cellular service is available then 25% of the current satellite phone subscribers will switch to the cellular service. Additionally, 25% of those who would have ever used satellite instead will chose to purchase a cellular subscription.

5.2.3 Substitute service

The primary substitute service being considered is cell phones which rely on the rollout of phone towers. Since data regarding when the towers were constructed is not available a substitute statistic is created by considering the 2023 status of 2G and 5G towers. The 'G'in 2G and 5G is an indication of the generation of the communication technology with 2G established 1991, followed by 3G (2001), 4G (2009), and 5G (2019). Rather than using historical data to look back in time, instead we use the status of these technologies and extrapolate backwards. A reader familiar with astronomy is invited to draw parallels with how we can look 'backwards' in time by looking at galaxies progressively farther and farther away. In this case we consider the present (2023) status of the very new 5G technology (Figure 68) to be a good analogue to the 1995 status of cellphone towers. In both cases, only major population centers have access to the latest technology. We assume the final cellphone tower distribution in 2005 to be identical to the one that exists today with 2G (Figure 69). Linearly interpolating between the two gives a good-enough approximation for the rollout of cell phone towers over the period of interest.

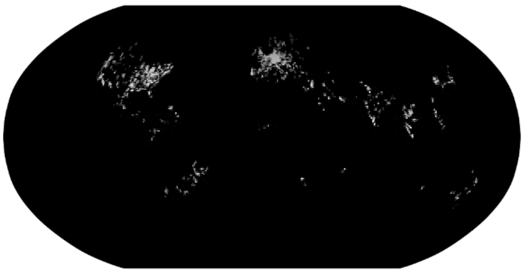

Figure 68: 5G availability, assumed to be equivalent to the 1995 cell phone tower coverage map. Capacity is tightly clustered around cities and major population centers.

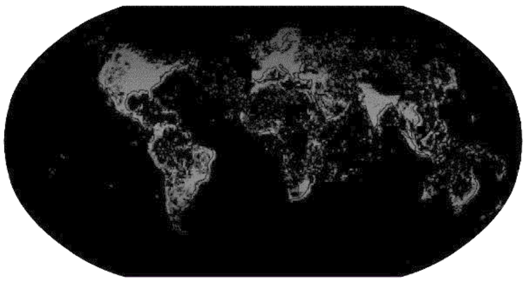

Figure 69: 2G availability, assumed to be equivalent to the 2005 cell phone tower coverage map. Capacity has spread considerably but is still restricted to land-based regions.

5.3 Original uncalibrated results

The ABSM was run for a ten-year simulation with prices fixed at their average actual values. Over the period, Inmarsat charged an average of $796/customer/year, Iridium $835/customer/year, Thuraya $245/customer/year, and Globalstar $700/customer/year.

Initially the model was run without calibration with results shown in Figure 70 to Figure 77. Weighted mean absolute percentage error (WMAPE) are shown for each.

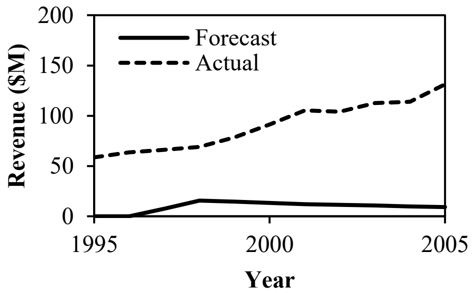

Figure 70: Uncalibrated Inmarsat forecasted and actual revenue. WMAPE = 89.5%, this is in the inaccurate forecasting region.

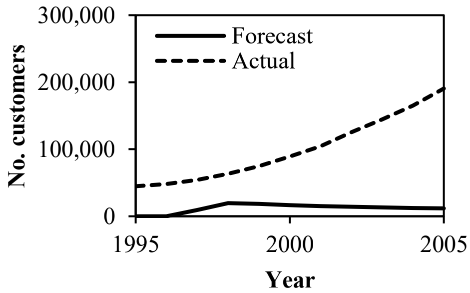

Figure 71: Uncalibrated Inmarsat forecasted and actual customer subscriptions. WMAPE = 88.2%, this is in the inaccurate forecasting region.

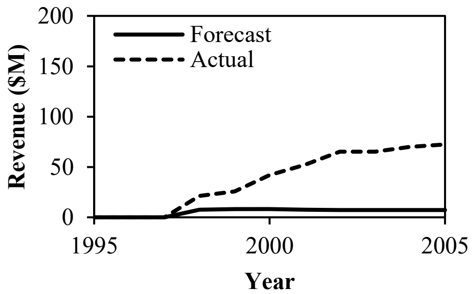

Figure 72: Uncalibrated Iridium forecasted and actual revenue. WMAPE = 85.4%, this is in the inaccurate forecasting region.

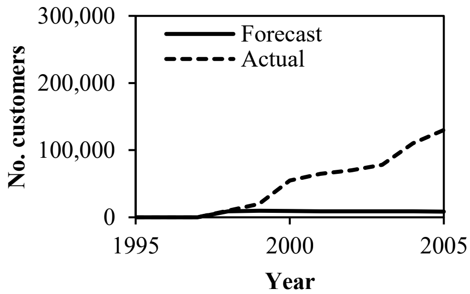

Figure 73: Uncalibrated Iridium forecasted and actual customer subscriptions. WMAPE = 86.5%, this is in the inaccurate forecasting region.

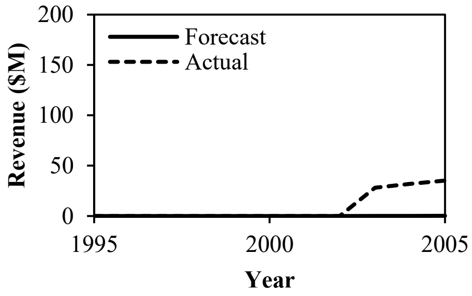

Figure 74: Uncalibrated Thuraya forecasted and actual revenue. WMAPE = 99.5%, this is in the inaccurate forecasting region.

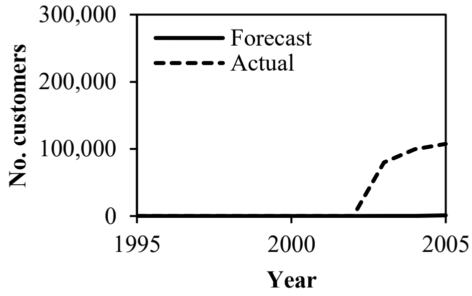

Figure 75: Uncalibrated Thuraya forecasted and actual customer subscriptions. WMAPE = 99.6%, this is in the inaccurate forecasting region.

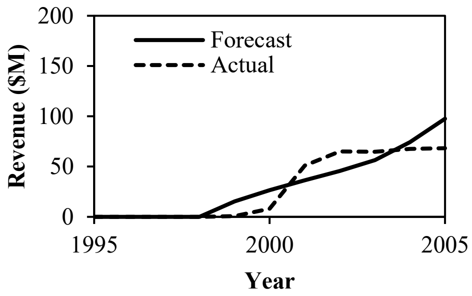

Figure 76: Uncalibrated Globalstar forecasted and actual revenue. WMAPE = 34.3%, this is in the reasonable forecasting region.

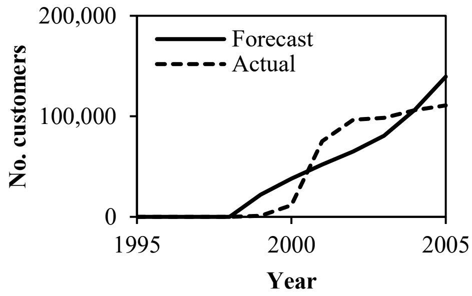

Figure 77: Uncalibrated Globalstar forecasted and actual customer subscriptions. WMAPE = 38.6%, this is in the reasonable forecasting region.

Overall, the uncalibrated model performed very poorly with an average WMAPE of 77.7%. This falls well within the inaccurate forecasting (>50%) region defined by [75]. Clearly significant calibration is required.

While all forecasts performed poorly Thuraya deserves additional mention. The forecast predicts around 1000 people purchasing the service as compared to the 172,000 actuals. WMAPE was 99.6%. From the theory of planned behavior, it appears that our customer agents were hesitant toward purchasing the product. With respect to attitude (individual utility) they were not aware of the benefits of the service and even if they were didn't act upon this. Subjective norms such as the influence of peers and the time that the product has been on the market for are understandably very low at the start of the simulation as none of their peers have yet adopted the product to influence each other (a 'chicken-and-egg' scenario). Price also appears to be underweighted as despite them having a price almost three times lower than the next cheapest competitor almost nobody chose the service.

5.4 Calibrated results

The next step was calibration. Obviously with enough knobs we could even replicate random noise, so to avoid this most parameters were fixed, and others only allowed to vary within a certain range.

- Income remained fixed but proportion of this income which could be spend on internet was allowed to vary. For example, we could change the proportion of a \$50,000/year income spent on communications from 2.3% to 3.0% but would not be able to modify the \$50,000/year income amount. This was fixed from 0.5% of income (representing the action of people purchasing multiple communications services and thus needing to reserve some budget) to 4.0% (representing the action of people understanding that sometimes you need to pay more for satellite connection than a regular one).
- Relative weightings for the decision theory of planned behavior were allowed to vary by 10% either way. That is if attitude, norms, and controls were 0.5, 0.1, and 0.4 they could only move up and down by 0.1 each (while still all adding to 1).
- The influence of adoption time was also only varied by 50%. That is, if people tend to adopt the product faster or slower than would be predicted solely by their country of origin. Note that segment-specific adoption rates remain fixed.
- Importantly, operator-specific calibration was disallowed; that is we are not able to adjust the parameters of each operator separately and can only adjust customer properties. This means that all results are as a direct result of the operator-specific fundamentals rather than an ill-defined and irreproducible 'scaling factor'. Note that when compared to a study that only considers one operator (such as [80]) this means that our model will almost certainly produce a worse WMAPE. It's easy to adjust enough knobs to fit one operator, it is hard to do the same for multiple operators if you can only calibrate the customers.
- All other factors (segment sizes, reserved capacity, rate of switching to cellular, etc.) were kept fixed.

Calibration was done with the goal of minimizing WMAPE and matching the general shape of the curves. This was done manually over multiple simulations with the intent on keeping weightings realistic rather than simply producing the lowest-possible forecast.

Calibration resulted in the following changes:

- Customers' willingness to pay has doubled. That is, customers who purchase satellite telephones may be aware that the service should inherently cost more than a regular connection. This could also imply that such customers are typically better-off than their non-satellite-phone-buying counterparts. Both are valid interpretations.
- Relative weightings from the decision theory of planned behavior remained relatively unchanged.
  - Service quality influence of 0.307. This value is taken directly from Irani et al. [149].
  - Price influence of 0.331. This value is taken directly from Irani et al. [149] and remained unmodified.
  - Peer influence of 0.100. Irani et al's [149] original value of 0.360 needed to be reduced. The network size in our model (a full 1° x 1° region) was very large compared with the more town-focused sizes in the original study. The value is also partially incorporated into the adoption modifier and stickiness values.
- Adoption modifier of -25%. This means that customers tended to adopt the technology 25% faster than historical data for their region. For example, if a typical user in Europe takes 4 years to consider buying a mobile phone after they are introduced to their local market, then an equivalent European user would take only 3 years to consider buying a satellite phone. Note that the satellite phone users are a self-selecting group that is more able to recognize the importance and need for the technology, therefore giving the faster adoption time. Location and segment-based modifiers are still present, thus if we knew the user was government-related we could estimate an extra four months (on average) to adopt while if it was industry, it would be four months less.

An additional function also needed to be implemented which allowed customers who were already subscribed to a certain operator also able to monitor the pricing of other operators. Customers were still resistant to changing operators (as this would require purchasing a new physical device) but would be prompted to reconsider their subscription choices if a new product was available at a cost less than half of their current subscription. As an example, let us say that operators A and B are selling identical phone plans for $100/year and $90/year. Our customer is currently subscribed to plan A. While plan B might be better, they're already subscribed to plan A and the $10/year benefit is not worth the effort of switching services. That is, there are lock-in contracts and switching costs. Now, if operator C decides to enter the market and sell the phone plan for $30/year our original customer notices this price drop and reconsiders all their options (or in terms of code, retriggers the theory of planned behavior routine which assesses products by their utility, peer influence, and cost). In response the customer switches to plan C. Again, this does not guarantee that the customer will switch but just prompts them to think that it might be an option, so another possibility is that they again keep with the original operator A and do nothing.

With these calibrations implemented, plots of the updated forecasts are shown in Figure 78 to Figure 85. 50 simulations were run with input parameters sampled randomly ±10% from the datum using a uniform random distribution. Error bars show one standard deviation from the mean.

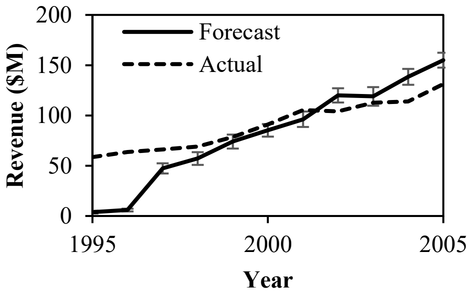

Figure 78: Calibrated Inmarsat forecasted and actual revenue. WMAPE = 23.4%, this is in the good forecasting region.

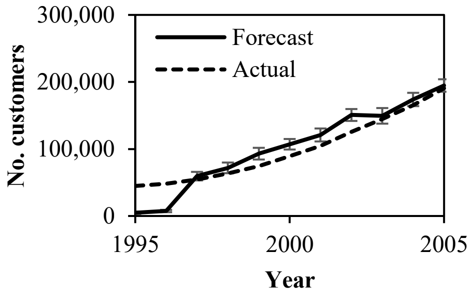

Figure 79: Calibrated Inmarsat forecasted and actual customer subscriptions. WMAPE = 17.1%, this is in the good forecasting region.

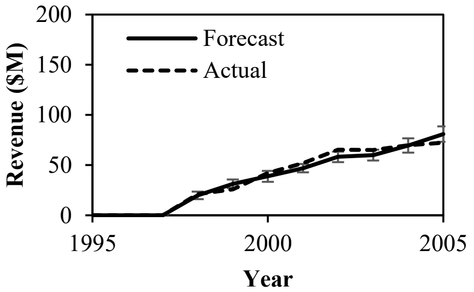

Figure 80: Calibrated Iridium forecasted and actual revenue. WMAPE = 8.8%, this is in the highly accurate forecasting region.

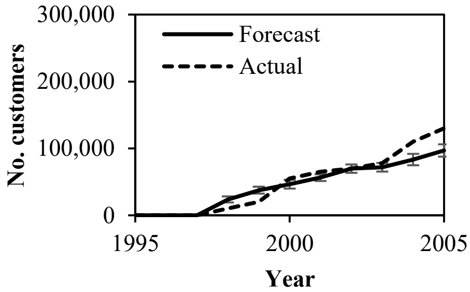

Figure 81: Calibrated Iridium forecasted and actual customer subscriptions. WMAPE = 21.3%, this is in the reasonable forecasting region.

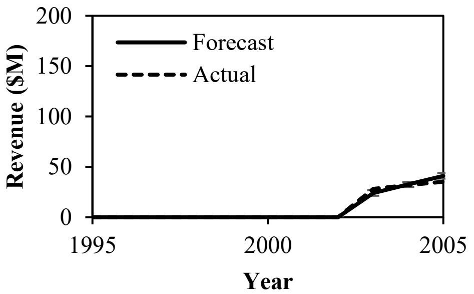

Figure 82: Calibrated Thuraya forecasted and actual revenue. WMAPE = 11.1%, this is in the good forecasting region.

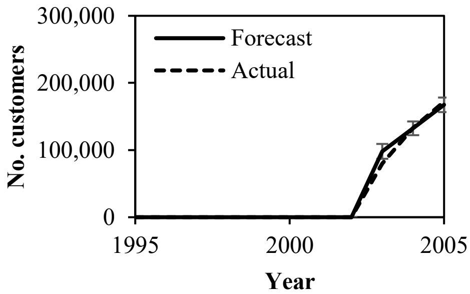

Figure 83: Calibrated forecasted and actual customer subscriptions. WMAPE = 6.0%, this is in the highly accurate forecasting region.

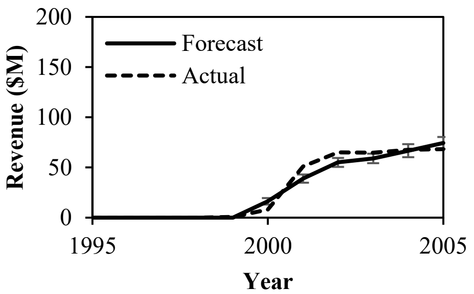

Figure 84: Calibrated Globalstar forecasted and actual revenue. WMAPE = 13.4%, this is in the good forecasting region.

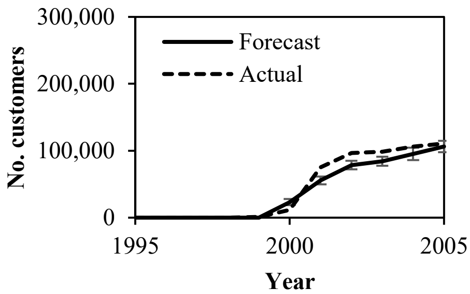

Figure 85: Calibrated Globalstar forecasted and actual customer subscriptions. WMAPE = 16.0%, this is in the good forecasting region.

Overall, the calibrated model performed well with an average WMAPE of 14.6%. This falls well within the good forecasting (10-20%) region defined by [75].

Looking more closely at the Inmarsat forecasts (Figure 78 and Figure 79) we see that, at the beginning, the model consistently underestimates the number of subscribers. This is likely due to the cold-start nature of the model. In the first time-step there were no customers assigned to an operator in the model, while in the historical data Inmarsat already did have some customers. This initial difference takes some time to rectify resulting in an underestimate of the number of customers (and thus revenue) over the first few timesteps. This is not an issue for the other operators as they only begin service during the model period and thus do not suffer from the cold-start problem. If we exclude the cold-star problem from the analysis WMAP of Inmarsat falls to 11.4% and to 12.4% overall.

These same calibration adjustments (i.e., the specific values identified here) will be used in the satellite-based internet model and should in theory produce similarly appropriate results.

5.4 Sensitivity analysis

The influence of customer size, subscription prices charged, the rollout of substitutes, and operator capacity, along with customer-specific weightings of attitudes, societal norms, and controls are assessed. These parameters were varied by ±10% and ±50% and the effect of NPV and number of customers are plotted. Note that in this context NPV is only concerned with the present value of revenue as expenses are not being modelled. Additionally, for this test, a customer year is defined as the sum of the total number of customers for each year. Three individuals purchasing the product in the year 1996 would be three customer years. Similarly, one individual subscribing to the service in 1996, 1997, and 1998 would also be recorded as three customer years. As the model generates a new set of random customer agents for each simulation, simulations were run 20 times each.

We expect that certain operators may be more sensitive to certain parameters than others. For example, one that provides a high quality, but expensive service would be harmed if customers became more price sensitive but would benefit if they were more quality sensitive. Sensitivity results for each operator separately is shown in Figure 86 to Figure 93. The overall most important factor is given at the top with less influential factors further down. Figure 94 and Figure 95 show sensitivities averaged across all operators. Finally, a description of each factor and its effect on the results is described in Table 5.

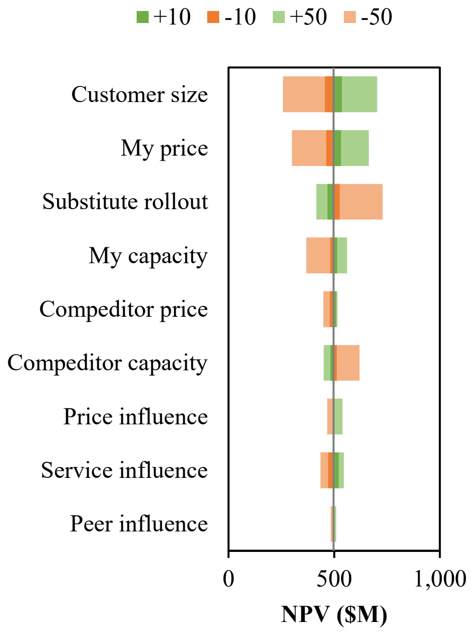

Figure 86: Inmarsat NPV sensitivity analysis. Relative to the other operators, Inmarsat is much more sensitive to competitor capacity.

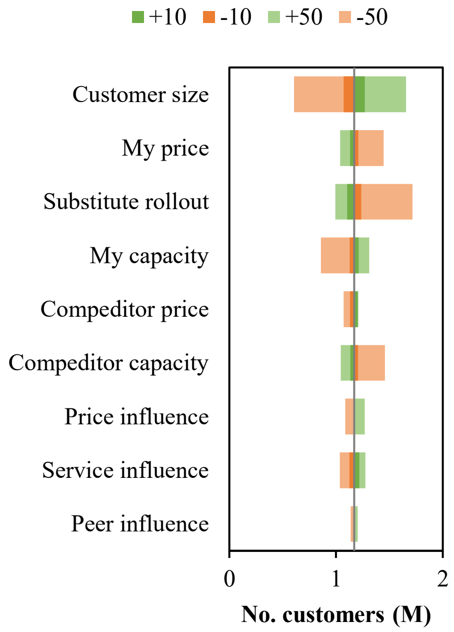

Figure 87: Inmarsat customer sensitivity analysis. Relative to the other operators, Inmarsat is much more sensitive to competitor capacity.

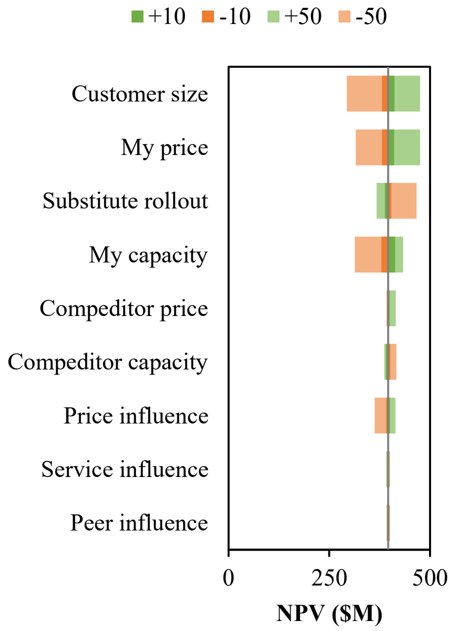

Figure 88: Iridium NPV sensitivity analysis. Relative to other operators, Iridium is more sensitive to their own capacity, especially with downside risk. They may be operating near the limit of their capacity.

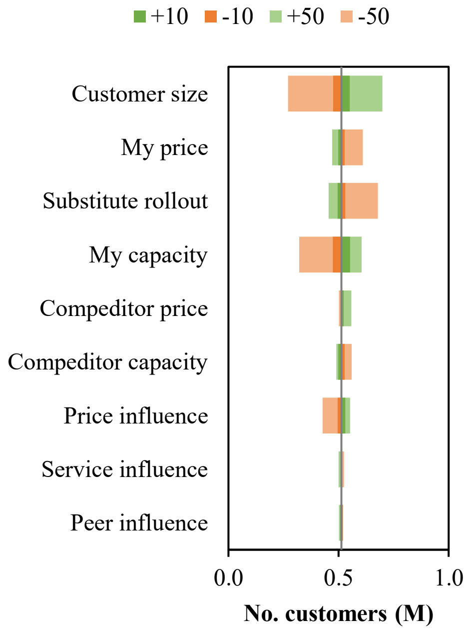

Figure 89: Iridium customer sensitivity analysis. Relative to other operators, Iridium is more sensitive to their own capacity especially with downside risk. They may be operating near the limit of their capacity.

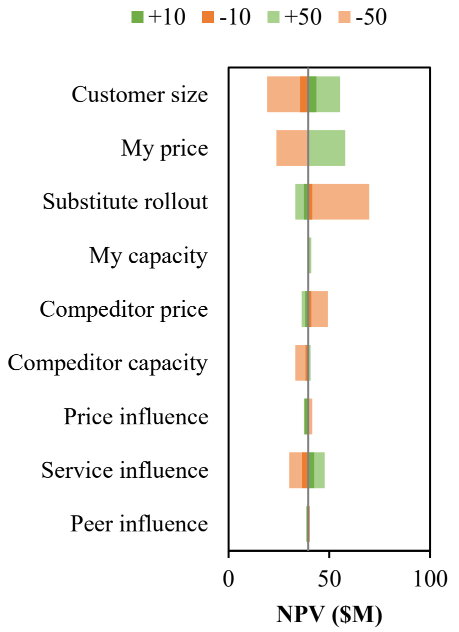

Figure 90: Thuraya NPV sensitivity analysis. Relative to other operators, Thuraya is more sensitive to the rollout of substitutes (perhaps due to a high reliance on land-based customers) and customer value attributed to service quality. People like Thuraya when they need quality service.

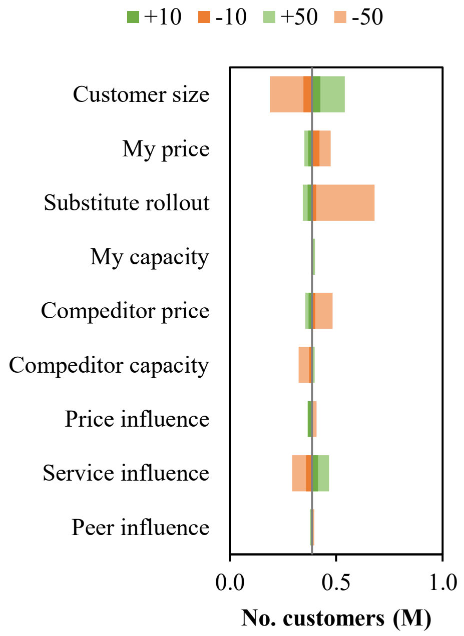

Figure 91: Thuraya customer sensitivity analysis. Relative to other operators, Thuraya is more sensitive to the rollout of substitutes (perhaps due to a high reliance on land-based customers) and customer value attributed to service quality. People like Thuraya when they need quality service.

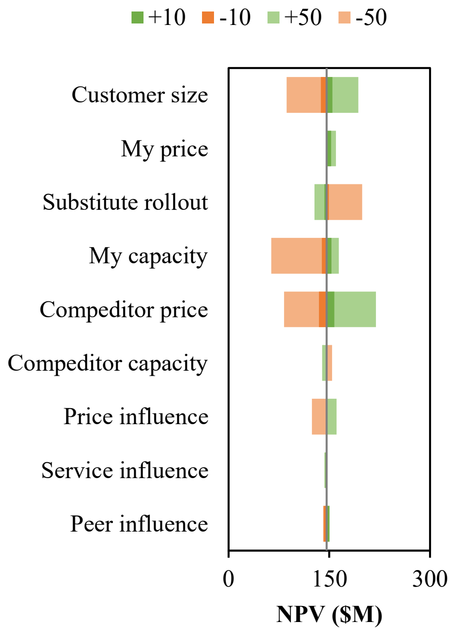

Figure 92: Globalstar NPV sensitivity analysis. Relative to other operators, Globalstar is more sensitive to the competitor pricing and experiences significant upside when competitors overcharge and switch to Globalstar instead.

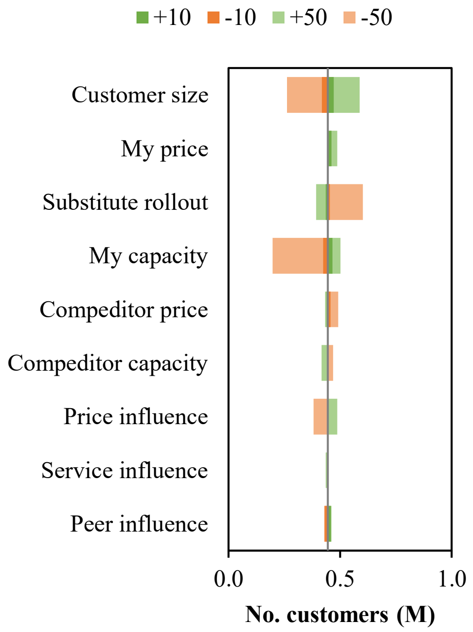

Figure 93: Globalstar customer sensitivity analysis. Relative to other operators, Globalstar is more sensitive to the competitor pricing and experiences significant upside when competitors overcharge and switch to Globalstar instead.

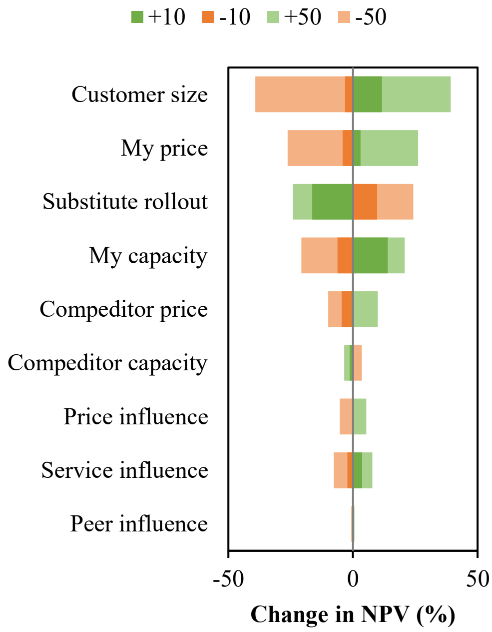

Figure 94: Overall NPV sensitivity analysis.

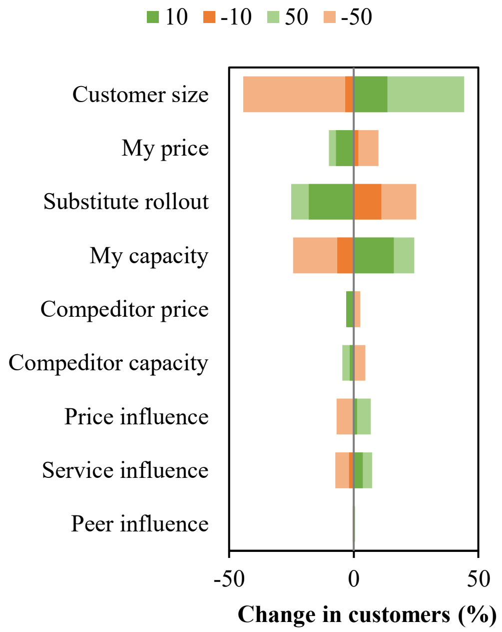

Figure 95: Overall customer sensitivity analysis.

Table 5: Sensitivity analysis results in order of greatest to least importance.

Parameter	Description	Influence on subscriptions and NPV
Customer size	The size of each customer segment is modified by the given amount. Higher means that there are more customers in each segment.	The model was very sensitive to the size of the segment with equal sensitivity in either direction. This suggests that operators were not restricted by capacity but rather the number of customers who were aware of and could afford their service. Therefore, increasing (or decreasing) the number of potential customers directly affected the number of realized subscribers and NPV. These subscribers also provide a feedback effect where having more people they can more effectively convince their peers to join.
My price	In this model the price being charged by each operator is fixed to their real-world amount. The price being charged by the operator is modified by a given amount. In this case "my" refers to the operator being considered, in the case on Intelsat only Intelsat would have their price increased while the other operators would remain at the original price. Higher means the operator charges more for the same product.	As expected, lowering price means more people subscribe while raising it means less. For most operators the gains produced by increasing the number of customers did not counteract the resulting drop in revenue. In the case of Thuraya it appears that they could have afforded to increase prices somewhat and still seen revenue gains. Perhaps their strategy of undercutting the competition was too aggressive.

Substitute rollout	The final extent of the substitute service rollout is modified. Higher means that there is a greater rollout of cell towers, and more customers switch to this service and away from satellites.	Similar to the effect of customer size, more rollout means fewer potential customers and therefore less subscribers and less revenue. Operators seem to be shielded from downside risk by virtue of the mobile segments which cannot use the land-based mobile service. However, they can capture significant upside by taking advantage of these land-based customers if rollout is less than expected. This is a good position to be in and points toward stability of the industry.
My capacity	The capacity available to the operator is modified. Again, "my" just refers to the single operator being considered. High implies more capacity such as could be obtained by using a more efficient routing algorithm or by launching additional satellites.	Although operators weren't capacity-limited, within the model we assume that additional capacity available in a region means that the operator can provide a better standard of service by reducing the number of dropped calls and improving data rates. Therefore, we see that increasing capacity does increase the NPV and number of subscriptions.
Competitor price	The price being charged by the other operators is modified. "Competitor" refers to all the other operators, in the case of Intelsat this would be Iridium, Thuraya, and Globalstar all changing their prices while Intelsat stays fixed. Higher means these competitors charge more for the same service.	Generally, as competitors increase price means that the operator being considered receives additional customers that would have gone with a competitor but now chose to partner with the relatively cheaper option. This improves the number of realized subscriptions and NPV. Interestingly, Thuraya experiences the opposite effect. If the competitors now have lower more reasonable prices, then customers are unlikely to want to jump to the new market entrant of Thuraya as there is less price incentive to do so.
Competitor capacity	The capacity available to the competitors is modified. As before, "competitor" refers to the other operators, in the case of Intelsat this would be Iridium, Thuraya, and Globalstar all changing their capacity while Intelsat stays fixed. High means more available capacity.	Increasing competitor capacity gives them a relatively higher quality of service which therefore results in them being preferentially chosen over the operator of concern. Thus, we see an increase in competitor capacity resulting in a decrease in the number of subscribers and NPV for the operator of concern.
Price influence	The price influence is the relative importance which the customer agent places on pricing. Higher influence means that the customer is very sensitive to price and will consistently purchase products with lower prices.	The influence of price varied for each operator. As should be expected, those with more price-competitive offerings fared better when compared to those with more expensive products when the price influence factor was increased. The results generally showed low sensitivity toward the three influence factors. This is important as it indicates that even if the factors aren't perfectly tuned the result will still be useful.
Service influence	The service influence is the relative importance which the customer agent places on service quality. In this case service quality is a measure of how much capacity is available. Operators with high available capacity (lots of high-capacity satellites with few subscribers) have better service and a customer with high service influence will preferentially partner with them.	Like price influence, operators with more capacity and better service fared better when customers placed additional emphasis on this quality.

Peer influence	Peer influence is the relative importance which the customer agent places onto actions made by their peers where peers are those in the same segment and same local region (1° x 1° cell). If many of the users in one cell have partnered with a given operator, then a customer with high peer influence will also partner with this same operator.	Overall, the influence of peers on the number of customers and NPV was small. However, this factor is already accounted for in the adoption rate statistics and therefore this should be expected. High peer influence was beneficial to operators who had been in the market longer.

5.5 Chapter summary and conclusions

An appropriate historical study was identified, developed, and used to calibrate the ABSM.

To begin, several industries including fast food, car years, and TV advertising slots were assessed before identifying satellite phones as an industry most like satellite internet. The satellite phone industry from 1995 to 2005 was researched and fed into the ABSM.

The satellite phone model initially ran without calibration with these the uncalibrated results showing poor forecasting performance with high weighted mean absolute percentage errors (WMAPE) for all operators. The average WMAPE was 77.7%, indicating inaccurate forecasting. Significant calibration was applied to improve the model's performance.

The calibration process involved adjusting various parameters within specific ranges to minimize WMAPE and match the general shape of the revenue and customer subscription curves. The calibrated model showed significant improvements in forecasting accuracy, with lower WMAPE values across all operators. The average WMAPE decreased to 12.4%, falling within the good forecasting region defined by [75]. This is in the same ballpark as previous studies. Agarwal's single-datapoint study saw a WMAPE of 11.3% [53]. Bennett et al. [80] achieved a WMAPE of 11.7% for their single-operator economic model. These also fall into the good forecasting region defined by [75]. With four customer segments and four different operators the ABSM was significantly more complex and by design, operator-specific calibration was not implemented. Thus, while still numerically worse than these previous studies, overall, the ABSM performs very well. Performing an analogous intra-species analysis for accurate comparative assessment (‘comparing apples to apples’) if we consider just a single operator with revenue only (as in Agarwal [53] Bennett et al. [80]) then the best performing forecast achieves a WMAPE of 8.8% or highly accurate forecasting. This is better than any of the published literature studies. However, this just again emphasizes that applying the model to a single operator produces can tend to provide undue confidence in model results.

Sensitivity analysis was conducted to assess the model's responsiveness to variations in customer size, subscription prices, substitute service rollout, and operator capacity. The results showed that different operators were more sensitive to competitor capacity, own capacity, rollout of substitutes, and competitor pricing and less sensitive to the specific theory of planned behavior weightings.

Overall, this historic case study has helped validate the model by demonstrating its ability to generate more accurate forecasts after calibration. The calibrated model provides valuable insights into the dynamics of the satellite internet market and can be utilized for forecasting modern satellite internet data. With its improved forecasting capabilities, the model can assist in making informed decisions regarding pricing strategies, capacity planning, and market competition in the satellite internet industry. This historic case study has helped to validate the model and showcase its usefulness. It is ready for use with modern satellite internet data.

Chapter 6

Satellite Internet Forecast 2020-2040

This chapter sets up and runs the satellite internet market forecasts for the years 2020 to 2040. It concluded the methodologies, results, and discussion components of this thesis. First (6.1 Setup of the satellite internet market forecast on page 130) the operators, customers, and substitute services are reviewed and input into the ABSM. Numerical calibration from the previous chapter is kept. Additional calibration as required for the shift from satellite-phones (original calibration) to satellite internet (this forecast) is implemented as required to match the 2020 – 2022 actuals. Then (6.2 Results of the satellite internet forecast on page 136), a series of forecasts are run. These are a datum case which is locked to current prices, then phase one gives the operator agents full autonomy of a phase-one constellation, where relevant phase two constellations are then implemented, and the forecast run again. Forecasts in the case of an Intelsat-SES and Starlink-SES merger are examined. Finally, a full range of substitute service forecasts are run where market response to varying levels of fiber rollout is implemented. Finally (6.3 Chapter summary and conclusions on page 155), the chapter is summarized, and conclusions drawn.

6.1 Setup of the satellite internet market forecast

The ABSM was configured to model the satellite-based internet market from 2020 to 2040. Segment growth and operator capacity had to be inferred from existing trends or SEC filings and company announcement data. An updated market model control structure diagram is presented in Figure 96. As before the inputs to the model are described and various scenarios studied.

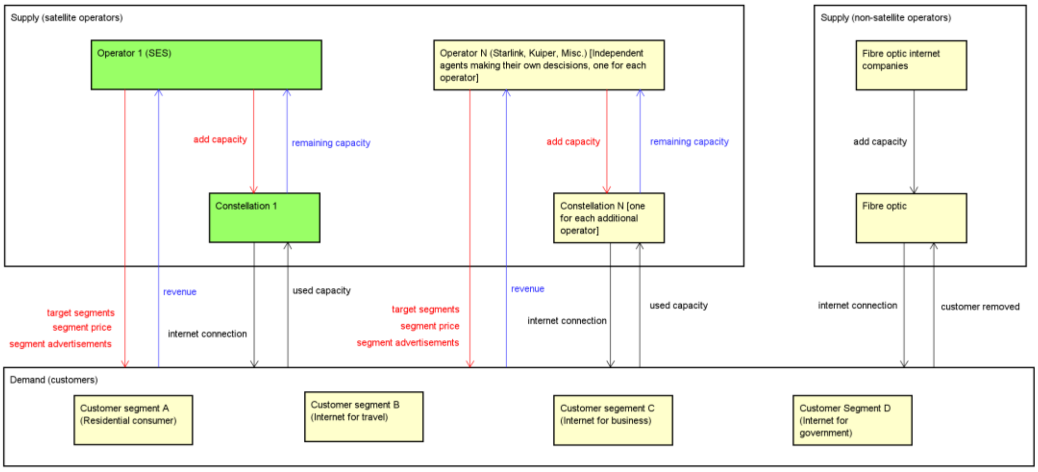

Figure 96: Satellite internet market model control structure diagram. The full market including all operators, customer segments, and substitutes are being modelled.

6.1.1 Operators

There are many satellite operators either currently operating in the market or else with plans to enter soon. Five operators SES, Intelsat, OneWeb, Starlink, and Kuiper were selected for detailed analysis. Each of these operators have signaled flexibility options allowing them to significantly increase constellation capacity if the need arises. This is incorporated into the modelling on a case-by-case basis.

SES

SES, previously Société Européenne des Satellite, is a large incumbent operator. They provide satellite communication services such as TV and internet to a range of customers across all industries. However, they generally tend to avoid residential households. For the purposes of this analysis only their internet division, SES Networks, will be considered. According to their 2020 annual report [161], 48% of revenue is from this division. Consumer trends away from traditional TV and towards streaming [162] paired with SES' commitment to internet-based constellations [30] suggests that this network division will grow to dominate business activities.

SES currently operates a constellation of 22 MEO satellites used for satellite-based internet and in December 2022 launches the first two of what is planned as an 11 high-throughput satellite network (Figure 97). Estimation of each satellite throughput is provided by Thales CEO Herve Derrey [163] at 40,000 Mbps per satellite with the resulting short-term planned capacity, Phase 1, shown in Figure 59. According to FCC filings SES is also planning a 62 satellite MEO constellation dubbed Cleosat [164]. Actual launch dates are not yet publicly available, but for this analysis it is assumed they will target a 12 satellite/year launch cadence starting in 2026. Subsequent analysis will reveal if, when, and to what extent this option will be exercised.

Figure 97: SES satellite converge map. Capacity is homogenous but not available at the poles.

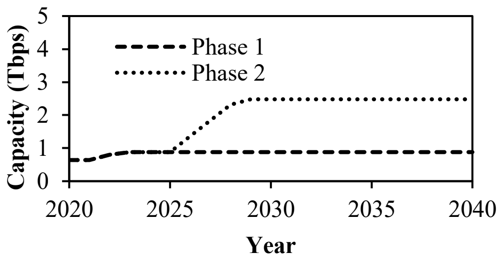

Figure 98: SES total system capacity. Inferred from [164].

Intelsat

Intelsat is a major incumbent satellite operator providing phone, TV, and internet services. It caters to predominantly business and government customers [165]. Although they employ a range of altitudes their focus is on GEO allowing for excellent coverage but at the cost of additional latency and weaker signals. Originally operating as an intergovernmental consortium to provide largely emergency-related services they have since reemerged as a private company [166].

Intelsat operates a fleet of 52 communications satellites with a coverage map shown in Figure 99. We will assume a capacity of 25,000 Mbps per satellite [167]. There do not appear to be any filings intended on extending the service and thus capacity remains consistent throughout the period of interest (Figure 100). In March 2023 it was confirmed that they are in talks with competitor SES about a merger [8]. This provides an interesting test case to see how this merger may affect the rest of the industry.

Figure 99: Intelsat satellite coverage map. Capacity is homogenous but not available at the poles.

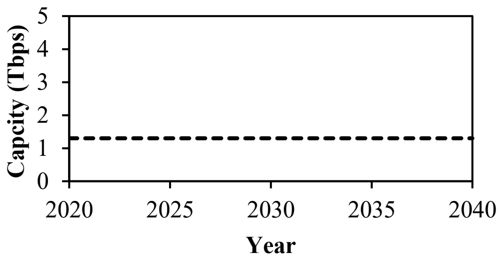

Figure 100: Intelsat total system capacity. Capacity is static with little investment in new infrastructure.

OneWeb

OneWeb also consists of a two-phase LEO constellation starting with 716 satellites and then expanding to 6,372 [167]. Operating at this low altitude reduces signal latency but at the expense of needing to launch additional satellites to maintain constant coverage. After launching the first part of their network they entered bankruptcy in 2020 but have since reemerged and are today owned by a range of government and private groups. OneWeb plans to sell to different longitudes at different times; starting with 5 degrees North by the end of 2020 followed by 22 degrees in mid-2022, and then global at the end of 2022 [168]. This staggered rollout has been intentionally included in the model as it gives an opportunity for operators to get ahead on market penetration in certain regions even before the main network is completed. System coverage (Figure 101) and capacity (Figure 102) were estimated by Pacher et al. [143] using spectrum filings.

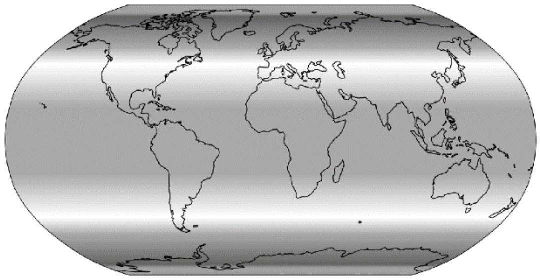

Figure 101: OneWeb satellite coverage map. Capacity is global with extra focus around mid-latitudes. Adapted from [143].

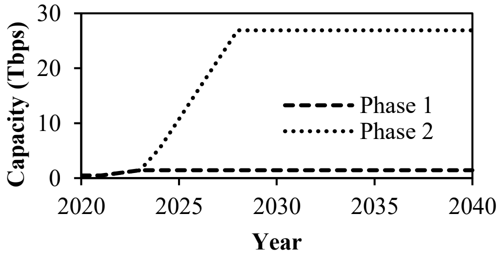

Figure 102: OneWeb total system capacity. After a small initial investment in phase one the constellation grows significantly. Adapted from [143].

Starlink

Starlink is a new entrant using new technology to disrupt the market. The company is vertically integrated with launch-provider SpaceX [169]. Starlink manufacture and operate their own satellites and sell their services direct to consumers without the bundling of contracts through a typical ISP. They have significant planned growth and have already launched more satellites than any constellation in history, but there is uncertainty in how this rollout will occur. Initially Starlink only marketed toward residential consumers but have since entered the business and government sectors as well [170]. Although they have not yet entered the travel segment it is unlikely that there are any structural reasons why they could not. System coverage (Figure 103) and capacity (Figure 104) were estimated by Pacher et al. [143] using spectrum filings.

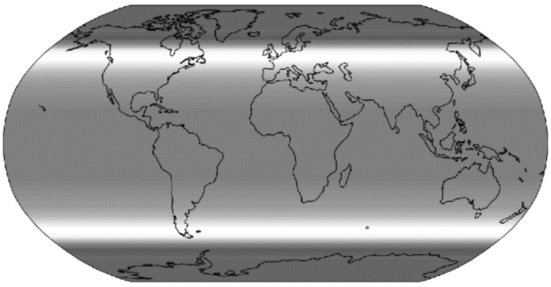

Figure 103: Starlink satellite coverage map. Although there is global coverage the poles see much less capacity than the rest of the planet. Adapted from [143].

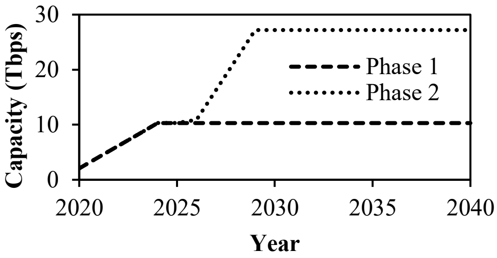

Figure 104: Starlink total system capacity. Adapted from [143].

Amazon Kuiper

The final operator being considered is Amazon Kuiper. As of 2023 the service is still not operational, but appears to follow a similar outline as Starlink [171]. Kuiper is also vertically integrated but rather than upstream satellite bus and rocket manufacture instead includes products such as Amazon Web Services (AWS) and Amazon shopping which have been successful in monetizing people's use of the internet rather than just purely access to it. A compelling strategy only available to Kuiper would be to intentionally sell their internet service at a loss only to recuperate this later through these downstream e-commerce services. System coverage (Figure 105) and capacity (Figure 106) were estimated by Pacher et al. [143] using spectrum filings.

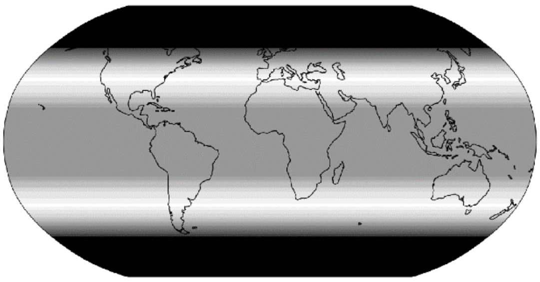

Figure 105: Kuiper satellite coverage map. There is effectively no capacity around the poles. Adapted from [143].

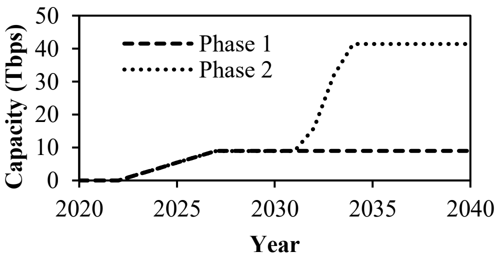

Figure 106: Kuiper total system capacity. Kuiper is a late market entrant but with the potential to launch significant capacity. Adapted from [143].

6.1.2 Customers

Not by accident, the same customer segmentation as provided in the satellite phone analysis is applicable to the satellite internet context. Geographic distributions, segment growth, and WTP statistics will remain largely unmodified. Income statistics are updated to reflect 2022 levels. That is, we inflated incomes upwards to their modern values but kept relative wealth distribution the same. Plots of segment growth are shown in Figure 107 and Figure 108. Irani et al's empirical studies on internet adoption using the theory of planned behavior [139] provide weightings for the importance of each factor on the decision to adopt. They were kept at their calibrated values upon which sensitivity analysis has already been run. While important to get in the right 'ballpark', precise values was not found to be important. We also update adoption statistics from phone data to internet data, again from [138]. The key difference is that rather than a phone call being the unit of capacity it is instead a reserved data rate. As identified by [64], typical household sold capacity is 100 Mbps, travel is 1000 Mbps, business 300 Mbps, and government 300 Mbps.

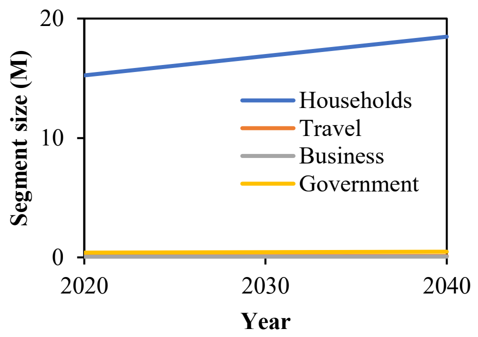

Figure 107: Household segment growth over the period. Using the same equations as in the satellite phone analysis.

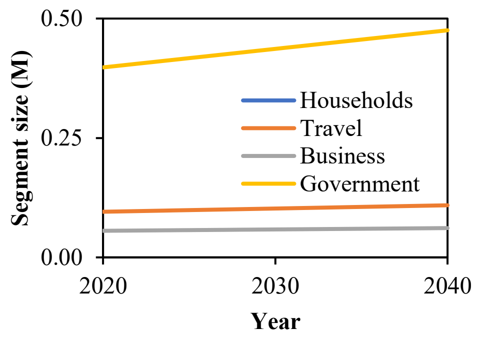

Figure 108: Travel, business, and government segment growth over the period. Using the same equations as in the satellite phone analysis.

6.1.3 Substitutes

The major substitute service is fiber-optic cable. We assume that its rollout over the period 2020 to 2040 follows the same growth as that of cellular networks. As before, we assume that the 2020 level corresponds to the 2023 rollout of 5G while 2040 the 2023 rollout of 2G.

6.1.4 Calibration

Due to the lack of long-term historical data calibrating the model directly was not possible and is why Chapter 5 Historical Calibration on the Satellite Phone Market 1995-2005 was implemented. Calibration figures for customer preference, relative WTP, and adoption rate were retained.

Some historical data for satellite internet was present (2020 to 2022) and these actuals were compared against the satellite internet forecast. Initially the forecast significantly underpredicted the number of customers adopting the service (WMAPE > 50%). Analysis found that this was because operators quickly filling up their capacity quota after accepting just a few thousand customers. The initially generous overbooking factors initially used in the analysis were reduced by a factor of ten and the forecast and actuals saw a closer (WMAPE < 20%) resemblance.

6.2 Results of the satellite internet forecast

This section describes six forecasts related to the satellite internet market. All use the same agent condition. The ABSM was run for a twenty-year simulation from 2020 to 2040 with prices estimated from available product offerings or business estimates. The model is run in its grouped-customer state to reduce required simulation time. This meant residential consumers were combined into groups of 250 with business, government, and travel into groups of 100. Thus, the model has 74,000 household agents, 1200 business agents, 9500 government agents, and 1000 travel agents with 85,700 independent customer agents in total. This includes the five independent operator agents.

The first forecast (6.2.1 Datum forecast) is based on a simulation run from 2020 to 2040 This forecast aims to estimate the revenues of satellite operators by closely matching their real-world pricing and segment strategies. It assumes the grouping of customers, such as residential, business, government, and travel, to reduce simulation time. The model uses available product offerings and estimates from operators to determine pricing. However, in cases where operators have not disclosed their pricing, a best estimate is made by comparing them to their peers.

The next set of forecasts (6.2.2 Phase one constellation optimization and 6.2.3 Phase two constellation optimization) focus on the optimization of pricing strategies for the phase one and phase two constellations of the satellite operators. The optimizer suggests new prices that maximize the expected operator return. The optimized pricing strategies for SES, Intelsat, OneWeb, Starlink, and Kuiper are presented in tables for different regions and customer segments. The forecasts also highlight competitive strategies such as region-based market segmentation and price differentiation based on customer groups.

The next (6.2.4 Intelsat – SES merger forecast) examines the impact of a merger between Intelsat and SES. The model assumes that all of Intelsat's assets and customers transition to SES with the merger occurring in 2024.

Following this the next forecast (6.2.5 Starlink – SES merger forecast) explores the effects of a merger between Starlink (a large new operator), and SES (an incumbent). The merger takes place in 2026.

The final forecast (6.2.6 Forecasted effect of substitute services rollout) assesses the potential impact of the rollout of land-based alternatives, such as fiber optic cable, on satellite operators. Different levels of rollout are considered, ranging from no change to faster-than-predicted rollout. The results indicate which operators are most vulnerable to competition from land-based alternatives.

Overall, these forecasts and simulations provide predictions and insights into the performance and pricing strategies of satellite operators in the communication industry. They help assess operators' behaviors, interaction with each other, and potential competitive strategies in different market segments and regions.

6.2.1 Datum forecast

For the datum forecast figures are kept as close to their real-world equivalents as possible. Thus, rather than allowing operators to choses their own prices or segments they are instead forced to match what is currently observed in the real world. Where operators have not yet signaled their intentions, we use a best estimate is made by comparing them to their peers. For example, since Kuiper has not yet announced pricing, we duplicate the modern-day Starlink pricing strategy. We assume that SES sells to the business, travel, and government sectors at a rate of $100,000/year for a 300 Mbps plan. Intelsat charges the same price but only for travel and government groups. OneWeb also charges $100,000/year for a 300 Mbps plan and sells to business, travel, and government. Starlink charges $1440/year for a 100 Mbps plan and sells to both residential consumers and business. Kuiper only sells to residential consumers and charges this same rate. For the moment we assume that only the phase one constellation is being launched.

These datum results are shown in Figure 109 to Figure 113. Only revenue figures are plotted as modern operators appear to be very unwilling to share subscriber statistics from which to make a comparison.

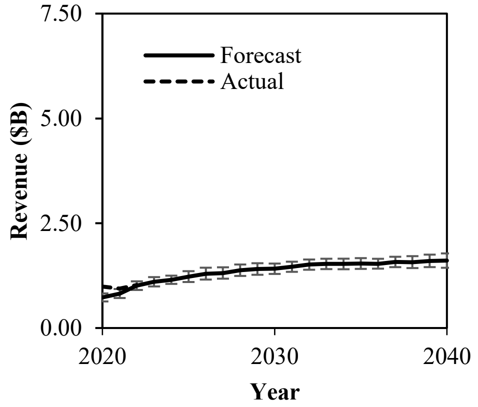

Figure 109: Datum SES forecasted and actual revenue. WMAPE = 13.3%, this is in the good forecasting region.

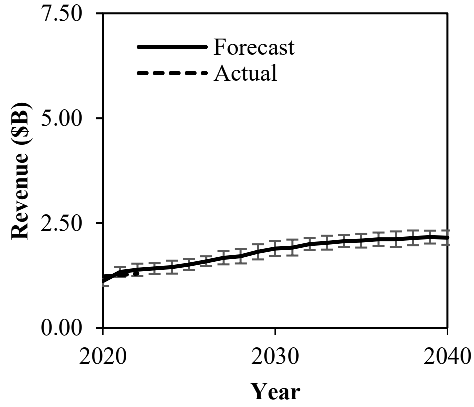

Figure 110: Datum Intelsat forecasted and actual revenue. WMAPE = 7.5%, this is in the highly accurate forecasting region.

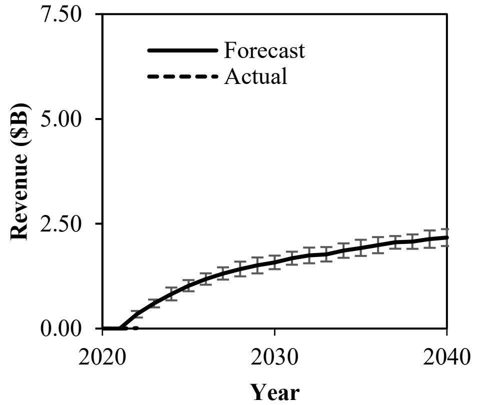

Figure 111: Datum OneWeb forecasted revenue. There are insufficient data from which to calculate a meaningful WMAPE.

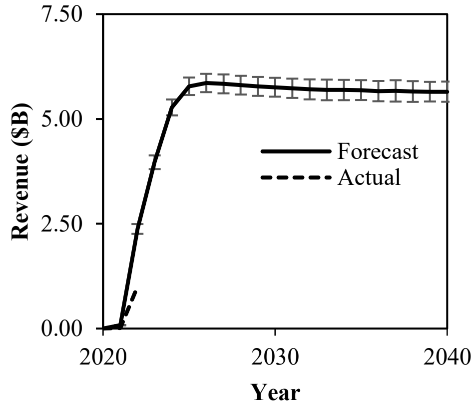

Figure 112: Datum Starlink forecasted and actual revenue. There are insufficient data from which to calculate a meaningful WMAPE.

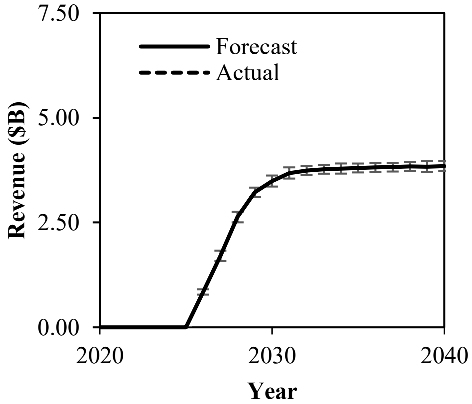

Figure 113: Datum Kuiper historic and predicted revenue. There are insufficient data from which to calculate a meaningful WMAPE.

The incumbent SES, Intelsat, and OneWeb operators show steady growth over the period, likely brought about due to good growth in their target segments. In this initial scenario they appear to have strong and stable revenue. WMAPE analysis is obviously challenging with such limited actuals but is within the <20% amount consistent with good forecasting. The incumbent SES, Intelsat, and OneWeb operators show steady growth over the period, likely brought about due to good growth in their target segments. In this initial scenario they appear to have strong and stable revenue. Relying on a highly mobile customer base may not see stellar growth, but they are reliable and unable to switch to land-based systems. In contrast, the more modern Starlink and Kuiper constellations with significant capacity see sharp growth closely matching the launch of their constellations. Over time, however, their revenue shrinks as their largely residential-type consumers transition to land-based alternatives.

Calculating the present value of revenue we see SES with \$11.5 B, Intelsat \$14.4 B, OneWeb \$9.7 B, Starlink \$39.4 B, and Kuiper \$14.2 B. As a reminder, we are using an industry-standard 10% internal rate of return to discount the future cash flows. To obtain a more complete understanding of how these operators earn this revenue and obtain their customers we need further analysis. Figure 114 to Figure 118 provides a year-by-year breakdown of customer makeup for each operator. Customers are classified as sticky, new, or stolen. A sticky customer is the most common type; someone who bought the service in a previous period and is continuing to purchase it in the current. New customers are ones with no previous affiliation with a satellite internet operator and are now buying it for the first time. A stolen customer is one who belonged to one operator in the previous period and has now switched to a different operator. Stolen customers are recorded in the statistics of the obtained which obtained them.

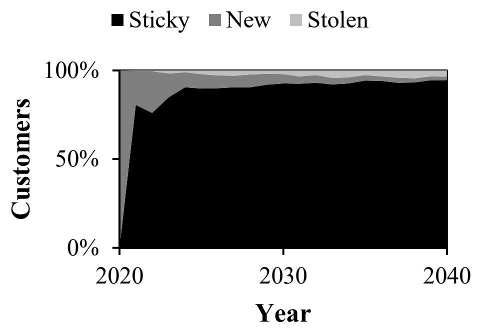

Figure 114: Datum SES forecasted customer proportion by year. 75.4% of customers are new stimulated demand and 24.6% are stolen from the competition.

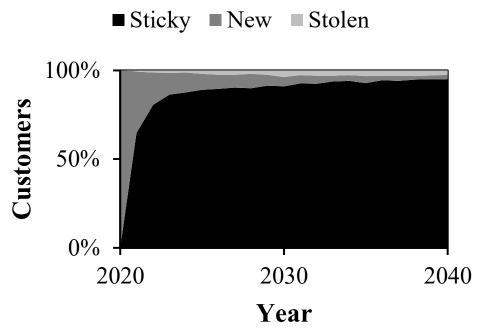

Figure 115: Datum Intelsat forecasted customer proportion by year. 75.1% of customers are new stimulated demand and 24.9% are stolen from the competition.

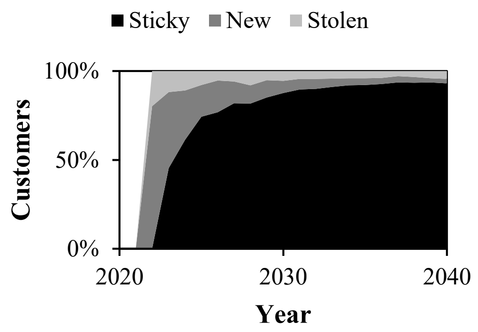

Figure 116: Datum OneWeb forecasted customer proportion by year. 60.7% of customers are new stimulated demand and 39.3% are stolen from the competition. This low new and high stolen portion could be due to their relatively late market entrance.

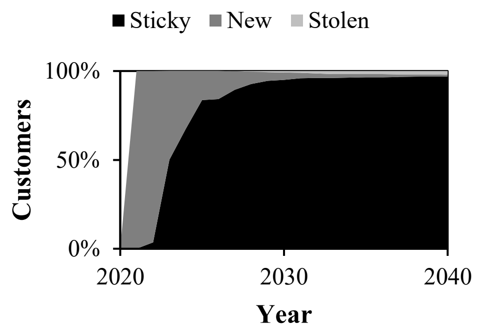

Figure 117: Datum Starlink forecasted customer proportion by year. 90.0% of customers are new stimulated demand and 10.0% are stolen from the competition. Starlink has a high portion of new customers; they can effectively stimulate demand.

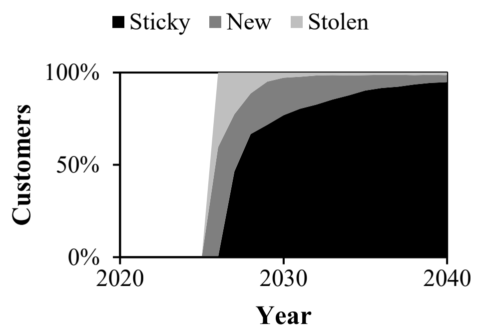

Figure 118: Datum Kuiper forecasted customer proportion by year. 78.6% of customers are new stimulated demand and 21.4% are stolen from the competition. Kuiper has a relatively high portion of stolen customers; by the time Kuiper is active perhaps all latent demand has already been stimulated and thus 'stealing' customers is a dominant strategy.

From this data we observe how Starlink is especially good at stimulating and taking advantage of latent demand by obtaining a significant proportion of new customers.

Alternatively, Kuiper seems to rely more heavily on the strategy of ‘stealing’ customers from other operations. This could be due to their later market entrance.

Finally, Figure 119 to Figure 122 breaks down each segment by weighted average operator market share. That is, the average number of customers each operator had for each year of the simulation.

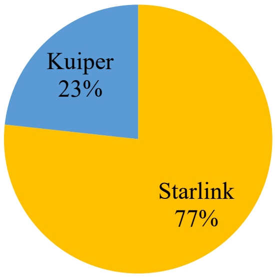

Figure 119: Datum Household segment market share by operator. Starlink leads this segment, perhaps due to more time in the market and significant capacity.

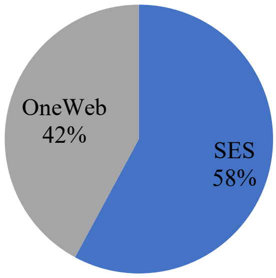

Figure 120: Datum Travel segment market share by operator. SES leads this segment.

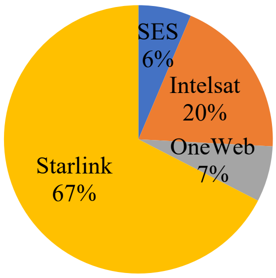

Figure 121: Datum Business segment market share by operator. Starlink with its lower costs seems to dominate this segment despite relatively late entrance.

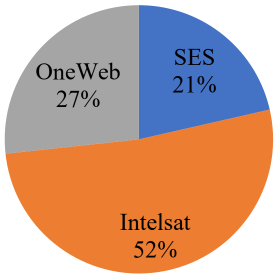

Figure 122: Datum Government segment market share by operator. Intelsat, founded with the express intent on servicing government customers, continues to dominate this segment.

From these results we see how different operators seem to specialize in each segment. For the household segment Starlink has had longer in the market, allowing them to dominate over Kuiper despite being otherwise very similar constellations. Another reason for different operators dominating different segments could be that certain operators are intrinsically better suited for certain customers. Both these factors may then be compounded by peer effects which tend to magnify differences between operators. For example (Figure 122), even if all else was equal a new government customer would be more likely to pick Intelsat because peer effects encourage this customer to partner with the dominant firm.

From before, the present value for each operator was SES with \$11.5 B, Intelsat \$14.4 B, OneWeb \$9.7 B, Starlink \$39.4 B, and Kuiper \$14.2 B. Now with an improved understanding of the market we can make some inferences. Starlink with their early market entrance and huge capacity appears to be a winning combination. Despite their late entrance Kuiper performs well due to competitive pricing (pegged to their only segment-specific competitor Starlink) and high capacity. OneWeb performs the worst, possibly due to their late entrance and relatively low phase one capacity. Of the incumbent operators Intelsat performs the best perhaps due to their dominance in the government sector.

Thus far the results are largely as anticipated and ABSM appears to produce believable predictions. The proceeding sections describe a range of more speculative forecasts. As mentioned previously, first is an optimized phase one constellation which gives the operator agents full autonomy of a phase-one constellation. Next and where relevant, phase two constellations are implemented, and the optimized forecast runs again. Next, forecasts examining cases of an Intelsat-SES and Starlink-SES merger are examined. Finally, a full range of substitute service forecasts are run where market response to varying levels of fiber rollout is implemented.

6.2.2 Phase one constellation optimization

In this scenario we allow the optimizer to select new prices which maximize the expected operator return. Note that operators are fixed to operate only within given segments. For example, SES will never enter the residential segment and Kuiper will never sell to the government. We assume operators only launch the first phase of their constellations. As shown in the satellite-phone case, this is expected to provide a reasonable estimate of the actual prices being charged and can even automatically develop competitive strategies which might be witnessed in the real world. Optimal prices for each operator across regions and segments are shown in Table 6 to Table 10.

Table 6: Phase one SES optimized pricing strategies.

Region	Residential	Business	Travel	Government
Original (unoptimized)	N/A	$ 100,000 / year	$ 100,000 / year	$ 100,000 / year
Maritime	N/A	$ 4,520 / year	$ 4,260 / year	$ 9,120 / year
North America	N/A	$ 3,230 / year	$ 3,040 / year	$ 6,510 / year
Europe and Central Asia	N/A	$ 4,520 / year	$ 4,260 / year	$ 9,120 / year
Middle East and North Africa	N/A	N/A	N/A	N/A
Latin America and the Caribbean	N/A	$ 3,230 / year	$ 3,040 / year	$ 6,510 / year
East Asia and Pacific	N/A	$ 3,230 / year	$ 3,040 / year	$ 6,510 / year
South Asia	N/A	$ 4,520 / year	$ 4,260 / year	$ 9,120 / year
Sub-Saharan Africa	N/A	$ 4,520 / year	$ 4,260 / year	$ 9,120 / year

Table 7: Phase one Intelsat optimized pricing strategies.

Region	Residential	Business	Travel	Government
Original (unoptimized)	N/A	N/A	$ 100,000 / year	$ 100,000 / year
Maritime	N/A	N/A	$ 8,890 / year	$ 9,090 / year
North America	N/A	N/A	$ 8,890 / year	$ 9,090 / year
Europe and Central Asia	N/A	N/A	$ 8,890 / year	$ 9,090 / year
Middle East and North Africa	N/A	N/A	$ 1,270 / year	$ 1,300 / year
Latin America and the Caribbean	N/A	N/A	$ 6,350 / year	$ 6,500 / year
East Asia and Pacific	N/A	N/A	$ 7,620 / year	$ 7,800 / year
South Asia	N/A	N/A	$ 7,620 / year	$ 7,800 / year
Sub-Saharan Africa	N/A	N/A	$ 5,080 / year	$ 5,200 / year

Table 8: Phase one OneWeb optimized pricing strategies.

Region	Residential	Business	Travel	Government
Original (unoptimized)	N/A	$ 100,000 / year	$ 100,000 / year	$ 100,000 / year
Maritime	N/A	$ 4,030 / year	$ 4,180 / year	$ 9,120 / year
North America	N/A	$ 4,030 / year	$ 4,180 / year	$ 9,120 / year
Europe and Central Asia	N/A	$ 4,030 / year	$ 4,180 / year	$ 9,120 / year
Middle East and North Africa	N/A	$ 4,030 / year	$ 4,180 / year	$ 9,120 / year
Latin America and the Caribbean	N/A	$ 3,450 / year	$ 3,590 / year	$ 7,820 / year
East Asia and Pacific	N/A	$ 4,030 / year	$ 4,180 / year	$ 9,120 / year
South Asia	N/A	N/A	N/A	N/A
Sub-Saharan Africa	N/A	$ 3,450 / year	$ 3,590 / year	$ 7,820 / year

Table 9: Phase one Starlink optimized pricing strategies.

Region	Residential	Business	Travel	Government
Original (unoptimized)	$ 1,440 / year	N/A	$ 1,440 / year	N/A
Maritime	$ 900 / year	N/A	$ 2,530 / year	N/A
North America	$ 900 / year	N/A	$ 2,530 / year	N/A
Europe and Central Asia	$ 900 / year	N/A	$ 2,530 / year	N/A
Middle East and North Africa	$ 770 / year	N/A	$ 2,170 / year	N/A
Latin America and the Caribbean	$ 260 / year	N/A	$ 720 / year	N/A
East Asia and Pacific	$ 770 / year	N/A	$ 2,170 / year	N/A
South Asia	$ 260 / year	N/A	$ 720 / year	N/A
Sub-Saharan Africa	$ 390 / year	N/A	$ 1,080 / year	N/A

Table 10: Phase one Kuiper optimized pricing strategies. Note the exceptionally low pricing even when compared to the already low Starlink.

Region	Residential	Business	Travel	Government
Original (unoptimized)	$ 1,440 / year	N/A	N/A	N/A
Maritime	$ 20 / year	N/A	N/A	N/A
North America	$ 100 / year	N/A	N/A	N/A
Europe and Central Asia	$ 20 / year	N/A	N/A	N/A
Middle East and North Africa	$ 70 / year	N/A	N/A	N/A
Latin America and the Caribbean	$ 50 / year	N/A	N/A	N/A
East Asia and Pacific	$ 80 / year	N/A	N/A	N/A
South Asia	$ 50 / year	N/A	N/A	N/A
Sub-Saharan Africa	$ 120 / year	N/A	N/A	N/A

On first inspection it may appear as if the optimizer is suggesting unrealistically low prices. First, we must recall that these prices are for a single user terminal with many of the larger purchasing multiple such terminals or with larger Mbps subscriptions. Second, these values are for the optimal pricing in a market that is heavily saturated with capacity. At the end of the simulation there are some 23 Tbps of capacity available, more than an order of magnitude greater than at the start. Since operators are only seeking to maximize their own revenue and have no per-unit-cost, it makes sense for them to lower prices and sell as much capacity as possible.

The model suggests several competitive strategies which may be prevalent. Operators tend to engage in region-based market segmentation charging the highest prices to maritime and North American segments while charging less to regions around the Middle East and North Africa. In fact, it appears that SES eventually leaves the North African market entirely, preferring to reserve its capacity for higher-paying customers in adjacent zones. Segmentation by customer group also occurs with the highest rates being charged to government-type customers, business, and travel around the same in the middle, and residential at a significant discount. This is as expected and is already what occurs in the market.

Using these optimal prices and running the simulation again, a customer breakdown by sticky, new, and stolen customers (Figure 123 to Figure 127) and segment (Figure 128 to Figure 131) is shown.

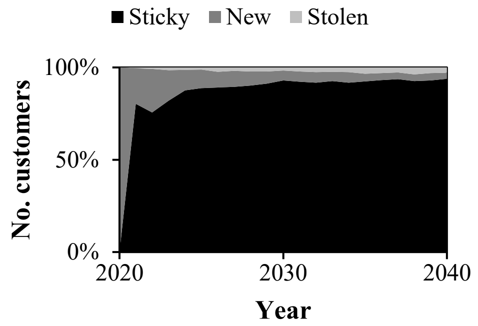

Figure 123: Phase one optimized SES forecasted customer proportion by year. 80.6% of customers are new stimulated demand and 19.4% are stolen from the competition.

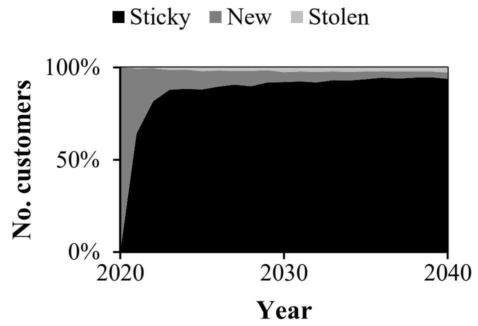

Figure 124: Phase one optimized Intelsat forecasted customer proportion by year. 80.9% of customers are new stimulated demand and 19.1% are stolen from the competition.

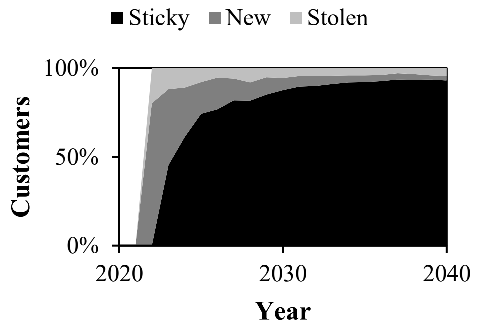

Figure 125: Phase one optimized OneWeb forecasted customer proportion by year. 66.3% of customers are new stimulated demand and 33.7% are stolen from the competition. OneWeb appears to be undercutting the competition in the major regions of maritime, North America and Europe, which could explain the relatively high stolen population.

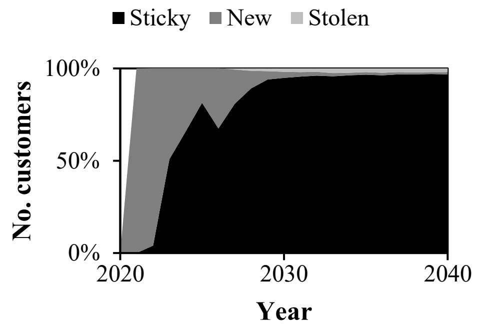

Figure 126: Phase one optimized Starlink forecasted customer proportion by year. 88.2% of customers are new stimulated demand and 11.8% are stolen from the competition. Starlink has a high portion of new customers; they can stimulate demand. The drop in sticky customers around the year 2026 corresponds to the entrance of Kuiper.

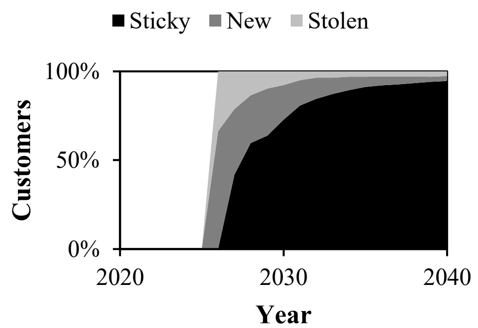

Figure 127: Phase one optimized Kuiper forecasted customer proportion by year. 68.2% of customers are new stimulated demand and 31.8% are stolen from the competition. Kuiper stimulates their own demand and steals customers from other operators by providing an unprecedentedly low price.

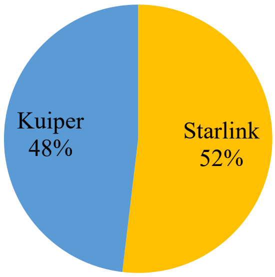

Figure 128: Phase one optimized Household segment market share by operator. Starlink still leads this segment, but Kuiper has gained significant share over the datum case.

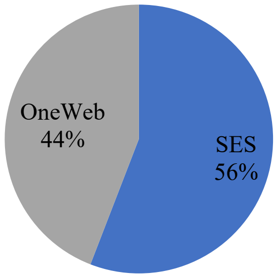

Figure 129: Phase one optimized Travel segment market share by operator. SES leads this segment.

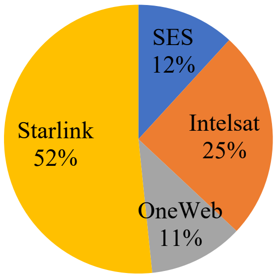

Figure 130: Phase one optimized Business segment market share by operator. Starlink with its lower costs seems to dominate this segment despite relatively late entrance.

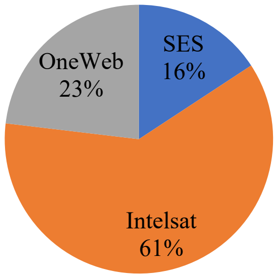

Figure 131: Phase one optimized Government segment market share by operator. Intelsat, founded with the express intent on servicing government customers, continues to dominate this segment.

Looking at the operators we observe that Kuiper has independently created a pricing strategy where they undercut the competition to stimulate demand and encourage customers already with an existing operator to switch. We see this in their high portion of stolen customers (Figure 127), the drop in customers for their competitor Starlink in 2026 at the same time Thuraya enters the market (Figure 126), and by the relatively high market share of the residential customer segment (compare Figure 128 with Figure 119). This is reminiscent of the strategy which the real-world satellite phone operator Thuraya engaged in when entering the satellite phone market relatively late in 2003. Entering the market late they achieve significant penetration by undercutting the competition and encouraging customers to switch. Owned by Amazon, Kuiper already had strong incentive to charge low prices and get customers online and using Amazon products, but this just emphasizes the importance of that strategy from a market penetration perspective. Operators should take this into account when planning strategies or targeting segments where Kuiper operates. For the remaining operators we see them generally following the principles of markets in oligopoly. Namely, similar prices for similar products with no operator wanting to drop prices and lose out in a race-to-the-bottom price competition.

As discussed previously, sustainability is more a function of cheap capital rather than revenue and falls outside the scope of this thesis. This means that the model is unable to definitively state the winners and losers; perhaps the low prices charged here are unsustainable and will result in operators declaring bankruptcy. However, for those which survive the revenues will be immense; this model predicts present value of revenue to be \$1.08 B for SES, \$3.41 B for Intelsat, \$1.33 B for OneWeb, \$27.3 B for Starlink, and \$1.31 B for Kuiper. Starlink appears to be the overall winner; they enter relatively early and have a huge amount of capacity. While performing roughly the same or better than the remaining operators, Kuiper perhaps fails to achieve its full potential due to its late entry, charging much less than market value, and only focusing on the residential customer segment. It's Starlink's dominance in the high-paying business segment which results in significant gains, not just the residential one.

6.2.3 Phase two constellation optimization

Many operators have indicated their desire to launch phase two constellations to expand capacity. Although it is unlikely that many of these will be fully realized, and perhaps even that the operators will exist throughout the entire period being simulated, their full phase two constellations were also simulated and run through the optimizer. Here we assume that all operators launch their phase two constellation and compare the market in such a scenario. Optimal prices for each operator across regions and segments are shown in Table 6 to Table 10.

Table 11: SES phase two optimized pricing strategies.

Region	Residential	Business	Travel	Government
Original (unoptimized)	N/A	$ 100,000 / year	$ 100,000 / year	$ 100,000 / year
Maritime	N/A	$ 4,520 / year	$ 4,260 / year	$ 9,120 / year
North America	N/A	$ 3,230 / year	$ 3,040 / year	$ 6,510 / year
Europe and Central Asia	N/A	$ 4,520 / year	$ 4,260 / year	$ 9,120 / year
Middle East and North Africa	N/A	N/A	N/A	N/A
Latin America and the Caribbean	N/A	$ 3,230 / year	$ 3,040 / year	$ 6,510 / year
East Asia and Pacific	N/A	$ 3,230 / year	$ 3,040 / year	$ 6,510 / year
South Asia	N/A	$ 4,520 / year	$ 4,260 / year	$ 9,120 / year
Sub-Saharan Africa	N/A	$ 4,520 / year	$ 4,260 / year	$ 9,120 / year

Table 12: Intelsat phase two optimized pricing strategies.

Region	Residential	Business	Travel	Government
Original (unoptimized)	N/A	N/A	$ 100,000 / year	$ 100,000 / year
Maritime	N/A	N/A	$ 4,180 / year	$ 9,010 / year
North America	N/A	N/A	$ 3,580 / year	$ 7,720 / year
Europe and Central Asia	N/A	N/A	$ 4,180 / year	$ 9,010 / year
Middle East and North Africa	N/A	N/A	$ 1,790 / year	$ 3,860 / year
Latin America and the Caribbean	N/A	N/A	$ 1,190 / year	$ 2,570 / year
East Asia and Pacific	N/A	N/A	$ 1,790 / year	$ 3,860 / year
South Asia	N/A	N/A	$ 2,980 / year	$ 6,430 / year
Sub-Saharan Africa	N/A	N/A	$ 4,180 / year	$ 9,010 / year

Table 13: OneWeb optimized pricing strategies.

Region	Residential	Business	Travel	Government
Original (unoptimized)	N/A	$ 100,000 / year	$ 100,000 / year	$ 100,000 / year
Maritime	N/A	$ 8,660 / year	$ 8,010 / year	$ 9,150 / year
North America	N/A	$ 7,420 / year	$ 6,860 / year	$ 7,840 / year
Europe and Central Asia	N/A	$ 8,660 / year	$ 8,010 / year	$ 9,150 / year
Middle East and North Africa	N/A	$ 3,710 / year	$ 3,430 / year	$ 3,920 / year
Latin America and the Caribbean	N/A	$ 4,950 / year	$ 4,570 / year	$ 5,230 / year
East Asia and Pacific	N/A	$ 7,420 / year	$ 6,860 / year	$ 7,840 / year
South Asia	N/A	$ 8,660 / year	$ 8,010 / year	$ 9,150 / year
Sub-Saharan Africa	N/A	$ 8,660 / year	$ 8,010 / year	$ 9,150 / year

Table 14: Starlink optimized pricing strategies.

Region	Residential	Business	Travel	Government
Original (unoptimized)	$ 1,440 / year	N/A	$ 1,440 / year	N/A
Maritime	$ 910 / year	N/A	$ 5,140 / year	N/A
North America	$ 910 / year	N/A	$ 5,140 / year	N/A
Europe and Central Asia	$ 910 / year	N/A	$ 5,140 / year	N/A
Middle East and North Africa	$ 780 / year	N/A	$ 4,400 / year	N/A
Latin America and the Caribbean	$ 260 / year	N/A	$ 1,470 / year	N/A
East Asia and Pacific	$ 910 / year	N/A	$ 5,140 / year	N/A
South Asia	$ 130 / year	N/A	$ 730 / year	N/A
Sub-Saharan Africa	$ 910 / year	N/A	$ 5,140 / year	N/A

Table 15: Kuiper optimized pricing strategies.

Region	Residential	Business	Travel	Government
Original (unoptimized)	$ 1,440 / year	N/A	N/A	N/A
Maritime	N/A	N/A	N/A	N/A
North America	N/A	N/A	N/A	N/A
Europe and Central Asia	$ 70 / year	N/A	N/A	N/A
Middle East and North Africa	$ 30 / year	N/A	N/A	N/A
Latin America and the Caribbean	$ 50 / year	N/A	N/A	N/A
East Asia and Pacific	$ 10 / year	N/A	N/A	N/A
South Asia	$ 60 / year	N/A	N/A	N/A
Sub-Saharan Africa	$ 40 / year	N/A	N/A	N/A

As summarized in Figure 132 and Figure 133, operators respond to the additional capacity in different ways. With very large phase two capacity increases the OneWeb, Starlink, and Kuiper operators find success by lowering prices to maximize constellation utilization. Kuiper with its especially large phase two constellation does this to the most extreme and receives significant benefit. We should expect that Kuiper will engage in aggressive growth behavior even if their phase one constellation isn't as successful as intended; it is their phase two which brings them the greatest benefit. SES and Intelsat have comparatively modest phase two rollouts and find an optimal strategy in slightly raising prices. The aggressive pricing behavior of the other constellations means that these smaller players must maximize revenue from existing 'sticky' customers. General pricing trends and strategies (such as Kuiper undercutting the competition and different regions being dominated by different players) hold out from the phase one analysis.

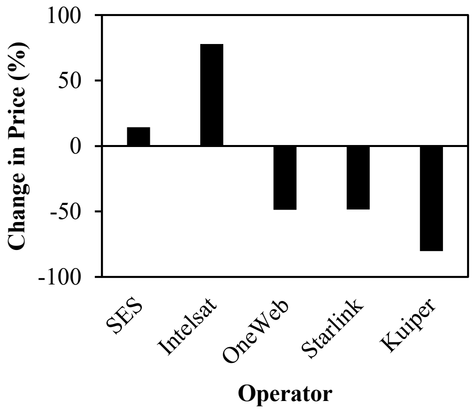

Figure 132: Effect of satellite launches on pricing. All operators launch their phase two constellation (except for Intelsat which has none).

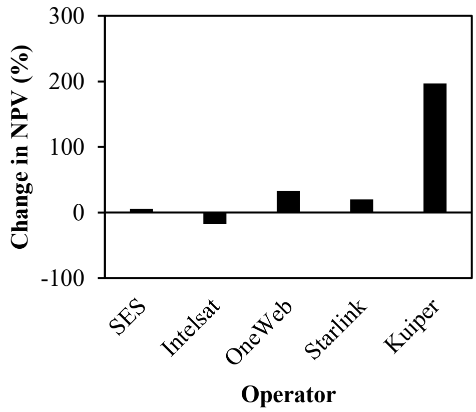

Figure 133: Effect of satellite launches on NPV. Kuiper has the greatest change in revenue and the largest phase two constellation.

6.2.4 Intelsat – SES merger forecast

In this scenario we see the effect of a merger of Intelsat and SES. As previously discussed, this is of key interest to customers, operators, and regulators as such an action has already been proposed by the operators. For this model we assume that all of Intelsat's assets as well as their customers move to SES in the merger. The merger event happens at the start of 2024 with the effect on operator NPV shown in Figure 134 and Figure 135. The model was run ten times with the average values shown. Note that because the model is calculated starting from 2020 and the merger only occurs in 2024, Intelsat still has NPV in the merger case: they don't just retroactively stop existing!

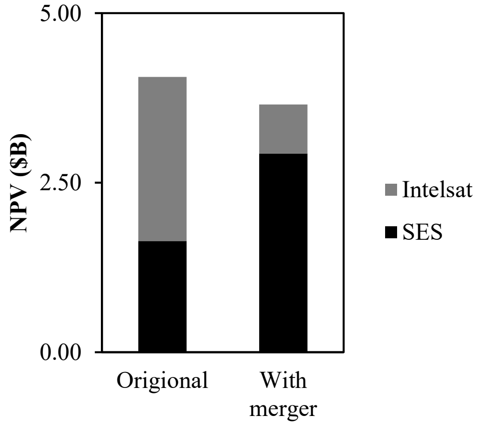

Figure 134: Effect of merger on participants. Total value of the participants falls because of the merger.

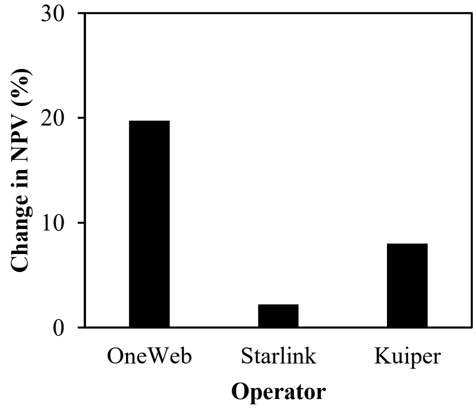

Figure 135: Effect of merger on other operators. Generally, they tend to benefit.

SES receives significant revenue gains, but surprisingly not as much as Intelsat would have earned had they remained separate. Overall there is a 10% loss in the present value of future revenues. One reason for this could be that the two were initially targeting different sub-segments of the travel category with Intelsat taking higher-value customers and SES a more competitive middle-tier. In this model the merger is formulated such that the legacy customers switch to the lower-cost SES service and thus do not provide the same value as they would if they had remained separate and these higher-value customers had persisted with Intelsat due to stickiness factors alone. From here we can recommend the decision makers behind the real merger to make the event as seamless as possible and continue to charge higher prices to legacy customers.

Operators not directly involved with the merger still see some benefits. After the merger customers are presented only with four potential suppliers rather than the original five. Therefore, we would naturally expect that with less competition customers are just statistically more likely to pick one of the operators who remains. This highlights the risks of abandoning an established brand during a merger; if the goodwill of the acquired is lost then the acquirer only benefits from the tangible assets.

6.2.5 Starlink – SES merger forecast

In this scenario we consider the effects of a merger between a large incumbent operator and a large new operator with Starlink acquiring SES in 2026. Results are shown in Figure 136 and Figure 137. In this case there are positive synergies with a increase in revenue of 2% for the merged operator. Such a cross-generational merger should be considered in further detail.

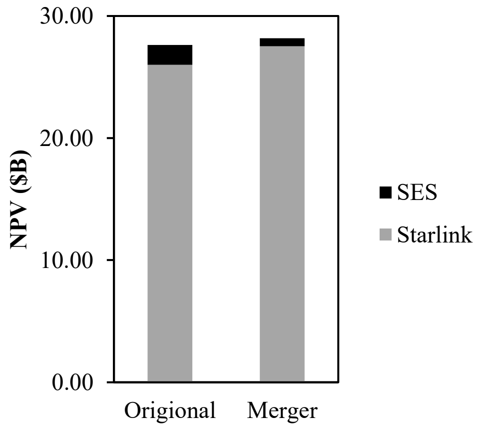

Figure 136: Effect of merger on participants. There are some synergies, although Starlink alone has very high revenue and the benefits are proportionally quite small.

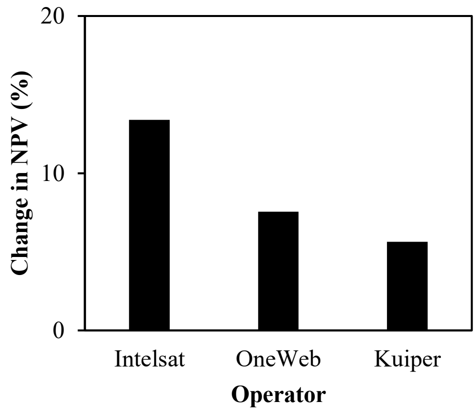

Figure 137: Effect of merger on other operators. As before, these other operators benefit from the merge.

6.2.6 Forecasted effect of substitute services rollout

An often-cited reason for the fiscal failure of Iridium and other satellite phone constellations was an unexpectedly high rollout of land-based alternatives – specifically fiber and cellular. In this final scenario we assess the effects of unexpectedly high and unexpectedly low rollout of fiber optic cable. In this case zero rollout means no change from 2023 values, a rollout of one is as predicted, and rollout of two is assuming rollout is twice as fast. To assist with understanding a plot of these different rollouts is shown in Figure 138 to Figure 140. This could also be considered snapshots of the fiber distribution over time if we used a rollout factor of two; starting in 2020 with Figure 138, moving to Figure 139 in 2030, and finishing with Figure 140 in 2040.

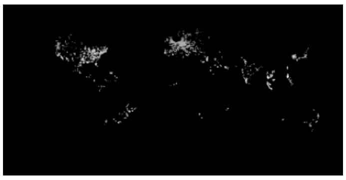

Figure 138: 2040 fiber distribution if we use a rollout factor of zero. This means no growth in fiber from the 2023 values.

Figure 139: 2040 fiber distribution if we use a fiber rollout factor of one (datum case).

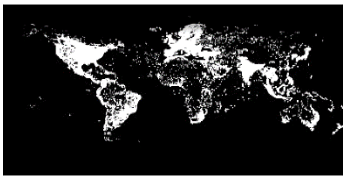

Figure 140: 2040 fiber distribution if we use a fiber rollout factor of two. Note that the rollout occurs twice as fast and thus we would expect to achieve the Figure 139 distribution by the year 2030.

Results with different rollout factors are shown in Figure 141 to Figure 145. Note the graphs are slightly bumpy due to each simulation needing to regenerate a random collection of customers. Results were averaged across three trials and performed in step sizes of 0.25.

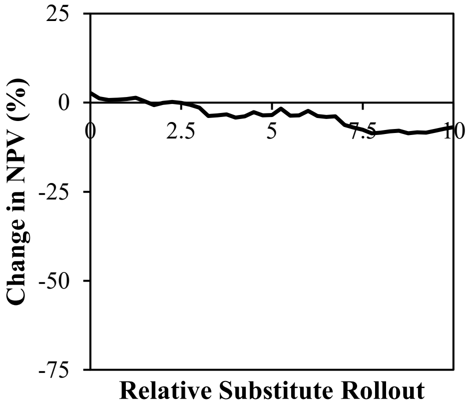

Figure 141: SES effect of relative fiber-optic rollout on operator NPV. SES is reletivly unaffected by additional fiber rollout.

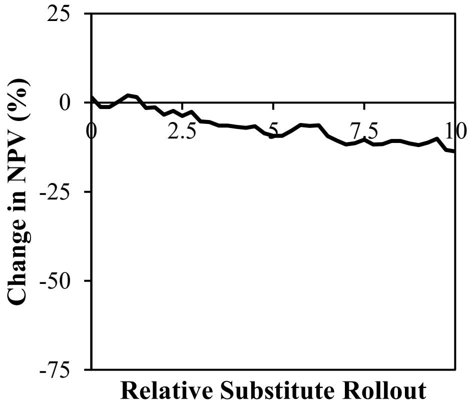

Figure 142: Intelsat effect of relative fiber-optic rollout on operator NPV.

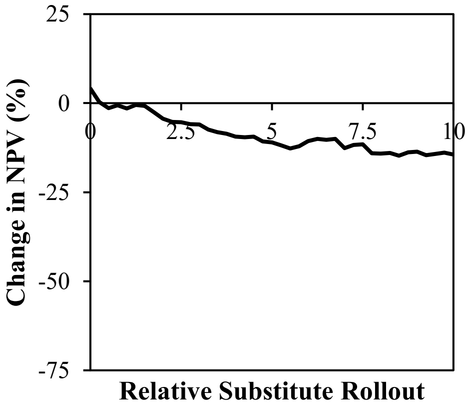

Figure 143: OneWeb effect of relative fiber-optic rollout on operator NPV.

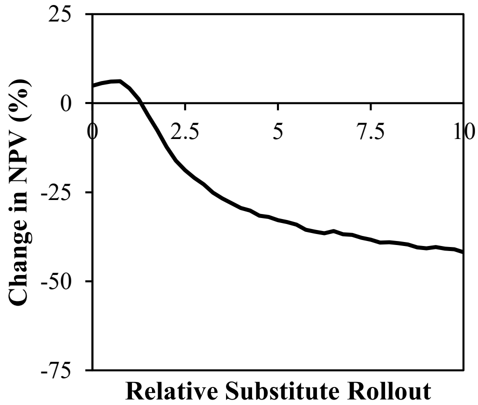

Figure 144: Starlink effect of relative fiber-optic rollout on operator NPV.

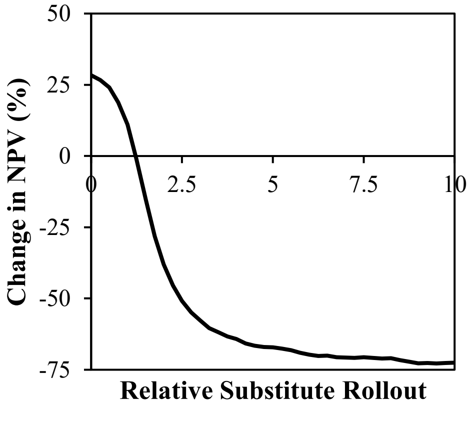

Figure 145: Kuiper effect of relative fiber-optic rollout on operator NPV. Kuiper stands to lose heavily from this substitute service.

From these results we observe that Starlink and Kuiper are most susceptible to land-based alternatives eating into their customer base. SES, Intelsat, and OneWeb rely more on mobile segments which are harder to replace, however they still experience a downwards trend as potential customers switch to the fiber alternative. SES with a mixture of travel, business, and government consumers was least affected and even in the ten-times-datum scenario lost less than 10% of their future revenues. Kuiper, comprised of exclusively household-type customers, was most affected and beyond a 2.5 x datum rollout lost more than 50% of their predicted revenues. This emphasizes the importance of a diversified customer base.

6.3 Chapter summary and conclusions

This chapter described the input parameters for the satellite internet market model and then presented the results of six forecasts conducted using ABSM. The forecasts provided insights into the performance and pricing strategies of satellite operators in various market segments and regions.

The first forecast, the datum forecast, aimed to estimate the revenues of satellite operators by closely matching their real-world pricing and segment strategies. It used available product offerings and estimates from operators to determine pricing, with best estimates made for operators that had not disclosed their pricing. The results showed steady growth in revenue for incumbent operators like SES, Intelsat, and OneWeb, while the more modern operators like Starlink and Kuiper experienced significant growth initially but faced revenue decline as households transitioned to land-based alternatives.

Further forecasts focused on optimizing pricing strategies for phase one and phase two constellations of satellite operators. The optimizer suggested new prices that maximize the expected operator return, considering different regions and customer segments. Competitive strategies such as region-based market segmentation and price differentiation were also highlighted. A key output of this section was the independent development of a price undercutting strategy exercised by Kuiper which has real-world parallels to the historical actions of satellite phone operator provider Thuraya in 2003.

The impact of mergers between satellite operators was examined in two forecasts: the Intelsat-SES merger and the Starlink-SES merger. These forecasts assessed the potential effects on the market and operator’s performance. The Intelsat-SES merger failed to produce significant synergies although Starlink-SES saw significant benefits.

Lastly, the forecasted effect of substitute services rollout, particularly land-based alternatives like fiber optic cable, was evaluated. Different levels of rollout were considered to assess the vulnerability of satellite operators to competition from these substitutes. Kuiper and Starlink, which rely on fixed land-based customers, were more at risk.

Overall, these forecasts and simulations provided valuable insights into the behavior and strategies of satellite operators in the communication industry. They shed light on market dynamics, customer acquisition, and revenue generation for different operators in various segments and regions. These findings can inform decision-making processes and help operators adapt to changing market conditions and emerging competition.

Chapter 7

Conclusion

The preceding chapters have delt with many of the interesting aspects of agent-based modelling (ABM) from where traditional tools fail, to the construction of a satellite-specific implementation of the approach (the Agent Based Satellite Market model or ABSM), historical calibration, and use in forecasting of the satellite internet market. This chapter reviews the key takeaways from the thesis, starting with a thesis summary (7.1 Thesis summary on page 172) and then continuing with a discussion on the key finding relating to ABM (7.2 Critical findings for agent based modelling on page 164) and satellite internet (7.3 Critical satellite internet findings on page 166). Next (7.4 Limitations on page 168), key limitations of the work are discusses and (7.5 Final comments on page 172) final comments made.

7.1 Thesis summary

Satellite communications have a long history and are expected to see significant future growth. Traditional equation-based modelling approaches are ill equipped for modelling the industry, but equation-based modelling shows promise. This thesis uses a custom agent-based tool to interrogate the market.

As described in the Literature Review on page 39, the existing literature on satellite network modeling has limitations in capturing the complexities of the satellite-based internet market. The assumptions of homogeneous demand distribution, neglecting competition, and revenue proportionality to capacity do not reflect the reality of the market. Structural model uncertainty, parameter uncertainty, and data uncertainty are identified as sources of uncertainty in these models. Overall, there is a need for more sophisticated and comprehensive models that capture the complexities of the satellite-based internet market. Improved modeling techniques and a deeper understanding of market dynamics can provide more accurate predictions and inform strategic decision-making for operators in this evolving industry with one promising approach being Agent Based Modelling (ABM).

In the best-case ABM has been shown to produce good results with low WMAP (<10%). It can generate new strategies and independently replicate existing ones. This makes it an important tool for predicting future system states and emergent behaviors. However, there is still a need to perform rigorous validation against historical data to make these results believable.

This literature review also highlighted the best ways to set up ABM for success. The model should begin by taking a broad and realistic view of the system being considered; physical realities of satellite-internet provision such as how satellites work, and supply data is essential. Some location-based considerations such as population centers and vacant zones ais essential. It is also useful to consider the complexities of customer agents, treating them as many individuals belonging to several segments rather than as a single homogeneous mass. Customers have different adoption times and can influence each other to buy or not buy a product. The model should be verifiable with significant existing data from which to compare.

Despite the strengths of existing literature there is a key gap which is filled by this thesis: the absence of comprehensive models that consider the dynamic interaction between satellite-based internet operators and customers in a competitive market environment. Existing studies have separately focused on operator behavior and customer adoption, but there is a pressing need for integrated models that capture the feedback mechanisms between operators and customers. Additionally, we observe that there has been limited consideration of market segmentation analysis within existing literature. To bridge these gaps, our research has utilized ABM techniques to simulate the complex dynamics of satellite-based internet markets. By integrating market segmentation analysis into the modeling framework, our provides a more accurate representation of the diverse customer base and their distinct demands. Through this analysis we contribute valuable insights into the dynamics of satellite internet markets and offer a more holistic understanding of this evolving industry.

As described in Model Assumptions on page 53, to go about making the model we began with several key assumptions of the market model, encompassing the system, operator, distribution mechanism, and customer aspects. These assumptions provide the foundation for simulating the dynamics of the market and understanding the interactions between operators and consumers. These assumptions can be summarized as

1. System Assumptions: The market consists of operators who supply products or services to customers using a distribution mechanism. The simulation represents the entire Earth as a sphere divided into cells, with high-resolution scale for customer distribution and amalgamated regions for operators. This assumption is supported by previous models and real-world examples.

2. Operator Assumptions: Operators aim to maximize their own net present value of cash inflows. Note that we do not consider cash outflows as these falls outside the

scope of this thesis. While operators cannot become bankrupt, they can merge with other operators. Operators cannot purchase or use each other's networks without a merger. Operators have the choice to launch or not launch additional capacity, and there is a time delay between deciding on an action and implementing it. Operators can only sell one product per customer segment and do not execute perfect market segmentation. Operators allocate capacity based on customer segment characteristics and an overbooking factor. Operators do not collude to fix prices, and some operators may be unable to supply certain segments. Operators can choose to exit a market even if they have the ability to supply it.

3. Distribution Mechanism Assumptions: The distribution mechanism consists of independent hubs (satellites) that service limited regions. Each hub has a limited capacity, which is divided evenly across the entire region. Hubs are at a steady state and cannot store capacity from one region to deliver it to the next. Constellations are comprised of identical hubs. Different constellation configurations have different efficiencies, and not all capacity can be fully utilized.

4. Customer Assumptions: Customers make decisions based on the theory of planned behavior, considering attitudes, subjective norms, and perceived behavioral control. The intention to purchase a product is influenced by these factors. Customers weigh these factors differently, leading to different purchasing decisions.

Building from this sturdy foundation Model Implementation on page 69 describes how the model is built and provides some basic test. The chapter began with a detailed breakdown of the model, including a control structure diagram illustrating the components of the model. The supply side is represented by industry operators and non-industry operators, while the demand side consisted of various customer segments. Operators aim to maximize their own present value of revenue. Customers make decisions according to the theory of planned behavior, considering factors such as service speed, peer adoption, and service cost.

The implementation of the model was followed by the validation using a generic satellite communications market. A series of tests were conducted to examine the effects of price, elasticity, capacity, and substitute products on revenue, number of subscriptions, and rejected subscriptions. The tests started with a single operator and customer segment and gradually introduced more operators and segments.

The results of the tests demonstrated the behavior of the model under different scenarios. For example, the effect of changing price showed that revenue increased until reaching a maximum, while the number of subscriptions and rejected subscriptions varied based on the willingness to pay and capacity. The effect of changing elasticity highlighted how different elasticity functions affected optimal prices and revenue. The effect of changing capacity demonstrated that revenue increased with capacity, but with diminishing returns.

The model was also benchmarked and when execution time was found to be intractably high the codebase was streamlined to reduce execution time from 122 days to 45 minutes.

With a working model the next chapter, Historical Calibration on the Satellite Phone Market 1995-2005 on page 93, used an appropriate historical study through which to compare accuracy of the model.

To begin, several industries including fast food, car years, and TV advertising slots were assessed before identifying satellite phones as an industry most like satellite internet. The satellite phone industry from 1995 to 2005 was researched and fed into the ABSM.

The satellite phone model initially ran without calibration with these the uncalibrated results showing poor forecasting performance with high weighted mean absolute percentage errors (WMAPE) for all operators. The average WMAPE was 77.7%, indicating inaccurate forecasting. Significant calibration was applied to improve the model's performance.

The calibration process involved adjusting various parameters within specific ranges to minimize WMAPE and match the general shape of the revenue and customer subscription curves. The calibrated model showed significant improvements in forecasting accuracy, with lower WMAPE values across all operators. The average WMAPE decreased to 12.4%, falling within the good forecasting region defined by [75]. This is in the same ballpark as previous studies. Agarwal's single-datapoint study saw a WMAPE of 11.3% [53]. Bennett et al. [80] achieved a WMAPE of 11.7% for their single-operator economic model. These also fall into the good forecasting region defined by [75]. With four customer segments and four different operators the ABSM was significantly more complex and by design, operator-specific calibration was not implemented. Thus, while still numerically worse than these previous studies, overall, the ABSM performs very well. Performing an analogous intra-species analysis for accurate comparative assessment ('comparing apples to apples') if we consider just a single operator with revenue only (as in Agarwal [53] Bennett et al. [80]) then the best performing forecast achieves a WMAPE of 8.8% or highly accurate forecasting. This is better than any of the published literature studies. However, this just again emphasizes that applying the model to a single operator produces can tend to provide undue confidence in model results.

Sensitivity analysis was conducted to assess the model's responsiveness to variations in customer size, subscription prices, substitute service rollout, and operator capacity. The results showed that different operators were more sensitive to competitor capacity, own capacity, rollout of substitutes, and competitor pricing and less sensitive to the specific theory of planned behavior weightings.

Now calibrated and ready for use with modern satellite internet data, Satellite Internet Forecast 2020-2040 on page 129 described the input parameters for the satellite internet market model and then presented the results of six forecasts conducted using ABSM.

The first forecast, the datum forecast, aimed to estimate the revenues of satellite operators by closely matching their real-world pricing and segment strategies. It used available product offerings and estimates from operators to determine pricing, with best estimates made for operators that had not disclosed their pricing. The results showed steady growth in revenue for incumbent operators like SES, Intelsat, and OneWeb, while the more modern operators like Starlink and Kuiper experienced significant growth initially but faced revenue decline as households transitioned to land-based alternatives.

Further forecasts focused on optimizing pricing strategies for phase one and phase two constellations of satellite operators. The optimizer suggested new prices that maximize the expected operator return, considering different regions and customer segments. Competitive strategies such as region-based market segmentation and price differentiation were also highlighted. A key output of this section was the independent development of a price undercutting strategy exercised by Kuiper which has real-world parallels to the historical actions of satellite phone operator provider Thuraya in 2003.

The impact of mergers between satellite operators was examined in two forecasts: the Intelsat-SES merger and the Starlink-SES merger. These forecasts assessed the potential effects on the market and operator’s performance. The Intelsat-SES merger failed to produce significant synergies although Starlink-SES saw significant benefits.

Lastly, the forecasted effect of substitute services rollout, particularly land-based alternatives like fiber optic cable, was evaluated. Different levels of rollout were considered to assess the vulnerability of satellite operators to competition from these substitutes. Kuiper and Starlink, which rely on fixed land-based customers, were more at risk.

Overall, the ABSM and the associated forecasts and simulations provided valuable insights into the behavior and strategies of satellite operators in the communication industry. These findings can inform decision-making processes, helping operators adapt to changing market conditions, emerging competition, and make informed decisions regarding pricing strategies, capacity planning, and market competition in the satellite internet industry. The validated model is ready for use with modern satellite internet data, offering a powerful tool for forecasting and strategic planning in the evolving satellite internet market.

7.2 Critical findings for agent based modelling

Creation and use of the Agent Based Satellite Market model (ABSM) has highlighted both the upsides and downsides of the agent base modelling technique and suggested future improvements available to researchers.

From a utility perspective it has been further demonstrated that that agent-based modelling can produce reasonable results with a close match to historical values with a WMAPE of 12.4%. This neatly complements existing literature which suggests 11-12% is reasonable for this approach. Unlike previous studies this model is applied simultaneously for multiple agents, demonstrating how good accuracy can be maintained even as model complexity increases.

ABM is often used for its ability to generate new competitive strategies. While previous literature for internet market modelling did not show this emergent property this thesis did. Agents generate some of their own strategies. For example in one forecast (6.2.2 Phase one constellation optimization on page 143) Kuiper independently created a pricing strategy where they undercut the competition to stimulate demand and encourage customers already with an existing operator to switch to the lower-cost Kuiper service. Customers are typically resistant to changing operators due to high switching costs such as needing to purchase new equipment. However we see evidence of this occurring with Kuiper's high portion of stolen customers (Figure 127), the drop in customers for their competitor Starlink in 2026 at the same time Thuraya enters the market (Figure 126), and by the relatively high market share of the residential customer segment (compare Figure 128 with Figure 119). This is reminiscent of the strategy which the real-world satellite phone operator Thuraya engaged in when entering the satellite phone market relatively late in 2003. Entering the market late they achieve significant penetration by undercutting the competition and encouraging customers to switch.

Another benefit of ABM is its flexibility in adapting to new restrictions of stakeholder needs. As is typical with engineering projects, the ABSM went through several iterations and with each the project stakeholders would review the results and recommend changes or additional customer behaviors. For example, the action of acquiring a competitor was implemented late into the project, and entirely new decision parameters for both operators and customers were added in as a response to initial results.

One problem identified with ABM highlighted was the cold-start problem. The simulation must start somewhere and if this is after one of the operators has already entered the market and is attracting customers then this results in an initial underestimation of revenues. This is most clearly demonstrated in the Inmarsat case (Figure 78 on page 120) where predicted revenue is well below historic revenue until 1998. This could be counteracted by pre-assigning customers or starting the simulation even earlier. Over time this problem becomes less pronounced as the model can evolve naturally.

As discussed within the literature review, an ongoing limitation of ABM is that it is difficult to determine the precise agent inputs required. Initially in this thesis it was (naïvely) anticipated that industry operators would willingly provide their customer statistics from which to build the model. However, not only would this likely violate company privacy agreements, but in many cases and especially with new industries such data does not exist. The use of historical case studies and reviewing the literature for useful inferences is still a requirement.

Another downside of ABM is that as the number of agents increases so does the computational demands of running the model. Initially the model took 144 days to run. Speed improvements made by grouping similar customers, calculating key values iteratively, and rewriting certain sections to run in parallel were found to take calculation time from months to minutes. This linearized problem complexity and provided a 4,500 times speedup; taking just 46 minutes to run. Although parallel computing and GPUs were used for some calculations this tended to reduce stability meaning that often such speed increases had to be abandoned to run the model for an extended period. An additional approach to reduce calculation time was to group similar agents together into a 'super agent' which would act on behalf of its constituents. Ten thousand and one hundred thousand super-agent models produced very similar results to the one million agent model with WMAPEs of 2.8% and 0.91% respectively.

7.3 Critical satellite internet findings

This thesis has interrogated many aspects of the satellite-based internet market. In general, the market looks like it will retain strong profitability over the coming decades with several key findings presented.

1. Even in the datum forecast (6.2.1 Datum forecast on page 138), which removes much of the operator's ability to respond to market conditions, operators have significant revenues. SES has present value of cash flows at \$11.5 B, Intelsat \$14.4 B, OneWeb \$9.7 B, Starlink \$39.4 B, and Kuiper \$14.2 B. Starlink with their early market entrance and huge capacity appears to be a winning combination. Despite their late entrance Kuiper performs well due to competitive pricing (pegged to their only segment-specific competitor Starlink) and high capacity. OneWeb performs the worst, possibly due to their late entrance and relatively low phase one capacity. Of the incumbent operators Intelsat performs the best perhaps due to their dominance in the government sector (see Figure 122 on page 142).

2. As capacity floods the market prices will be driven downward (see Table 6 to Table 15), connecting an ever-increasing number of people from across the planet. For North American Business-type consumers the predicted subscription price falls from \$100,000/year to \$4,520/year and eventually \$3,230/year as operators adopt to the market conditions and launch additional phase two capacity. For households there is even more extreme dropping from \$1,440/year to \$900/year to \$70/year. This is especially driven by price undercutting strategies by late market entrants. Low prices and high volumes suggest a trend toward commodification of the market.

3. A diversified strategy is less risky in the face of land-based substitutes. While residential customers are a large and lucrative segment due to its size (see Figure 107 on page 135) these segment is most likely to switch to land-based alternative services. Forecasting the effects of fiber rollout, we see how different operators respond. SES with a mixture of travel, business, and government consumers was least affected and even in the ten-times-datum scenario lost less than 10% of their future revenues (see Figure 141 on page 154). Kuiper, comprised of exclusively household-type customers, was most affected and beyond a 2.5 times datum rollout lost more than 50% of their predicted revenues (see Figure 145 on page 154). This emphasizes the importance of a diversified customer base. While operators targeting traditional segments are unlikely to benefit from such explosive growth, they are likely to remain profitable into the foreseeable future.

4. Late market entrants such as Kuiper are likely to engage in extreme price undercutting to drive market share. For example in one forecast (6.2.2 Phase one constellation optimization on page 143) Kuiper independently created a pricing strategy where they undercut the competition to stimulate demand and encourage customers already with an existing operator to switch to the lower-cost Kuiper service. Those with existing networks and strong customer bases may instead keep prices high in the hopes of maintaining profitability by keeping a loyal pool of high-paying customers (see Figure 123 on page 146). If significant switching costs cannot be established, then it is likely that these operators will reduce prices to keep up with these new entrants.

5. As prices fall operators will engage in merging behavior and regulators should be vigilant against a single operator gaining too much control and being able to exert undue rents. Mergers of similar operators do not tend to produce synergies (compare Figure 134 with Figure 136 on page 151). Examination of merger scenarios saw that an Intelsat-SES merger would result in an overall 10% loss in the present value of future revenue. It appears that SES was unable to provide the services anticipated by the original Intelsat customers and these customers either switched providers or else paid for the cheaper SES service rather than keeping at their original higher subscription

cost. Examination of a Starlink-SES merger found slight synergies (2% increase in present value of revenue). However, some level of merging appears to be beneficial to all market participants (see Figure 135 and Figure 137 on page 151). Cross-generational mergers also provide significant synergies and should be studied in further detail.

7.4 Limitations

Despite this model's rigorous foundations, historical calibration, and reasonable results, such results should be taken with some level of skepticism.

Among the assumptions discussed, perhaps the least realistic assumption is that operators do not become bankrupt. While the assumption is based on the observation that modern satellite operators have been able to survive longer periods of financial struggle, it overlooks the inherent risk and uncertainty associated with business operations. In reality, operators, especially in competitive markets such as satellite internet, can face financial challenges that may lead to bankruptcy if they cannot sustain profitability or secure affordable funding for their ventures. The assumption of operators not becoming bankrupt simplifies the model and disregards the potential consequences of financial instability in the market. Closely tied to this issue there is no mechanism to estimate the costs of doing business and therefore operators are revenue-maximizing agents rather than profit-maximizing. This means that the simulated operators will typically choose behaviors such as expanding the constellation or selling to as many customers as possible while in reality the costs of performing such actions may often outweigh revenue increases. At the very least, a one-off sale (i.e., without ongoing subscription revenue) of an internet terminal for \$10 that costs \$100 to make while increasing revenue will be actively harmful to income.

Another assumption of note is that of the rollout of substitute services, specifically how the data for cell tower rollout (5.2.3 Substitute service on page 115) and fiber rollout (6.1.3 Substitutes on page 136) may not accurately reflect the realities of the situation. As a reminder, since data regarding when the towers were constructed, and the stages involved in the rollout of fiber were not available a substitute statistic was created by considering the 2023 status of 2G and 5G towers. The ‘G’in 2G and 5G is an indication of the generation of the communication technology with 2G established 1991, followed by 3G (2001), 4G (2009), and 5G (2019). In this thesis we have we use the status of these 2G and 5G technology to extrapolate the hypothetical rollout of cell towers and fiber internet. A reader familiar with astronomy is invited to draw parallels with how we can look ‘backwards’ in time by looking at galaxies progressively farther and farther away. In this case we consider the present (2023) status of the very new 5G technology 5G to be a good analogue to the original status for the start of substitute rollout (1995 status of cellphone towers or the 2020 status of fiber internet) and then the present rollout distribution of the older 2D technology to represent the end of substitute rollout (2005 status of cellphone towers of the 2040 status of fiber internet). This assumption was assumed to be reasonably accurate as it provides a comparative case to show technology starting in cities and places of high population density (current 5G status) and then spreading to more rural areas but still with a bias for populated regions with budget for infrastructure investment (current 2G status). Obviously, such a simplistic approach has limitations.

1. Assumption of accurate substitute statistics: The assumption that the present status of 5G technology can be used to extrapolate the hypothetical rollout of cell towers and fiber internet assumes that it accurately reflects the realities of the situation. However, this may not be the case. The substitute statistics created based on the status of 2G and 5G towers in 2023 may not accurately represent the actual rollout of cell towers and fiber internet in previous years. Without specific data on tower construction and rollout stages, the substitute statistics are speculative and may not capture the complexities of the real situation. Without accurate historical data on the actual rollout of cell towers and fiber internet, it is challenging to make reliable extrapolations or comparisons. The approach assumes that the 2023 status of 2G and 5G towers can be used to represent the past and future rollout, respectively, but this assumption may not hold true.

2. Oversimplification of the rollout process: The approach assumes a simplistic model of technology rollout, starting in cities and high-density areas (represented by the current 5G status) and gradually spreading to rural areas (represented by the current 2G status).

While this model may capture some general trends, it overlooks the complexities and variations in the rollout process. Factors such as infrastructure investment, regulatory considerations, geographical constraints, and market dynamics can significantly impact the rollout, and a simplistic model may not accurately reflect these nuances. The model interpolates linearly while it may proceed in a non-linear fashion tied to local election cycles and the availably of resources.

3. Lack of validation: Since the approach relies on substitute statistics and assumptions, it lacks empirical validation. Without comparing the extrapolated results with actual historical data or conducting thorough analysis and validation, the accuracy and reliability of the approach remain uncertain.

Overall, while the approach may provide some insights and analogies, it has inherent limitations due to the reliance on substitute statistics, oversimplification of the rollout process, lack of historical data, and insufficient consideration of other relevant factors.

The model also fails to account for some operational realities of real satellite operators. We assume that satellite operations are not affected by atmospheric conditions or space weather. In reality, atmospheric conditions such as temperature, humidity, and atmospheric pressure can impact satellite communication links, leading to signal attenuation and interference. Factors like rain, fog, and atmospheric turbulence can degrade the quality and reliability of satellite communications. Additionally, space weather events like solar flares, coronal mass ejections, and geomagnetic storms can generate intense radiation, charged particles, and magnetic disturbances, causing disruptions, power outages, communication blackouts, and potential damage to satellite components. Ignoring the influence of these environmental factors in the model assumes an idealized scenario where satellites operate unaffected by external conditions, whereas in practice, they are crucial considerations in satellite system design, operation, and risk management.

While modelled to a greater level of detail than any previously published work, the customer agents are still limited. The market is only divided into 32 segments (four classes and eight regions) which is inherently reductive. New technologies such as drones, driverless cars, and IOT devices were largely ignored from the analysis or combined with these broader historical groups. If these technologies do take off (especially likely in the case of drones) then operators will need to develop new products and new strategies to target them. Such strategies remain outside the scope of this work and should rely on in-person interviews and product tests to better estimate. The ABSM has showed its potential in generating novel operator strategies but was not given the opportunity to do the same for customers. Modelling smaller 1° x 1° regions and allowing those customers to engage in game-theory-type cooperative behavior such as the establishment of communal connectivity hubs or the development of ISPs could be a useful tool in recommending future product offerings. These regions could then be combined to simulate the entire internet ecosystem.

Operator agents are similarly limited. Only five major operators were considered, and their analysis hindered by lack of detailed customer and strategy information. Making predictions based on what operators say they will do rather than what they will do is also difficult. Of especial concern, this model was only concerned with operator revenues and not their expenses. Such expenses are hard to establish (even for the operators themselves!), but even approximations could help to better estimate minimum pricing and whether an operator will engage in capacity expansion. For example, if it costs Starlink $100 to build a user terminal then it is unlikely that they will sell internet subscriptions for less than this price. This will exert an upwards pressure on pricing, suggesting that the values calculated here act as a lower bound for the true cost of internet products. Further simplifications such as the use of only a single price (except in cases of responding to extreme price undercutting) should also be interrogated further.

7.5 Final comments

The satellite-based internet market is one of significant growth potential and a windfall too for those who can compete. As the market is flooded with capacity old operators will find new ways to remain profitable, entrants will carve out their own niche, and low-cost internet will be made available to hitherto unreached populations. Agent-based modeling gives us the tools through which to imagine what this future will bring.

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