5-1-2010

Print media paper consumption patterns through a system dynamics approach

Alicia Tejada Abreu

ROCHESTER INSTITUTE OF TECHNOLOGY

Print Media Paper Consumption Patterns through a System Dynamics Approach

A Thesis

Submitted in Partial Fulfillment
of the Requirements for The Degree of
Master of Science in Sustainable Engineering

In the

Department of Industrial and Systems Engineering
Kate Gleason College of Engineering

by

Alicia M. Tejada Abreu

May, 2010

DEPARTMENT OF INDUSTRIAL AND SYSTEMS ENGINEERING

KATE GLEASON COLLEGE OF ENGINEERING

ROCHESTER INSTITUTE OF TECHNOLOGY

ROCHESTER, NEW YORK

CERTIFICATE OF APPROVAL

M.S. DEGREE THESIS

The M.S. Degree Thesis of Alicia M. Tejada Abreu
has been examined and approved by the
thesis committee as satisfactory for the
thesis requirements for the
Master of Science degree

Approved by:

____
Dr. Marcos Esterman, Thesis Adviser

____
Dr. James Winebrake

____
Dr. Brian Thorn

ACKNOWLEDGEMENTS

I would like to thank my thesis supervisor Dr. Marcos Esterman in the most grateful way possible for his guidance, teaching, and endless patience and morale support through the completion of this thesis. I learned a great deal through my interaction with Dr. Esterman and I am particularly thankful for his advice and encouragement throughout this process.

I am also grateful to members of my committee, Dr. James Winebrake and Dr. Brian Thorn for their critical opinion, recommendations and valuable suggestions. Being an experienced systems thinker, Dr. Winebrake always brought to the table practical advice and gave me the guidance and confidence to learn and practice system dynamics modeling. Sitting in several of Dr. Thorn's courses, I was formally introduced to sustainability issues, which spurred my intellectual curiosity and passion on the topic.

I would like to recognize my parents Roberto and Margarita, and my siblings Roberto Enrique and Ana Carolina. Thank you all for your unconditional love and support, and for have instilled in me the importance of work ethic and personal and professional growth. This thesis is dedicated to you.

Finally, I wish to express my deepest appreciation to my dear friends. Thank you for your friendship, love, and encouragement, and for your honest and professional opinion.

The support, guidance, and encouragement of all the above mentioned people throughout my educational endeavors, gave me the strength and confidence to complete this degree.

Thank you all very much!

ABSTRACT

As awareness of the current unsustainable state of our society increases, it has become evident that immediate action is needed to change this state. Many of the ecological changes that threaten the long-term survival of humans and of other species have anthropogenic origins. Industry's impact and its role in mitigating these impacts is the focus of much discussion and debate. Two industries that are working to deal with these issues are the printing and paper industries. The environmental impacts associated with the entire life-cycle of paper are significant, yet the socially redeeming value of the content printed can be equally as significant. A curious paradox is that advances in information and communication technology (ICT) have long been predicted to lead to a reduction in media use, resulting in the so-called *paperless office*, but this has not been the case. Until recently, the observed trends worldwide demonstrate that in most countries paper consumption has been on the rise, however in some developed countries there is some suggestion that this trend may be reversing. The work of Sellen and Harper (2002) provides a qualitative explanation of why paper consumption is on the rise. Nonetheless, there is little research that develops quantitative models to explain paper consumption patterns. This thesis leverages Sellen and Harper's qualitative models to develop a system dynamics model to explain the effects and interactions between ICT, the *affordances* of paper and *paper-like* technologies, and knowledge work flows. Specifically, the Bass Diffusion technology adoption model and the path dependence patterns of behavior are modified in an attempt to reproduce the paper consumption patterns observed in the United States (US). Sensitivity analysis through the use of a fractional factorial experiment has been performed to identify the most influential model parameters to set the model parameters at values that best represent US data. An assessment of the system dynamic model's utility based on a publically available quantitative study of the amount of original information that is produced and stored each year is also presented in this study. The thesis will close with recommendations to improve the model and for future research work.

Contents

FIGURES

Tables

1. Introduction

Chapter 1 gives a short description of the motivators for understanding print media paper consumption patterns through a system dynamics approach. This chapter first introduces the main environmental problems related to the production, consumption, and final disposal of printing and writing paper. Next, historical trends for paper and paperboard production and consumption, worldwide and for the United States are presented. Then, System Dynamics is introduced as a powerful methodology and technique that can help to assess paper consumption patterns in a holistic manner. Subsequently, the problem statement, together with the research objectives and the novel contribution of this thesis is presented and discussed. Finally, an outline of the thesis structure is presented and concludes Chapter 1.

1.1 Motivation to Understand Print Media Paper Consumption Patterns

The adoption of sustainable practices and the respect and wise use of natural and human capital cannot be delayed any more. Many of the ecological changes that might affect the survival of humans and millions of other species are from anthropogenic origins (Cairns Jr., 2009). This means that the solutions to build a better today and tomorrow are in the hands of those who created the problems in the first place, in our own hands. Change will be required of everyone and needs to come from many sources: from all types of companies and business, from the general public, and from the government. Nowhere is this more critical than in developing countries where the paradigm for development has yet to be defined. It is not written in stone that the path to a higher standard of living will require the environmental and social impacts that are typically attributed to the economies that are currently considered developed.

Along these lines, economic growth should no longer be the only metric to measure progress and standard of living. The often unaccounted effects on our natural and human capital and the ability of a nation to sustain healthy progress over time also have to be taken into account. The importance of measuring progress through these three vectors (economy, environment and society) is becoming more obvious and is drawing institutions', the government's and the general public's attention into the search of new ways to embrace sustainable development. Not only it is ethical to respect our natural resources, but it is also necessary to remain competitive in the market.

For this reason, in recent years, an increasing number of corporations have started to focus on their business practices that effect the environment and many are publicly advertising their efforts targeted towards ecological sustainability and social responsibility. Whether their objective is to reduce costs through ecological efficiency, capture "green" markets, improve their image, or establish better community relations (Shrivastava, 1995), corporations have come to realize that when they operate efficiently, it's not just a matter of eco-image; it's about making money (Amory Lovins, 2007). Examples of corporations that are taking the lead with sustainability initiatives are Nike, with their *old sneaker take back and recycling* program, Coca Cola with their *100% bottle recycling* campaign (Veleva, 2008), Dell who became the first computer maker in the United States to take back its end-of-life computers (Veleva, 2008), and Wal-Mart with their ambitious *Sustainable Product Index* (Walmart, 2010). Two specific industries that are working to deal with sustainability issues are the printing and paper industries. The environmental impacts associated with the entire life-cycle of paper are significant, yet the socially redeeming value of the content printed can be equally as significant.

Figure 1-1 shows the typical phases of the lifecycle of paper products. The paper cycle typically begins in the forest where fiber for paper and paperboard production is extracted from wood. The fiber is then transported to the pulp mills where it is prepared for paper and paperboard production. After paper and paperboard is produced, it continues to the conversion phase in which the paper and paperboard is transformed depending on the desired final use, such as packaging, sanitary, or periodical uses. The use phase follows, and in the case of printing and writing paper (PW paper hereafter), printing processes might take place. For the end-of-life of paper products, several strategies may take place: paper can be sent to a landfill, incinerated, used for composting, or recycled. For recycling end-of-life strategies, waste paper is collected, sorted, and separated from non paper contaminants. After the recovered fiber is processed it can be used for papermaking. Depending on the quality of the final paper, quantities of virgin pulp may be added. However, some paper products, such as newsprint and corrugated materials can be made from 100% recycled paper.

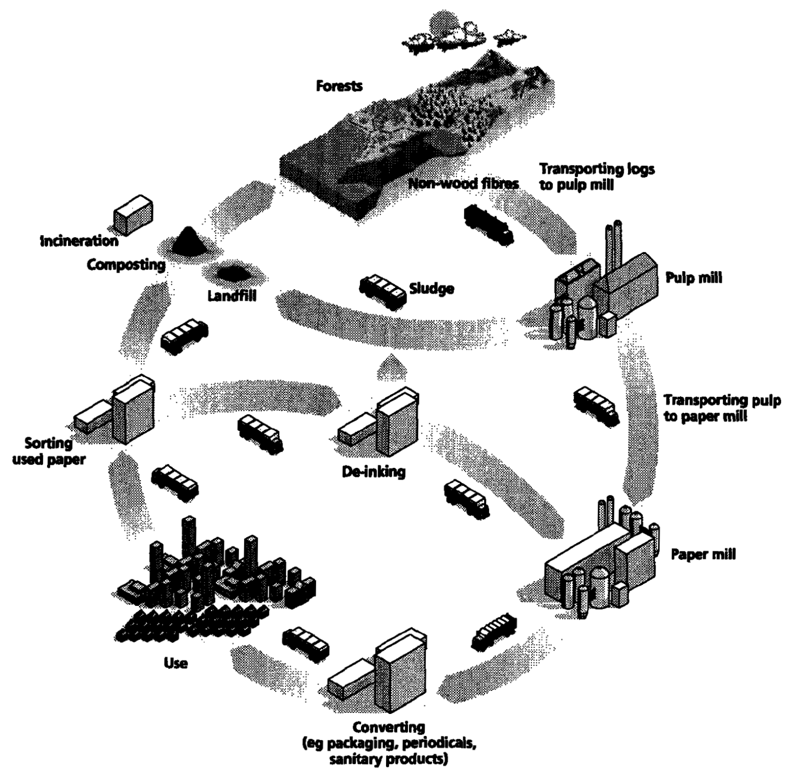


Figure 1-1.The Paper Cycle (Maryanne Grieg-Gran, 1997)

Contrary to expectations of a paperless office, the consumption of printed and writing paper has significantly increased as humanity's economy and population continue to grow.

With paper consumption on the rise, the environmental problems or negative environmental externalities associated with every stage of the paper lifecycle has also increased. The negative environmental externalities of the paper cycle include problems related such as deforestation, toxic pollution, excessive water and high-energy consumption, solid waste production, and air pollution. For instance, 42 percent of the industrial wood harvest is used to make paper and even though current harvest of pulp for paper products is in its majority from managed forests, as demand rises, pressure on unmanaged forests is likely to increase (WRI, 1998, updated June 2001). Within the forest products industry, the pulp and paper industry uses 84 percent of the energy consumed by the forest products industry (EIA, 2000), and the 2006 Manufacturing

Consumption Survey conducted by the Energy Information Association, ranked the industry as a whole the third largest industrial consumer of energy, only behind the petroleum and chemicals industry (EIA, 2006).

The paper industry also generates large volumes of wastewater that negatively affects fresh water resources (Abbasi & Abbassi, 2004). For example, liquid effluents from mills include a whole range of organic, toxic, and chlorinated organic matter that adversely affects water quality and can be lethal to fish (WRI, 1998, updated June 2001). Paper accounts for 38.1 percent of landfill waste, and paper and paperboard are included within the products that are projected to increase faster than population until 2010 (EPA, 2008). The significance of these negative externalities increases, as the demand for paper products increases as well, and as the natural reservoirs of dilution and assimilative capacities become exhausted (Ayres & Kneese, 1969).

Regardless of the negative externalities, the inherent value delivered by paper products can be equally or even more significant. The pulp and paper industry is an important economic agent, and paper products make a vital contribution to education, communications, packaging, and health care (Maryanne Grieg-Gran, 1997).

Consequently, when considering the sustainability of paper consumption, one must not only factor in the negative impacts, but one must also consider the inherent value delivered by it, discussed further in the following sections.

1.1.1 Historical Paper Consumption Patterns

Advances in Information and Communication Technologies (ICTs), along with its rapid spread throughout the world have created new and revolutionary ways to communicate, store, and have access to vast amounts of information. For this reason, it was expected, and actually it still is,

that ICTs would have substituted, if not all at least in great part, the use of paper by this time; however, this hasn't been the case.

Contrary to these predictions, according to data from Earth Trends (2008), instead of going paperless, world paper consumption per capita experienced exponential growth, at least from 1962 to 2005 (WRI, 2008), which translated to an increase in paper consumption by a factor of 20 last century meaning that it tripled in a period of 30 years, from the 70s to the ends of 2000s (WRI, 1998, updated June 2001).

Figure 1-2 and 1-3 are a good representation of the recent state of paper and paperboard production and consumption worldwide. Specifically, figure 1-2 shows the amount of paper and paperboard produced by country, while figure 1-3 compares per country paper consumption vs. GDP. The size of the bubble in both figures indicates the total amount of paper that is being produced and consumed in each country respectively. The color of the bubble in figure 1-3 indicates the change in paper consumption from 2000 to 2005.

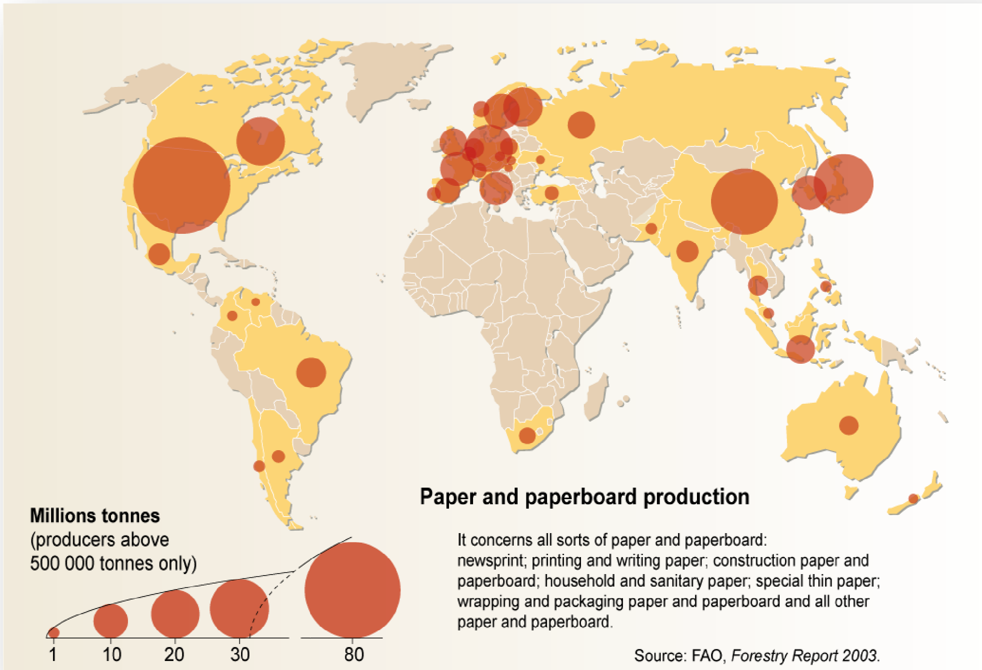


Figure 1-2. Total Paper and Paperboard Consumption Per Capita by Country (Marin, 2003 published in 2006)

In figure 1-2 and 1-3 one can observe how the U.S., and developed countries in general, are the greatest producers and consumers of paper and paperboard, although in figure 1-3 for the majority of the developed countries the bubble's light blue color suggests that paper and paperboard consumption might be starting to decrease. However, while paper and paperboard use is decreasing in many developed countries, there are many places in the world where paper use is still on the rise, such as China, South America (Fairfield, 2008) and developing countries in general. For instance, China, although with one of the lowest GDPs, constitutes one of the greater paper and paperboard consumers, consumption that increased by at least 20 percent in a five year period, from 2000 to 2005.

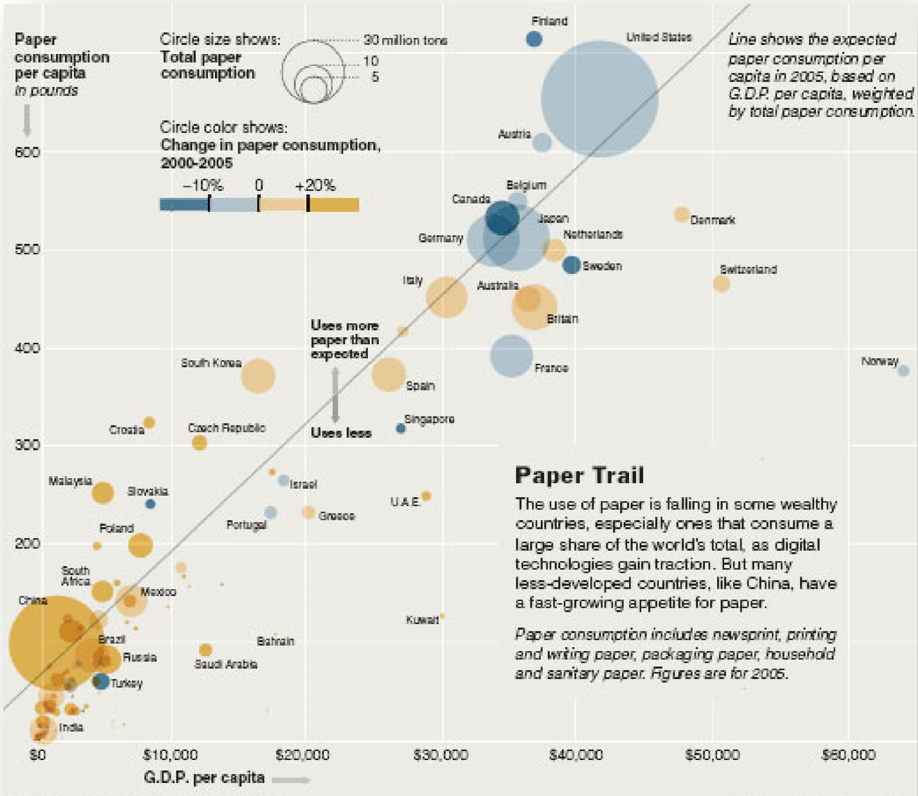


Figure 1-3. Total Paper & Paperboard Consumption vs. GDP (Fairfield, 2008)

Even though the data for these two figures accounts for all types of paper and paperboard, including packaging and sanitary materials, office PW paper consumption constitutes at least 30 percent of total paper consumption (AFPA, 2000).

How Much Information? 2003, a study that attempts to measure how much information is yearly produced worldwide (Lyman & Varian, 2003), also contains several interesting facts about paper consumption worldwide and in the U.S.:

- Inhabitants in North America consume 11, 916 sheet of paper each (24 reams). At least half of this paper is used in printers and copiers to produce office documents.
- The single largest component of print media flow is office documents.

- U.S. companies are estimated to produce a total of more than 4 billion archival pages each year, equivalent to 1, 400 terabytes.

- The U.S. print information flow is dominated by office documents, but unlike for global data, the second most prevalent source of print information is not mass-market periodicals, but books.

- Developing countries have proportionally higher information being created in mass distribution channels like magazines and newspapers than in books.

- Nearly 500 billion copies are produced on copies in the U.S. and nearly 15 trillion copies are produced on copiers, printers, and multi-function machines.

- Figure 1-4 depicts the trends of produced and imported graphic paper to meet US PW paper demand. Also, in this plot one can see how, for the United States, paper consumption showed increasing trends from the 1960s to around middle 1990s but is suggesting that paper consumption might be starting to level off.

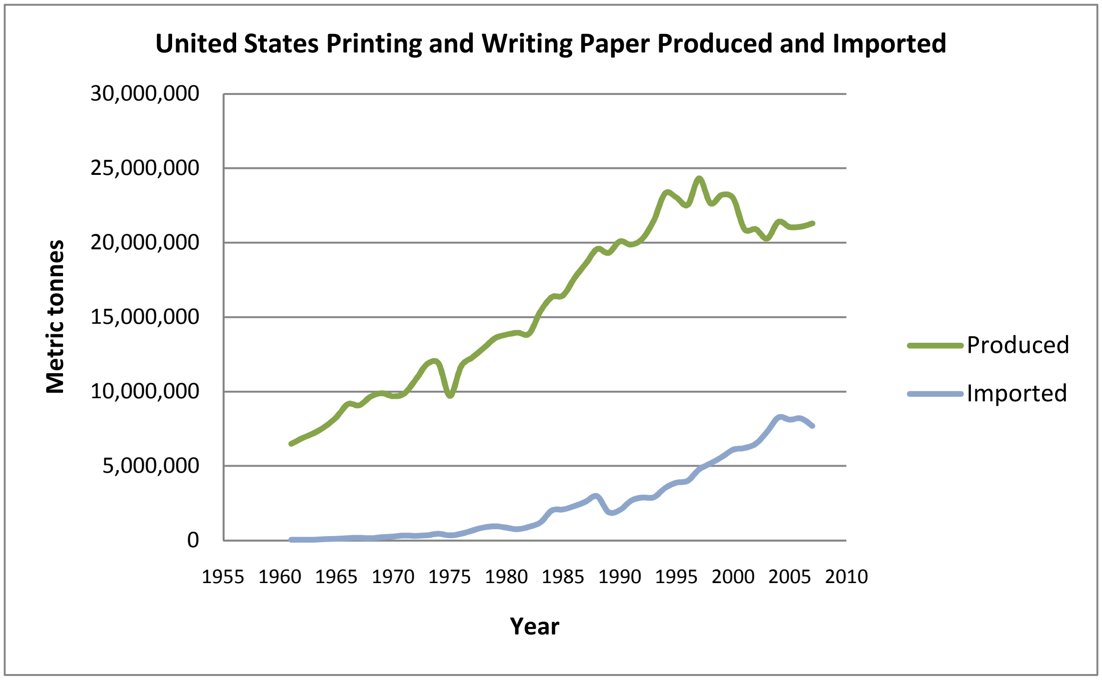


Figure 1-4. United States Printing and Writing Paper Produced and Imported (FAOSTAT, 2009)

Contrary to notions of a paperless office in the late 80s and early 90s, the consumption of office paper has grown substantially in the recent years (Lyman & Varian, 2003). Different factors have fueled paper consumption, but many agree that advances in ICTs, and specifically advances in interconnectivity and print technology (Sellen & Harper, 2002), are the main factors that have influenced this behavior.

Another key factor that has fueled paper consumption is the fact that our society has been gradually turned into a "knowledge based society", in which we are more likely to work in an office, where we not only have to process efficiently information, but also create information and knowledge (Nonaka, 1994).

Sellen and Harper (2001), discuss how knowledge workers do their job and how they tend to use the media in which they produce, store and transmit information. They focused specifically in the characteristics (or affordances) of paper that make possible certain human actions such as note

taking, spatial lay out, collaborative work, etc. A summary of the chapter Paper in Knowledge Work from the book *The Paperless Office* by Sellen and Harper (2002) is provided in the literature chapter of this thesis.

Our knowledge based society is thirsty for information and uses paper and ICTs as the media to produce, modify, and consume it. The increasing consumption of PW paper and the so far frustrated hope of the substitution of this medium by digital technologies, explain how difficult it is to predict the behavior of such complex systems.

However, the historical data presented and the trends of paper consumption have not gone unnoticed to several entities that recognize the environmental problems related to the paper cycle, and are constantly in the research and development of better and more efficient practices to mitigate the negative environmental and social impact of the paper cycle. For instance, paper recycling is a practice that has been highly encouraged by paper industry's managers, consumers, and regulators (AFPA, 2000) to alleviate some of the previously stated problems. Paper recycling has many benefits: it reduces deforestation, helps to save water, and reduces energy consumption (EIA, 2008). However, paper recycling does not constitute the solution by itself. To illustrate the case, it is well known that one of the drawbacks of paper recycling is that paper pulp can only be recycled a finite number of times before it degrades, and there are significant costs and energy use associated with the reverse logistic of recovered paper, such as the collection, sorting, and transportation activities of the waste paper (Clean-Energy-Ideas, 2008), just to mention a few.

Given the dynamic nature of the paper cycle, mainly characterized by the hard to quantify consumer behavior, it is hard to predict accurately the trends that this sector will perform.

Traditional methods have been useful to convey a better understanding of paper and pulp production and wastepaper management, as it will be explained further in the literature review chapter of this thesis. However, none of them have attempted to explain the main problem: why paper consumption has grown exponentially in the last decades and the role of ICTs and knowledge workflows in this behavior. A method to assess holistically this issue, one that considers the main stakeholders of the system along with their interactions, was investigated. System dynamics emerged as a potential and powerful technique to understand problems in a holistic manner and uncover the causes the potential implications of printing and writing paper consumption.

1.1.2 The Need for a System Dynamics Approach

As discussed previously, the paper industry as a natural resources based commodity, has a history of environmental impacts such as the traditionally high energy requirements associated with the paper lifecycle (Sundin, Svensson, McLaren, & Jackson, 2002).

Because of the dynamic nature of this system, one cannot simple expect that the usage of PW paper will soon disappear, and with it, all the environmental, social and economic problems that come with the print media lifecycle.

By the same token, it is necessary to understand how paper consumption patterns have behaved in the past and how they are currently behaving in order to determine how these trends might evolve in the future, and to determine how changes to the system may lead to more sustainable consumption patterns. This study is strongly motivated by the current challenges the print, paper, and ICT industry face regarding adopting sustainable practices and the impact these industries have on the economic, social and environmental sector.

The analysis tool chosen to conduct this study is System Dynamics (SD), because SD thinking can help analyze the system in a holistic way and consequently, help to assess the behavior of the paper, print, and ICT industry to guide sustainable change. SD is a thinking modeling and simulation methodology that was specifically developed to support the study of dynamic behavior in complex systems (Hjorth & Bagheri, 2006) such as the one discussed in this document. The opinion of the researcher is that this methodology represents the most accurate way to identify feedback processes and loops in the PW paper consumption system. This is attributed to the fact that "one feature that is common to all systems is that a system's structure determines the system behavior" (Hjorth & Bagheri, 2006).

1.2 PROBLEM STATEMENT

As was explained previously, there is a clear need for more sustainable practices in our society and in our economy. The paper, printing, and communication industries as a whole are good candidates for developing more sustainable practices, because they simultaneously deliver great benefits to the society and create many negative impacts as well. Many of these negative impacts reside in the life cycle of paper, yet paper also presents an opportunity given that the root resource is a renewable. Thus, there is a great deal of merit in furthering our understanding of paper consumption patterns. The literature review of this thesis (Chapter 2) will explain how both, academics and industry practitioners alike, appreciate the issues discussed above even when there has been very little in the way of quantitative modeling of paper consumption patterns.

It has been argued that a clear implication of the high levels of PW paper consumption is that the burdens placed on the environment continue to grow and threaten to cause unpredictable

consequences. Therefore, the general public and policy makers push for better choices and more sustainable media to manage information. Technology designers, PW paper producers, the print and ICT industry, and policy makers need a clear understanding of what influences paper consumption and the potential implications of the penetration of alternative digital technology that is aimed to substitute PW paper. The method must draw from engineering, a strategic system dynamics approach, and the environment.

Environmental issues combined with a system dynamics view and engineering research address the complex problem of analyzing PW paper consumption patterns in order to understand what designers and policy makers need to take into account to develop technologies and policies that alleviate the environmental impact of the paper cycle. Many other methods have been used to understand the impact of the paper industry but are not directly useful to comprehensively understand the role of all the pertinent stakeholders in the PW paper consumption system. Pulling together the role of these diverse parties is complicated but must be accomplished to understand the system under study and reach a solution.

1.3 RESEARCH OBJECTIVES

The main goal of this work is to develop a system dynamics model to explain current and past paper consumption as a function of time. In particular, the observed trends shown in 1-3, 1-4, and 1-5 which one might have expected to decrease due to ICT developments. Furthermore, this study intends to identify the key leverage points that could eventually lead to decreased paper consumption.

The purpose of this study can be summarized as follow:

First, it is aimed to develop a “simple enough”, flexible, and comprehensive SD model that helps to understand current and past paper consumption behavior as a function of time. The second objective of this study is to identify the key leverage points that could eventually lead to decreased paper consumption in the future. The third objective is to build up a base against which different alternative assumptions can be compared.

1.4 Outline of Thesis

The previous section presented the importance of analyzing printing and writing (PW) paper consumption patterns through a holistic approach as a first step to drive the PW paper industry towards sustainable development. The remainder structure of this thesis is organized as follows:

Chapter 2 presents a review of the literature related to the print, paper and ICT industry to provide the background and basis for this study. In this chapter, the relevance of the addressed problem to sustainability and sustainable development is discussed. Past research works that focus on the environmental impact of the paper cycle and the importance of addressing this type of issues in a holistic manner are also discussed. This chapter concludes with a summary of the chapter *Paper in Knowledge Work* from Sellen and Harper’s (2002) book *The Myth of the Paperless Office*. In chapter 3 the problem statement, and research objectives of this thesis are presented.

Chapter 3 is devoted to describing the research methodology that was followed to conduct this study. The research activities described in this chapter are based on the general research procedure described by Sterman (2000).

Chapter 4 discusses the dynamic hypothesis that represents the researcher’s theory of how the problem arose. A model for paper consumption, together with the subsystem and causal loop

diagrams that describe how the relevant organizations of the system interact, is also presented. This chapter also focuses on the development of a system dynamics simulation model to explain print media paper consumption patterns. The model represents the interactions of three main subsystems: information access, authoring work production, and information consumption subsystem. The methodology and details of how each subsystem was modeled and populated is also explained in this chapter. The resulting behavior of a base run of the model is presented and discussed. Finally, real data from the base year 2002 is used to determine to compare the model results with real data.

Chapter 5 discusses the methodology that was used to test the paper consumption SD model. A fractional factorial design of experiments is presented as the strategy of experimentation conducted to discover how the model parameters should be set up to reduce variability between the SD model results and real trends, and replicate the real data in the most accurate possible way. The results of a test run of the model, based on the insights that resulted from the design of experiments, are presented and compared with the data from the 2002 scenario.

Chapter 6 summarizes the main research points and lessons learned of this research, and identifies potential areas for future work.

1.5 SUMMARY

As discussed previously, this study is motivated by the observed increase in the demand of PW paper and the subsequent environmental burden related to the paper cycle. Although ICTs have substituted paper in many of its roles, in many cases they are complementary goods that fuel the consumption of paper. Our increasing knowledge based society is another critical factor that needs to be accounted when explaining PW paper consumption patterns.

The overall goal of this study is to provide a systematic understanding of why paper consumption trends have behaved in the observed manner, by not only determining which are the key factors that have influenced this behavior, but also how these factors interact between each other. This type of understanding is valuable for designers to understand the relationship of ICTs and paper, and what type of technology could eventually lead to a decrease in paper consumption.

This research uses system dynamics as a powerful methodology to address the interactions between the printing, paper consumption, and ICTs. Thus far, there isn't any empirical study in the literature aimed at understanding the interactions of these three factors and their implications to sustainability. The following chapters of this thesis present how this new knowledge was created.

2. LITERATURE REVIEW

The significant impact of the PW paper lifecycle to the environment and society makes it a topic of great interest. Consequently, an important phase of this study involved a review of the literature related to the sustainability of the PW paper cycle in order to identify the areas where further research is required.

This literature review is organized around three main areas: sustainable development, paper consumption, and system dynamics. A summary about the role of paper in knowledge work activities as described by Abigail Sellen and Richard Harper in their book *The Myth of the Paperless office* (2002) is also included in this chapter.

To understand the relevance of this study to sustainability, section 2.1 of this review of the literature summarizes important concepts about sustainability and sustainable development. Section 2.2 contains a summary of past studies that have been conducted in order to understand the paper cycle impacts. These past studies demonstrate the public concern for the environmental, social and economic impact of the paper industry. Moreover in this section are presented various studies that address the role of ICTs in paper consumption. Section 2.3 of this literature review will present several studies that describe how system thinking can be used to model complex problems and approach sustainability issues. Finally in section 2.4, key insights from the chapter *Paper in Knowledge Work* by Sellen and Harper (2002) are discussed in order to understand why paper is still predominant in all activities that involve interpretation and production of information.

2.1 Sustainable Development

This study is strongly motivated by the current unsustainable state of paper consumption. Thus, one of the main objectives of this research is to understand what needs to happen in order to enable a decrease in paper consumption to alleviate the burden in the Earth's ecosystems. To translate this objective into specific research aims, it is important to understand what sustainable development means.

Sustainable development is a very dynamic and broad concept and its definition is highly dependent on the context in which it is used. While sustainable development has become a topic of great interest recently, its original discussions can be tracked back almost 40 years, back in 1971. The core of this concept, although with a different label, "Equilibrium", was discussed in several books by a group of system dynamicists lead by the pioneer in the area Jay Forrester (Randers, 2000). In these books, Forrester and associates presented three versions of what they called "The World Model" to describe their observations about the population's unsustainable growth and the Earth's carrying capacity. They concluded that the exponential growth in the use of our planet Earth's finite resources could ultimately lead to their depletion and hence to the overshoot and collapse of the world socio-economic system (SystemDynamicsOrganization, 2009a). However, the ideas presented by Forrester et al. caused resistance and skepticism within the scientific community.

The concept was then formally discussed in 1972 in the United Nations Conference on the human environment (also known as the Stockholm Conference). The definition of sustainable development emerged for the first time as the "means of realizing developmental needs of all people without sacrificing the earth's capacity to sustain life" (EPA, 2009). However, it wasn't

until 1987 after the Report of the World Commission on Environment and Development "Our Common Future" (also known as the Brundtland Report) that the term was popularized (Lumley & Armstrong, 2004). According to the Brundtland report, Sustainable Development is the "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (UnitedNations, 1987). This concept continued to be discussed in subsequent "world meetings" such as "The Earth Summit" held in Rio de Janeiro in 1992, and the second Earth Summit held in Johannesburg in 2002 (EPA, 2009).

Ever since, sustainable development has been recognized as a goal for human development in many parts of the world; however, it is hard to tell when a system, community, city, region, country, and even the world is on a sustainable path or development (Bossel, 1999). Assessing sustainability problems is a hard task because it depends on the context in which the problem is being defined and on the established sustainability goals used to compare the unsustainability degree of the system under study. Sustainability problems are also complex, because sustainability is a dynamic concept: the world is in constant change and sustainability must allow and sustain such change. To be able to recognize the presence or absence of sustainability in a system, proper indicators are needed to provide information of where the state of the system stands with respect to the established sustainability goals (Bossel, 1999). Integrative indicators and frameworks used in sustainable-based assessments of systems, play a significant role in providing information to guide policy making and decisions at all levels of society. Examples of sustainable-based indicators, methods, and tools are the traditional life-cycle assessment of products and processes, material flow analyses (MFA), general economy and demographic models, biogeochemistry and climate models, multi-criteria analyses, human and sustainable

development indicators, and scenario tools such as system dynamics modeling and simulation (Videira, Antunes, Santos, Lopes, & Tavares, 2009).

When it comes to assessing the sustainability of PW paper consumption patterns, it is vital to do so in a holistic manner identifying and understanding the critical feedback that shapes the behavior of the system under study. According to Bossel (1999), a systematic approach requires "a process of aggregation and condensation of available information, and the directed search for missing information needed for a comprehensive description of the system. This process of systems analysis is guided by the particular task, and the knowledge and experience of the analysts. It requires choice and selection at every stage. A circumspect and self-critical approach by analysts is essential. It should be coupled with independent analysis by others with different points of view, representing in particular the interests of those who may be affected by policy decisions. The result of this effort is some kind of a model—a mental model, a verbal description, or a more formal mathematical or computer model. This model is then used to identify indicators providing essential information about the system" (Bossel, 1999).

This study attempts to precisely understand through a holistic approach the patterns of paper consumption in the United States. Modeling past and current paper consumption patterns and incorporating the key players in the system that have influence a rise in paper consumption, will yield a better understanding on how to move towards more sustainable consumption patterns.

2.2 Paper Consumption

The paper industry has been often in the public eye because of its already mentioned impacts. For instance, the IIED conducted an independent study on the environmental, economic and social terms of each stage of the paper cycle. These investigations revealed many areas of debate

between different stakeholders. In addition, this study concluded that although there have been significant improvements in the paper industry, there are still areas where there is scope for future improvement; for example, although there has been significant improvement in the environmental impacts of the paper industry, little attention has been given to the social impacts (Maryanne Grieg-Gran, 1997).

Ruth and Harrington (1998) tested a series of scenarios in a dynamic model to determine the future profile of fiber and energy use of the pulp and paper industry. Another objective of this study was to determine how fast technological change would have to occur in order to reduce energy use if production rates continue to increase (Ruth & Harrington, 1998). The conclusions drawn from this study suggest that to lower total energy consumption by 2020, future annual increases in energy efficiency have to be almost two times as high as the reported energy efficiency of the period of 1972-1992 (Ruth & Harrington, 1998).

Motivated by the importance of the paper and pulp sector to the economy, in addition to the increasing public concern about the negative impact of every stage of the paper cycle to the environment, Sundin and colleagues conducted a Material and Energy Flow Analysis (MEFA) for the United Kingdom (U.K.) for the period of 1986 to 1997. The purpose of the study was twofold: first the study aimed to determine the annual energy requirements associated with consumption of paper in the U.K. based on the results of the MEFA; and second, the study intended to test different assumptions, under different scenarios, and through a system quasi-dynamic ("quasi" because it does not includes significant time lags) approach to determine under what conditions the energy consumption associated with the paper cycle might be stabilized. The results of the analysis suggests that in order to achieve a significant reduction in the energy

requirements of the paper and pulp sector, efforts to control consumption growth of paper products must take place (Sundin et al., 2002).

Jones, Seville, and Meadows (2002) also expressed their concern on the paper industry focusing upstream in the paper's supply chain, in the sawmill industry. In this work Jones and colleagues explored, using a system dynamics model, the forest resource commodity. The goal of the study was to "model, understand and disseminate understanding of commodity systems" (Jones, Seville, & Meadows, 2002).

These studies underline the need of developing clean technologies to reduce the dependence on natural resources and the total energy consumption in the paper cycle. Also, these authors recognize the need of modeling the dynamics of the industry to better understand what could be its future economic, social, and environmental impact.

As stated before, progress in ICTs has created a curious debate about whether advances in digital technology will substitute in the near future the need of paper for printing and writing. To that effect, Sellen and Harper conducted a number of case studies to test their hypothesis that paper will remain as the lead medium for quite some time. To better explain the dominance of paper in most activities that involve knowledge work, the authors use the term "Affordances". Affordances refers to the fact that the physical properties of an object make possible different functions for the person perceiving or using that object (Sellen & Harper, 2002). The authors concluded that digital technologies will continue to grow and could replace paper in different roles, but they will only support in a large scale these roles if designers look at paper use for guidance to create paper-like technology (Sellen & Harper, 2002).

York (2006) also discusses the paradox of the paperless office by comparing it to the Jevons Paradox. The Jevons paradox, states that "the development of a substitute for natural resources

is sometimes associated with an increase in consumption of that resource”. The author uses this paradox to compare and explain the increase in print paper consumption and the role of ICTs fueling this behavior, calling it “The Paperless Office Paradox” (York, 2006). York explained how the prominent practice for reducing the consumption of a particular resource is to develop substitutes for it. This way the Paperless Office Paradox points to the fact that one should not assume that the development of substitutes for a natural resource, improvements in efficiency, and/or relying on technology alone to solve our problems will lead to a reduction in consumption of that resource ceteris paribus (York, 2006).

Frank Cost (2005) discusses in his book *The New Medium of Print* how there will soon be few scenarios where print and web will stand apart from each other. According to Cost, print media and digital products are already tied together. In many cases print media products are packaged with a variety of other forms of digital media. For example, textbooks publishers often include digital media products such as software programs, video games etc. that can be used to justify higher prices for printed products, but that have no value if sold separately (Cost, 2005). Additionally, he compares the four major media: radio, TV, print and internet to conclude that the enduring value of print, in relationship with the internet (its greater competitor), is tied to its materiality. Moreover when print primarily serves as a medium of communication, its value is largely determined by human response (Cost, 2005).

All these authors agree that advances in ICTs have created a series of possibilities that have contributed significantly to economic growth. ICT tools have given us access to a huge amount of information and have defied barriers of distance and time connecting people all around the world. On the other hand, advances in ICTs, and specifically in interconnectivity and print technology (Sellen & Harper, 2002), have also fueled consumption. ICTs have not only fueled

consumption of paper, but also of electronic devices that are designed to have a short shelf life and are commonly substituted after a relatively short period of time for newer and more sophisticated versions. If one of the premises of ICTs is to contribute to a significant reduction of print media in general, then cleaner digital technologies that provide sustainable and better options over paper must be co-developed with better print technologies and new print media that solve the characteristic problems of the paper cycle and does not create side effects.

2.3 System Dynamics

Understanding paper consumption is a complex issue. A comprehensive systems approach to understand paper consumption patterns is essential for effective decision making with regards to global sustainability, since industrial, social, and ecological systems are closely linked (Fiksel, 2006). Yet, understanding PW paper consumption patterns and assessing the broad impacts of policy and technology choices in order to reduce paper consumption constitute a great challenge. One technique that can yield at least a partial but significant understanding of the dynamic behavior of this system, enabling a more integrated approach to systems analysis, beneficial intervention, and improvement of resilience is *System Dynamics Modeling* (Fiksel, 2006).

John D. Sterman, a lead authority in the field, defines SD as a "perspective and set of conceptual tools that enable us to understand the structure and dynamics of complex systems"(Sterman, 2000). Also, "system dynamics is a rigorous modeling method that enables us to build formal computer simulations of complex systems and use them to design more effective policies and organizations"(Sterman, 2000). The concept of "System" is defined by Meadows and Colleagues as "an interconnected set of elements that is coherently organized around some purpose [….Systems]can exhibit dynamic, adaptive, goal-seeking, self-preserving and

evolutionary behavior" (Meadows, Meadows, & Randers, 1992). However, although *system* is the word to describe all types of situations, f*eedback* is the different descriptor here (SystemDynamicsOrganization, 2009b). Feedback, or the effect an event's output has on the present or future state of the same event, along with stocks and flow structures, time delays and nonlinearities determine the dynamics of a system, and it is from this feedback and interactions among the components of a system that most complex behaviors arise (Sterman, 2000).

A number of research groups are using SD to explore the environmental and social impact of different industries including the paper industry. In fact, SD can be applied in the environmental and energy management field, as a tool to build platforms to test the impact of policy intervention and the introduction and diffusion of new technologies. The Pangaea Climate Simulation Model is one example of this type of applications. Pangaea is a model that has been constructed using SD tools so that the users can see the path of carbon dioxide (CO2) emissions from specified regions over the next century. The model calculates the concentration of CO2 in the atmosphere, global mean surface temperature, and sea level rise resulting from these emissions (Jones et al., 2008). The Pangaea, offers decision makers a way to determine if they are on track towards their goals, and if they are not, they can discover what additional measures and on what time scale would be sufficient to meet those goals (Jones et al., 2008).

Georgiadis and Besiou used feedback loop concepts and SD methodologies to present a model of a "single product closed-loop supply chain with design for the environment (DfE) and recycling activities that operates under pressure of environmental regulations" (Georgiadis & Besiou, 2008). Prototypes of SD have also been developed to explain how price influences the use and consequences of tobacco in New Zealand to depict the importance of system dynamics for public policy analysis (Cavana & Clifford, 2006).

Another application of SD is the one linked to Project Management (PM) (often called "Project Dynamics"). SD tools and characteristics have proven to be successful to improve PM mainly because project performance and conditions evolve over time and many of them have nonlinear relationships (Lyneis & Ford, 2007). However, despite the hundreds of applications of SD in PM, it is a relatively unknown field probably because of the few publications of this literature in PM journals (Lyneis & Ford, 2007).

Gonçalves and colleagues investigated the feedback between supply chain performance and demand variability (Gonçalves, Hines, & Sterman, 2005). Bushi and Javalagi also reviewed applications of SD in logistics and Supply Chain Management (Bhushi & Javalagi, 2004). Taylor and Ford focused on tipping point feedback structures' impacts in product development projects (Taylor & Ford, 2006). Wolstenholme presented various examples from his personal consulting experience where he applies structural archetypes (problem archetypes with solution archetypes) to understand organizational boundaries. The purpose of Wolstenholme's study was to "assist people more widely and constructively with the use of archetypes" (Wolstenholme, 2003).

SD can also be useful to address many types of business problems. Sterman in his book Business *Dynamics: System Thinking and Modeling for a Complex World* lists a series of examples of policy resistance real life cases. In this list of examples, Sterman specifically mentions the paper consumption paradox as case of policy resistance. Quoting Sterman, "Information Technology has not enabled the 'paperless office'- paper consumption per capita is up" (Sterman, 2000).

The value of SD lies in the fact that it helps us see the big picture and how problems arise from the interactions of different forces. SD can be applied to virtually any discipline and it is a very

intuitive tool that makes full patterns clearer and helps to understand the forces that must be mastered to improve the studied system (Senge, 2006).

2.4 PAPER IN KNOWLEDGE WORK

In the chapter *Paper in Knowledge Work* from the book *The Myth of the Paperless Office*, Sellen and Harper (2000) share their findings regarding the role of paper in knowledge work. To draw their conclusions, the authors conducted an in-depth case study of a knowledge-based workplace, specifically the International Monetary Fund (IMF) located in Washington DC. Their purpose was to explain qualitatively why paper is the dominant medium to support activities such as authoring work, reviewing the work of others, thinking and planning, collaborative work, and delivery of reports. In this chapter the authors argue that there are several complex reasons that make paper the persistent medium to analyze and produce information in knowledge work activities. One important conclusion is that the knowledge workers from the IMF continued to use paper because the functionalities of the technologies alternative to paper, at least in the time, didn't support important aspects of their work.

In order to better understand the key role of knowledge workers in paper consumption it is important to understand what the authors mean by knowledge work. The authors introduce this chapter explaining why, contrary to past generations, "workers are less likely to be using their hands and more likely to be using their minds to monitor, manage, and control the flow of information" (pg. 51). Consequently, the media (paper, digital/electronic devices, and the knowledge workers themselves) with which knowledge workers store and distribute information are key components to their work.

The authors chose the IMF to conduct their study to better understand the role of paper in knowledge work activities for two main reasons: first, “it is knowledge centered and document intensive”; and second, “staff members have all the technology they want to support their work” (pg. 55). The authors used a series of combined methods (ethnographic and other techniques) to capture the behavior and patterns of document use across all different activities for a group of workers in the IMF.

The conclusions of this study can be summarized in five general categories:

- *Authoring Work*- Most of the drafting and editing of documents are made electronically. However, in most cases paper was used in conjunction with online editing. The reason for this is that because the authoring work was nearly in all cases co-authored, paper constituted a great medium to support the integration of the different reports and drafts. For instance, paper can be spread out on the desktop making the reports easily accessible. The authors remarked on the fact that “even when knowledge workers had multiple windows opened on their personal computers, these were mainly used for electronic cutting and pasting, not for the back-and-forth cross-referencing of other materials during their authoring work” (pg. 61).

- *Reviewing the Work of Others*- This knowledge work activity was found to be an almost entirely paper-based process. Knowledge workers review the work of others, and they prefer to use paper for this activity because of the tangibility and flexibility characteristic of paper. The individuals preferred paper because when they are

reviewing the work of others they like to mark up, make annotations and comment on the report .

- *Thinking Planning and Document Organization*- the authors' observations in this category can be summarized by the fact that "paper is important in [thinking, planning and document organization activities] because it makes information accessible and tangible and gives it a persistent presence" (pg. 63).

- *Collaborative Work*- in the case study, paper was found to be essential to support collaborative work because it supports what the authors call the "social mechanisms" (pg. 66) that occurs during collaborative work and face-to-face meetings. Some of the aspects that make paper the ideal medium to carry out this type of activities include its physicality, and the fact that with paper the workers could have discussions carried on, in parallel with marking up and examining parts of the report..

- *Delivery of reports*- Although hand delivery of documents was not a frequent activity in the IMF, when it occurred, the affordances of paper played a significant role. Whenever a major report was completed, the workers wanted to be involved in the point of delivery of those documents..

With these findings Sellen and Harper concluded that paper is still used in many of the knowledge work phases, not because they resist changing to alternative technology, but because alternative technology can't afford the actions paper does. Although electronic and digital technologies also play a key role in knowledge work, they haven't been able to substitute paper and its affordances. In some cases digital technologies replace the use of paper, but more often

than not, both media are used in conjunction and in many cases resulting in an increased use of paper.

2.5 SUMMARY

The review of the literature for this thesis reveals that the importance of analyzing paper consumption patterns and its sustainability has been recognized by many industry and academic practitioners. Different arguments of why a system and holistic approach should be used to understand paper consumption patterns where presented to provide the basis for the selected research methodology which is described in following chapters. In addition, the review of the literature reveals that although paper consumption and its negative environmental impacts have been well recognized by many, there isn’t any study that empirically addresses the relationships between paper consumption, advances in ICTs and print technology, and the effects of our increasing knowledge based society. This literature review serves as the background for the novel research contribution of this thesis in the field described in the following chapters.

3. Research Methodology

In this chapter the modeling steps that were followed to construct a system dynamics simulation model of print media paper consumption patterns are described. The modeling steps are based on the ones outlined by Sterman (2002). A process map of the modeling steps is also presented to summarize the overall activities that were completed.

As it is outlined by Donella Meadows in her article *Dancing with Systems* (2002):

> *"Systems cannot be predicted, they can be envisioned and brought into living; systems cannot be controlled, but they can be designed and redesigned. We can't surge forward with certainty into a world of no surprises, but we can expect surprises and learn from them and even profit from them. We can't impose our will upon a system; we can listen to what the system tells us, and discover how its properties and our values can work together to bring forth something much better than could ever be produced by our will alone" (Meadows, 2002).*

Along the same lines, Sterman (2002) argues that modeling is an extremely creative process and that there is no formal procedure one can follow that guarantees successful modeling of the results. However, he continues explaining, that all successful modelers follow a disciplined procedure that can be divided into five stages: (1) problem articulation, (2) formulation of dynamic hypothesis, (3) formulation of a simulation model, (4) testing, and (5) policy design and evaluation (Sterman, 2000). The research methodology for this thesis only focuses on the four

first steps. Policy design and evaluation are proposed for future work. Each phase can be described as follows:

3.1 Phase one- Problem articulation

This phase constitutes the most important step in the modeling process. In this phase the key variables and concepts that must be considered, as well as the time horizon, historical behavior of the key concepts and variables are determined. It is important to mention that for a model to be useful, “it must address a specific problem and must simplify rather than attempt to mirror the entire system in detail” (Sterman, 2000).

3.2 Phase two- Formulation of dynamic hypothesis

The next step of the modeling process involves the development of a working theory that accounts for the already identified problematic behavior (Sterman, 2000). The dynamic hypothesis explains the behavior of the system as a result of endogenous types of interactions between the main stakeholders of the system. A dynamic hypothesis is a provisional explanation, meaning that it is subjected to change or abandonment as the modeler’s understanding of the system evolves, and it is dynamic because it must explain the root cause of the problematic behavior in terms of the underlying feedback and stock and flow structure of the system (Sterman, 2000).

3.3 Phase three- Formulation of the simulation model

Once the dynamic hypothesis has been articulated, modelers have to test this hypothesis to find the potential flaws it might have. This step involves the translation of the conceptual explanation of the problem to stock and flow structures, with equations, conditions, decisions and assumptions (Sterman, 2000).

3.4 Phase four- Testing (Validation of the model)

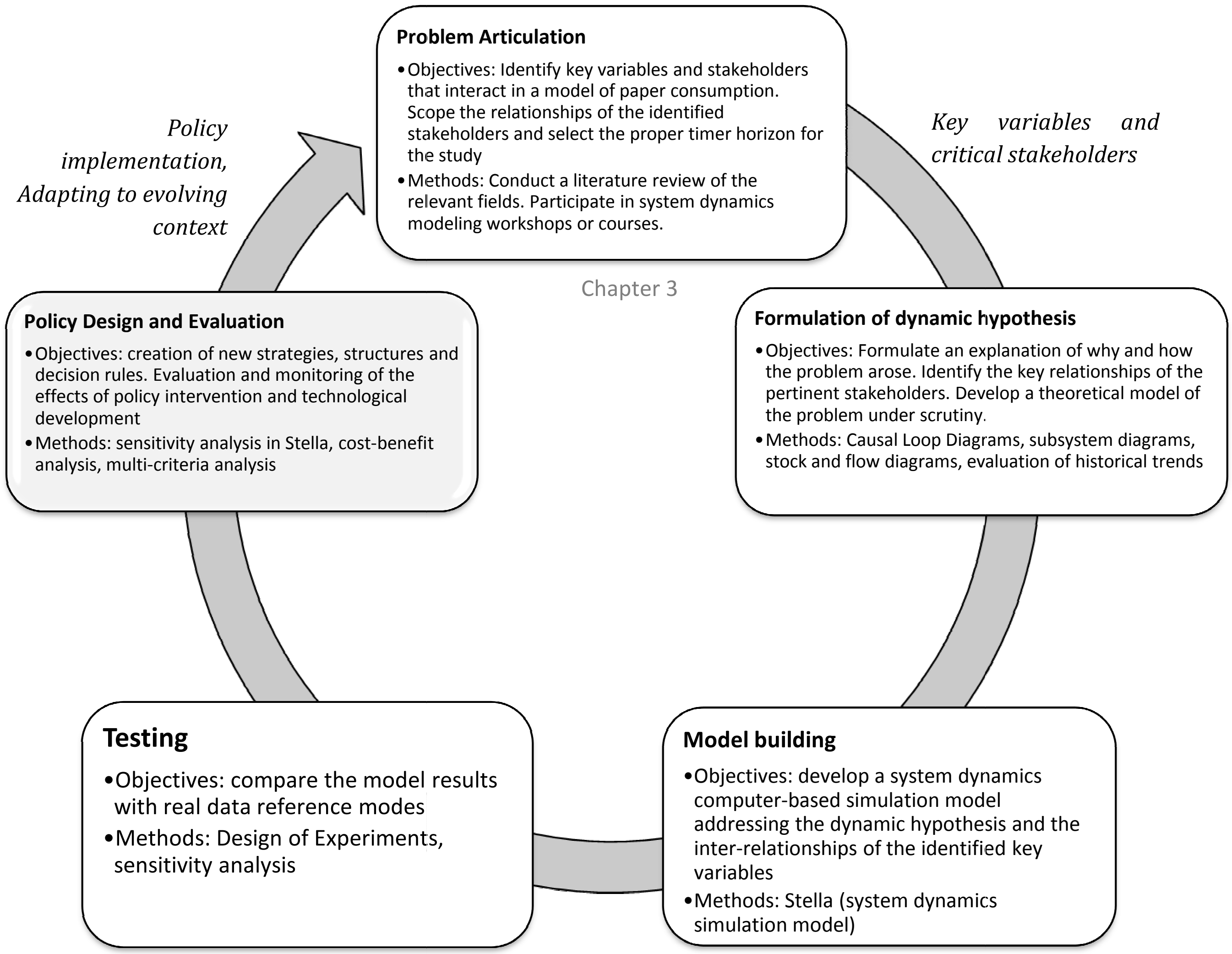
According to Sterman (2002) testing is a continuous effort that begins as soon the first equation is written (Sterman, 2000). In this phase the results of the model are compared to reference modes, the robustness of the model under extreme conditions is tested and sensitivity analysis might be conducted to test the model under different scenarios and assumptions (Sterman, 2000).

3.5 Phase five- Policy Design and evaluation

Once a valid model is constructed and tested it can be used to design and evaluate policy intervention and the effects of technological development to design and evaluate the creation of new strategies, structures and decision rules (Sterman, 2000).

3.6 Summary

Although the above described modeling steps shouldn't be seen as a template of strict and rigid activities, they can serve as general guidance for the important considerations that have to be accounted for when developing a system dynamics model. Figure 3-1 provides a closed-loop road map for the modeling steps that were conducted in this research based on the modeling steps outlined by Sterman (2000). Phase one of this methodology was already discussed in chapter 2 of this document; phases two, three, and four are carefully described in chapters 4 and 5; phase five was not explored in this work but is proposed for potential future work.


Problem Articulation
•Objectives: Identify key variables and stakeholders that interact in a model of paper consumption. Scope the relationships of the identified stakeholders and select the proper timer horizon for the study
•Methods: Conduct a literature review of the relevant fields. Participate in system dynamics modeling workshops or courses.
Key variables and critical stakeholders
Chapter 3
Formulation of dynamic hypothesis
•Objectives: Formulate an explanation of why and how the problem arose. Identify the key relationships of the pertinent stakeholders. Develop a theoretical model of the problem under scrutiny.
•Methods: Causal Loop Diagrams, subsystem diagrams, stock and flow diagrams, evaluation of historical trends
Model building
•Objectives: develop a system dynamics computer-based simulation model addressing the dynamic hypothesis and the inter-relationships of the identified key variables
•Methods: Stella (system dynamics simulation model)
Testing
•Objectives: compare the model results with real data reference modes
•Methods: Design of Experiments, sensitivity analysis
Policy Design and Evaluation
•Objectives: creation of new strategies, structures and decision rules. Evaluation and monitoring of the effects of policy intervention and technological development
•Methods: sensitivity analysis in Stella, cost-benefit analysis, multi-criteria analysis
Policy implementation, Adapting to evolving context

an (2000)

4. MODEL DEVELOPMENT

This chapter is devoted to the detailed description of the dynamic hypothesis of the problem under study. First, a full description of the developed dynamic hypothesis is provided; then, a subsystem diagram is presented in order to provide an overview of the overall architecture of the system; later, the complete causal loop diagram (CLD) is presented and a description of the decisions and assumptions that were made to construct the theoretical diagram are also discussed. A brief discussion of the limitations of CLDs and the loops that were omitted is also presented. In Chapter 4, the details of the formal print media paper consumption patterns' simulation model are also discussed. This model was developed in order to test the initial dynamic hypothesis and the developed theoretical and conceptual model. The parameters, equations, and initial conditions of the model are fully discussed in this chapter. The resulting behavior of a model's *base run* is presented and then compared with 2002 real data.

4.1 DYNAMIC HYPOTHESIS

A dynamic hypothesis is a working theory of how the problem arose (Sterman, 2000). Discussions of the possible causes of the increase in PW paper consumption are typically related to the effect that ICTs play in consumer behavior. Also, as explained by Sellen and Harper (2002), the increase in knowledge-based work and the prominent role that paper plays in those workflow are other factors that have fueled the consumption of paper (Sellen & Harper, 2002).

Paper consumption in the United States is starting to show that it may be leveling off. This is a trend that is also observable in other developed countries (Fairfield, 2008). Figure 4-1 depicts this trend, showing how per capita consumption of paper and paperboard for the United States

increased from 1960 to end of the1990s, and how by the beginnings of 2000, paper consumption looks to be leveling off.

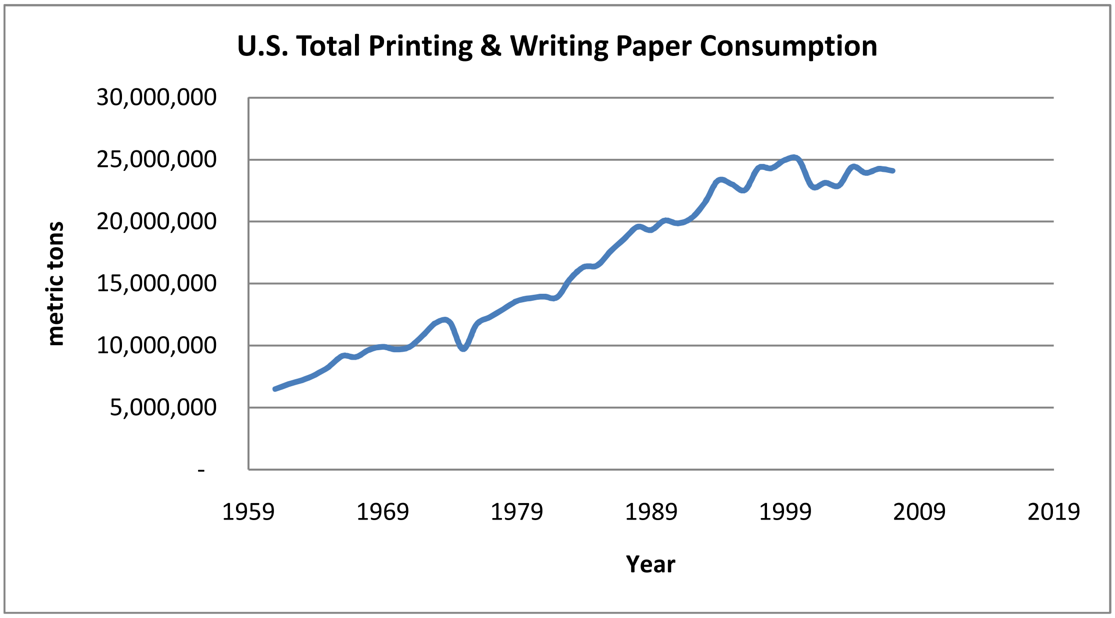


Figure 4-1. United States Total Printing & Writing Paper Consumption (FAOSTAT, 2009)

Based on this type of statistical data and on the ICT progress, current wisdom might suggest that at least in developed countries total paper consumption is starting to decrease. However, the dynamic hypothesis of this study states that, because of endogenous feedback loops, even if paper consumption decreases, is not likely that it will go down to sustainable levels, at least not until the appropriate technologies, forestry practices, and policies are in place (which are out of the scope of this study). The endogenous factors that influence paper consumption include, but are not limited to, the actions PW paper makes possible because of its characteristics in knowledge work environments and the increasing amount of information accessed by individuals that need the affordances of PW paper. If PW paper consumption patterns can be replicated, then

what will happen if nothing changes in the system can be projected, as well as what changes may promote sustainable development.

In addition, this thesis hypothesizes that in order for PW paper to lose dominance, alternative technology that meets the affordances paper, but that also leverages the affordances that digital technologies already meet, must be developed and become accessible to the majority of population. Only then per capita and total paper consumption will start to decrease.

4.2 PAPER CONSUMPTION MODEL

Given the intertwined and interdependent nature of the problem, the overall hypothesis of this study is that a system thinking approach will help to tackle these complexities by uncovering the main stakeholders and the critical feedbacks that governs the state of the system. A quantitative model of the system under study will give useful insights of what needs to happen to enable a transition to more sustainable paper consumption patterns. Moreover, understanding paper consumption patterns and the role of ICTs could help inform designers in the innovation process for more sustainable alternative paper-like technologies. Therefore, this study is conducted on the basis of SD principles. The SD simulation model of paper consumption patterns has been developed in the *isee* system thinking for education and research software *Stella* © (http://www.iseesystems.com/ (2009)).

In order to provide an overview of the overall architecture of the system, to guide the more complex causal loop diagram (CLD) and stock and flow diagram (SFD) model construction, a subsystem diagram was built and is presented in figure 4-2.

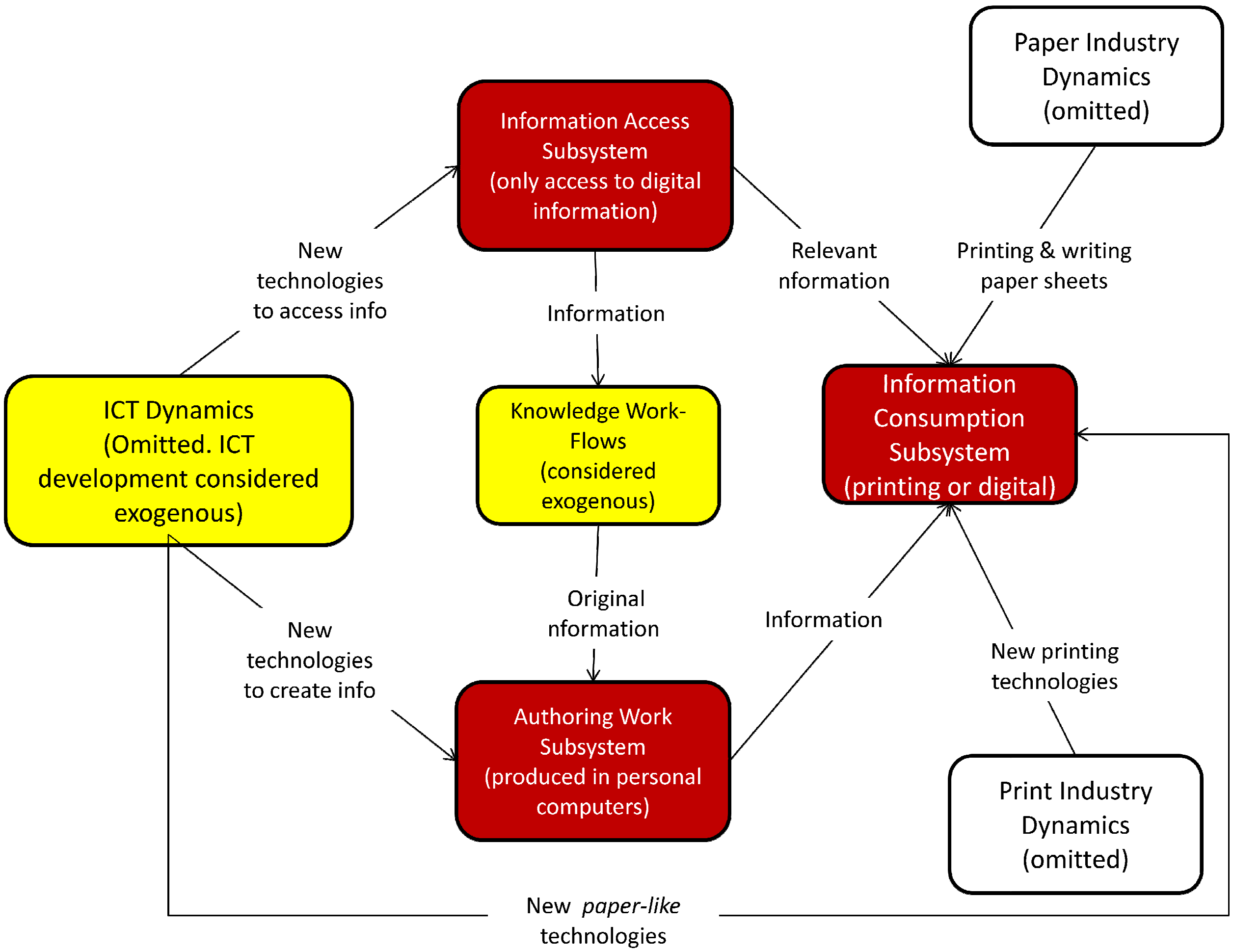


Figure 4-2. Subsystem Diagram for the Paper Consumption SD Model

This Subsystem Diagram communicates the number and type of different relevant organizations in the system of interest (Sterman, 2000). The red squares in this diagram represent the main sectors that will be developed in further detail in the CLD and SFD. The yellow squares represent the subsystems that are considered exogenously. The white ones show the market dynamics that are not being considered within the boundaries of this work. The diagram also shows the direction of the flow of information, goods and material.

4.2.1 SUBSYSTEMS DESCRIPTION

A. *ICT Dynamics*: this subsystem is considered exogenous. Therefore, the type of dynamics that occur in the entire lifecycle and development of ICTs is captured in a single index. The description of this ICT index is described in full detail in section 4.3.1. Progress in ICTs provide newer and more sophisticated media to access, manage, and produce information in a more friendly and efficient manner.

B. *Information Access*: once a person has access to ICTs (internet and personal computers) that person has access to a vast amount of information available in the Indexable World Wide Web (IWWW)[1]. This subsystem captures the relationships between ICTs and the amount of information a person accesses.

C. *Knowledge Workflows:* this variable, considered exogenous, represents the amount of relevant information that is used to produce new information. The amount of accessed information is filtered after it has been processed on the different stages of a knowledge work-flow (such as thinking, planning, reading, and reviewing, as well as collaborative work).

D. *Authoring Work Production:* here, the relationship between ICTs, the amount of accessed information, and the amount of produced information is captured. It is assumed that all the authoring information is produced digitally. The amount of information that is drafted and edited when producing new documents are captured in this subsystem.

E. *Information Consumption:* the accessed relevant information and the produced information can be subsequently managed in a digital or print version. This subsystem attempts to capture how the decision of the medium to consume the information is made.

[1] Indexable is the part of the WWW that is of free access to everyone, it does not require password or payment

F. *Paper Industry:* this omitted subsystem would have captured all the pertinent dynamics related to the production of printing and writing paper.

G. *Print Industry:* this omitted subsystem would have captured the main dynamics that are typical of print manufactures and shops.

Once the subsystem diagram is developed, a causal loop diagram that illustrates the main relationships of the relevant stakeholder of each subsystem can be developed.

4.3 Causal Loop Diagram (CLD)

Causal loop diagrams (CLD) are one of the tools for system thinking. CLDs give a qualitative and heuristic depiction that captures our mental model of the cause-and-effect relationship between the main stakeholders in the system. According to Sterman "a causal diagram consists of variables connected by arrows denoting the causal influences among the variables. The important feedback loops are also identified in the diagram"(Sterman, 2000). The variables are connected by arrows, *causal links,* which are denoted by a positive (+) or negative (-) polarity depending on the effect of the independent variable on the dependent variable of the relationship. Sterman also explains that a "positive link means that if the cause increases the effect increases above what it would have otherwise been and if the cause decreases, the effect decreases below what it would otherwise have been (Sterman, 2000)". On the other hand, "a negative link means that if the cause increases the effect decreases below what it would otherwise have been and, if the cause decreases, the effect increases above what it would have otherwise been" (Sterman, 2000). Feedback loops arise from the relationship of these variables and are denoted as R (for reinforcing loops) and B (for balancing loops); these relationships are meant to inform the modeler what *would* happen, instead of what *will* happen, if the variables change (Sterman, 2002).

The CLD for paper consumption patterns is based on the development of each of the considered endogenous subsystems presented in figure 4-2 (red squares). To be able to capture the feedback that arises from the interaction of the main stakeholders of each subsystem, first a brain storm to identify the key variables that should be included was conducted. The following is a list of the determined essential variables that should be considered in the system.

4.3.1 Identifying Key Variables

The provided description of the problem and the presented subsystem diagram suggests several variables important in a model of paper consumption patterns (units of measure are given in parenthesis):

Web pages access rate: the rate at which total number of web pages is accessed by knowledge workers (number of web pages per year)

Original Information production rate: the rate at which new information is produced (Megabytes of new information per year)

Demand for a medium to display information: amount of paper reproducible information needing the affordances of paper to be consumed, analyzed or managed (Megabytes)

Preference of reading from paper or digital display: amount of information that is preferred to be consumed in paper or digital display (Megabytes)

ICT development index: this index tracks the level of access and intensity of use of ICTs. The ICT development index by the Information Telecommunication Union (ITU, 2009) was adapted and used to measure a country's ICT development in one single unit (dimensionless quantity that goes from 0 to 10 each year). The original index includes the following sub-indices that

were calculated by summing up the weighted values of the indicators included in the respective subgroup; the indicators included in each sub-index were given equal weights (ITU, 2009).

The *ICT Access* sub-index includes indicators to provide information on the available ICT infrastructure and individuals' access to ICT (ITU, 2009). This indicator is measured by:

- *Fixed telephone lines per 100 inhabitants: "Fixed telephone lines refer to telephone lines connecting a subscriber's terminal equipment to the public switched telephone network (PSTN) and which have a dedicated port on a telephone exchange" (ITU, 2009).*
- *Mobile cellular telephone subscriptions per 100 inhabitants.*
- *International internet bandwidth per Internet user.*
- *Proportion of households with a computer.*
- *Proportion of households with internet access at home.*

The *ICT Use* sub-index is measured by:

- *Internet users per 100 inhabitants.*
- *Fixed broadband internet subscribers per 100 inhabitants.*
- *Mobile broadband subscriptions per 100 inhabitants.*

The *ICT skills* sub-index, which includes:

- *Adult literacy rate.*

- *Secondary gross enrolment ratio.*
- *Tertiary gross enrolment ratio.*

Table 4-1 provides a description for each sub-index and indicator according to the definition provided by the ITU (2009).

As mentioned above, the ICT development index for the U.S. was adapted to just include the indicators of each sub-index that are relevant to this study. Table 4-2 shows how the new ICT development index for the U.S. was recalculated

The modified *ICT Access* sub-index, for the purpose of this study, is just measured by the *proportion of households with a computer* and the *proportion of households with internet access* indicators. The reason to exclude the indicators *fixed telephone lines per 100 inhabitants and mobile* and *cellular telephone subscriptions per 100 inhabitants* is that this study is mainly concerned on the effects the internet and personal computers have on how much information that can be printed is accessed, and how much of that accessed information is actually printed. The indicator *international internet bandwidth per internet user* was excluded due to lack of data.

The modified *ICT Use* sub-index is just measured by *internet users per 100 inhabitants and broadband users per 100 inhabitants.* The indicator *Mobile broadband subscriptions per 100 inhabitants* is not included given the fact that, although with the introduction of smart phones people can access the internet and navigate in the web, just a small fraction of the population owns a smart phone and the information accessed via this medium is rarely printed. The modified *ICT Skills* indicator only includes s*econdary gross enrolment* ratio and *tertiary gross enrolment ratio.* The remaining indicators were excluded due to lack of data.

Table 4-1. Description for the ICT Development Index Indicators (ITU, 2009)

Indicator	Definition
Fixed telephone lines per 100 inhabitants	"Fixed telephone lines refer to telephone lines connecting a subscriber's terminal equipment to the public switched telephone network (PSTN) and which have a dedicated port on a telephone exchange." (ITU, 2009)
Mobile cellular telephone subscriptions per 100 inhabitants	"Number of subscriptions to a public mobile telephone service using cellular technology, which provides access to the Public Switched Telephone Network (PSTN)." (ITU, 2009)
International internet bandwidth per Internet user	"Refer to the capacity that backbone operators provide to carry Internet traffic. this variable is measured in bits per second (per Internet users)." (ITU, 2009)
Proportion of households with a computer	"A computer refers to a desktop or a laptop computer. This variable does not include equipment with some embedded computing abilities such as mobile cellular phones, personal digital assistants or TV sets." (ITU, 2009)
Proportion of households with internet access at home	The Internet is a world-wide public computer network. It provides access to a number of communication services including the World Wide Web and carries e-mail, news, entertainment and data files, irrespective of the device used (not assumed to be only via a computer – it may also be by mobile phone, games machine, digital TV etc.). Access can be via a fixed or mobile network." (ITU, 2009).
Internet users per 100 inhabitants	"While more and more countries capture the number of Internet users through household surveys, data are estimated for many countries, usually based on the number of Internet subscribers and the prevalence and popularity of public or shared Internet access." (ITU, 2009).
Fixed broadband internet subscribers per 100 inhabitants	"Refer to subscriptions to high-speed access (at least 256 kbit/s) to the public Internet (a TCP/IP connection)." (ITU, 2009)
Mobile broadband subscriptions per 100 inhabitants	"Refer to subscriptions to mobile cellular networks with access to data communications (e.g. the Internet) at broadband speeds (greater than or equal to 256 Kbit/s in one or both directions)." (ITU, 2009)
Adult literacy rate	"Adult literacy rate is defined as the percentage of population aged 15 years and over who can both read and write with understanding a short simple statement on his/her everyday life. Adult illiteracy is defined as the percentage of the population aged 15 years and over who cannot both read and write with understanding a short simple statement on his/her everyday life." [(UIS) as cited in (ITU, 2009)]
Gross enrolment ratio (secondary and tertiary)	"Total enrolment in a specific level of education, regardless of age, expressed as a percentage of the eligible official school-age population corresponding to the same level of education in a given school-year." [(UIS) as cited in (ITU, 2009)]

Table 4-2. United States ICT Development Index Calculations (ITU, 2009)

	Indicators	Ideal Value		1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
ICT Access(ntia)														
a	proportion of households with computers	100		42.10	46.55	51.00	56.20	59.00	61.80	68.20	68.20	70.20	74.20	75.00
b	proportion of households with internet access	100		26.20	33.85	41.50	50.40	52.00	54.70	58.21	61.71	62.46	63.20	67.00
ICT Use														
c	Internet users per 100 inhabitants	100		30.09	35.85	43.08	49.08	58.79	61.70	64.76	67.97	68.93	71.83	70.59
d	broadband users per 100 inhabitants	60		0.25	0.97	2.46	4.40	6.76	9.34	12.46	15.88	19.80	22.74	25.35
ICT Skills														
e	Secondary Gross Enrolment ratio	100		88.10	95.00	94.00	94.00	93.00	94.00	94.00	94.00	94.00	94.00	94.00
f	Tertiary gross enrolment ratio	100		72.60	73.00	69.00	70.00	80.00	82.00	82.00	82.00	82.00	82.00	82.00
Normalized Values														
ICT Access		**Formula**	**Weight**											
z1	proportion of households with computers	a/100	0.5	0.21	0.23	0.26	0.28	0.30	0.31	0.34	0.34	0.35	0.37	0.38
z2	proportion of households with internet access	b/100	0.5	0.13	0.17	0.21	0.25	0.26	0.27	0.29	0.31	0.31	0.32	0.34
ICT Use														
z3	Internet users per 100 inhabitants	c/100*weight	0.5	0.15	0.18	0.22	0.25	0.29	0.31	0.32	0.34	0.34	0.36	0.35
z4	broadband users per 100 inhabitants	d/60*weight	0.5	0.00	0.01	0.02	0.04	0.06	0.08	0.10	0.13	0.17	0.19	0.21
ICT Skills														
z5	Secondary Gross Enrolment ratio	e/100*weight	0.50	0.44	0.48	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
z6	Tertiary gross enrolment ratio	f/100*weight	0.50	0.36	0.37	0.35	0.35	0.40	0.41	0.41	0.41	0.41	0.41	0.41
Sub-indices														
ICT access sub-index (L)		**z1+z2*weight**	**0.40**											
				0.14	0.16	0.19	0.21	0.22	0.23	0.25	0.26	0.27	0.27	0.28
ICT use sub-index (M)		**z3+z4*weight**	**0.40**											
				0.06	0.07	0.09	0.11	0.14	0.15	0.17	0.19	0.20	0.22	0.23
ICT skills sub-index (N)		**z5+z6*weight**	**0.20**											
				0.16	0.17	0.16	0.16	0.17	0.18	0.18	0.18	0.18	0.18	0.18
ICT Development Index		**(M+N+L)*10**		**3.58**	**4.04**	**4.42**	**4.90**	**5.35**	**5.64**	**6.00**	**6.25**	**6.45**	**6.70**	**6.86**

This set of variables provided the starting point for conceptualization of the feedback structure of the system. Other variables where identified when the construction of the CLD and SFD was exercised and are described in the respective sections of this document.

4.3.2 Complete System CLD

The CLD conceptual tool aided in the problem mapping, and in the identification of the system's main feedback loops. The paper consumption CLD revealed six feedback loops that are represented in figure 4-3. The complete system CLD, features two balancing loops and four reinforcing loops.

The CLD for paper consumption patterns contains information of the three main subsystems that were identified in the subsystem diagram (figure 4-2): the information access subsystem, the authoring work production subsystem, and the information consumption subsystem.

4.3.2.1 Information Access Subsystem CLD

One of the hypotheses of this study is that advances in interconnectivity are one of the main contributors to the rise in paper consumption. Advances in interconnectivity, together with cheaper connectivity and increases in network bandwidth have enabled people to bring vast amount of information to their desktop (Sellen & Harper, 2002). In other words, people have much more access to paper reproducible information than before that could be and actually is, printed. The dynamics that arise from the interaction of the growth rate of the internet and progress of ICTs, and how much relevant and printable information is accessed by knowledge workers, are captured in this part of the CLD.

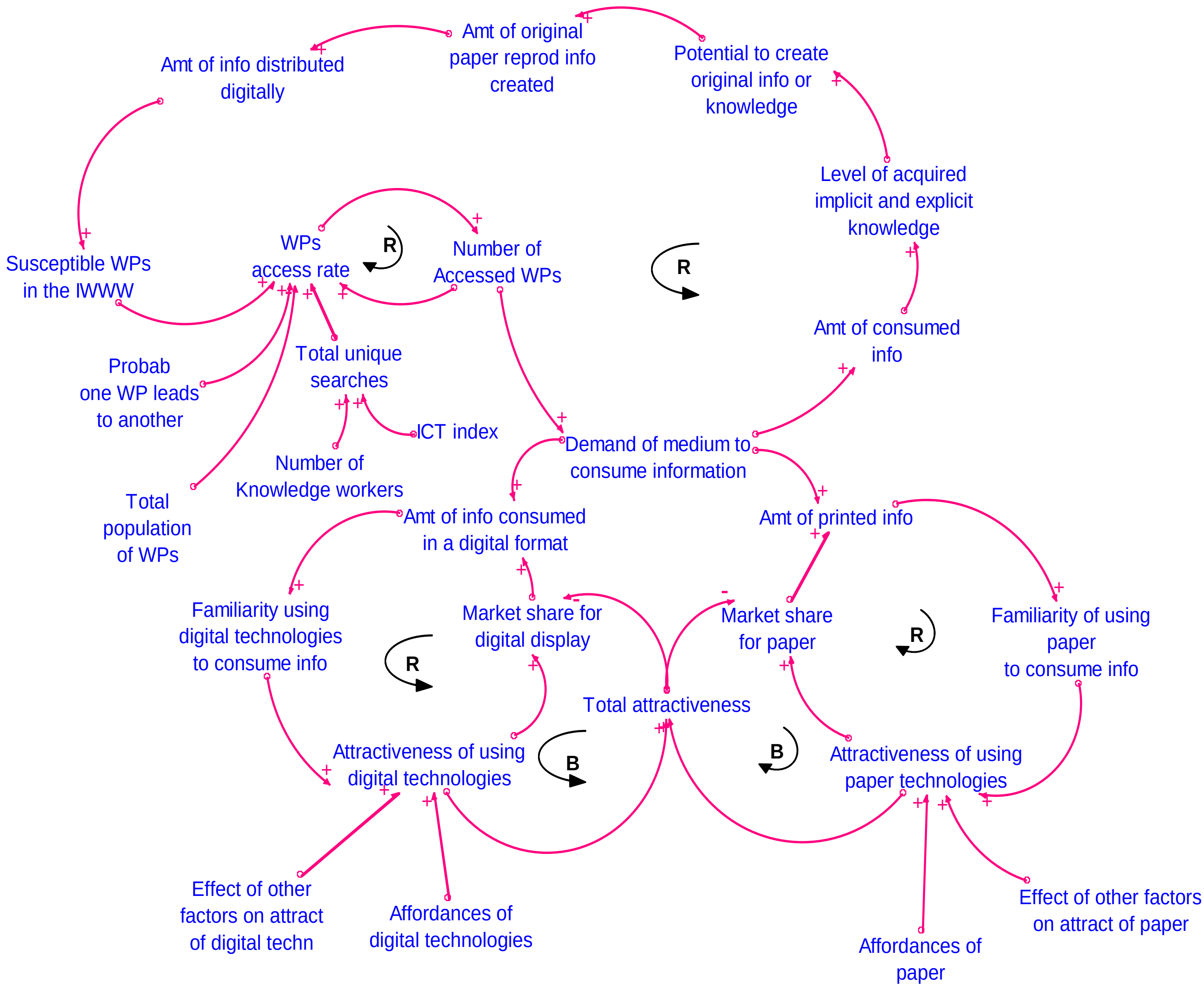


Figure 4-3. Paper Consumption Patterns Complete Causal Loop Diagram (CLD)

The Information Access Subsystem CLD and subsequent SFD were modeled based on the Bass Diffusion Model (BDM hereafter). Frank Bass (1969) developed a model for the diffusion of innovations that captures the positive and negative feedback that affect the adoption of new technologies (Sterman, 2000). The BDM is very useful to explain how the growth of new technologies (in our case the growth of the IWWW occurs, and it specifically addresses the start up problem of the birth of the initial adopters of the new technology (Sterman, 2000). When growth processes begin, positive feedbacks that only depend on the installed base of the technology are absent or weak because there are no or just few adopters; other important feedbacks, produced by several channels of awareness, are the ones that stimulate the adoption of the technology (Sterman, 2000). In the BDM, the channels of awareness include word of mouth and related feedback effects, as well as advertising, media reports, and direct sales efforts feedback effects that depend on the size of the adopting population (Sterman, 2000). Figure 4-4 depicts the basic set up for the BDM.

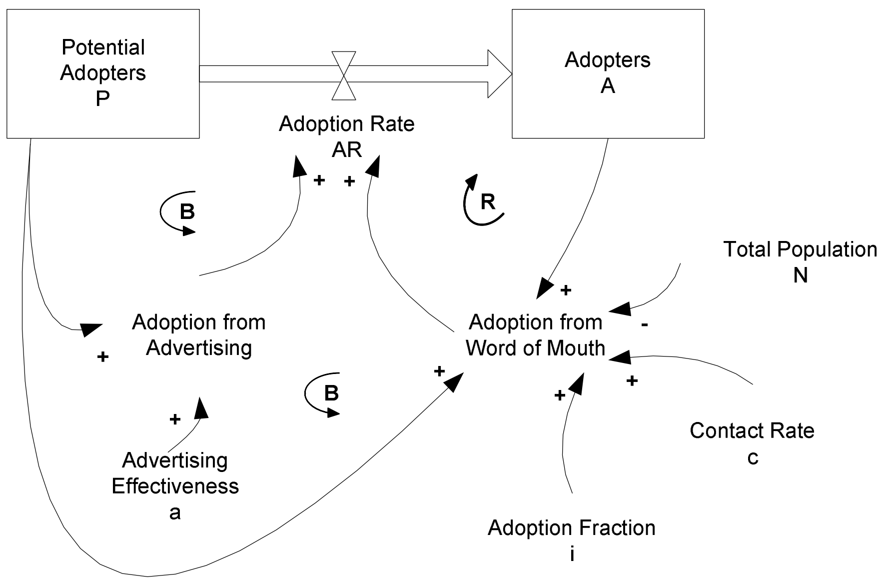


Figure 4-4. The Bass Diffusion Model (Sterman, 2000)

In figure 4-4 the total adoption rate is the sum of adoptions resulting from word of mouth and adoptions resulting from advertising and any other external influences (Sterman, 2000). The equations for the BDM, using the terminology on figure 4-4, are:

$$AR = Adoption\ from\ Advertising + Adoption\ from\ Word\ of\ Mouth \tag{4-1}$$

$$Adoption\ from\ Advertising = aP \tag{4-2}$$

And,

$$Adoption\ from\ Word\ of\ Mouth = ciPA/N \tag{4-3}$$

In our PW paper consumption model, Web Pages (WPs) would be analogous to the "technology" that has the potential to be adopted by a selected population of knowledge workers. Knowledge workers will access WPs to do research on a specific subject, to find general information, for leisure, or for any other reason. The access rate at which knowledge workers come into contact

with WPs (in the BDM, this variable is equivalent to the contact rate (c)) will depend on the average amount of unique searches, the total number of WPs (same as the potential adopters (P) variable in the BDM), and the probability that a WP once accessed leads to another one (the same as the adoption fraction variable (i) in the BDM).

The negative or balancing loop of the BDM, that in this case would decrease the stock that contains the number of susceptible web pages, is ignored in this model. The reason why this loop is ignored is based on the fact that once a WP is accessed, it does not mean that it cannot be accessed again. Table 4-3 provides a list of the all of the identified variables for this subsystem with a brief description for each one of them. The mathematical formulations for each variable are discussed in the SFD section and presented in Table 4-6.

Figure 4-5 depicts the CLD for this part of the system. The identified reinforcing feedback loop explains how the amount of WPs in the IWWW increases as more information is shared and distributed digitally. WPs are accessed, as the unique searches[2] made from the knowledge workers hits a specific WP, and the probability of accessing another WP after accessing previous one, increases as well (reinforcing loop).

[2] Unique Searches is the number of different searches made by an internet user

Table 4-3. Information Access Subsystem Variables Description

Variable	Description
Amt of info distributed digitally	Total amount of information in mega bytes that is shared and distributed digitally. Just the information shared and distributed on web pages is considered
Susceptible WPs in the IWWW	Number of Web Pages from the Indexable World Wide Web that have the potential of being accessed
Probability one WP leads to another	Probability that after entering one page, the user goes to another page related to something in the content of the web page accessed
Total population of WPs	Number of web pages in the IWWW
WPs access rate	Rate at which WPs are accessed
Total unique searches	Average number of actual searches run on the internet.
Number of knowledge workers	total number of knowledge workers that are online searching for information for their job
ICT index	ITU's ICT development index (more details in section 5.3.1)
Number of accessed WPs	Total number of web pages that are accessed per year, given a number of unique searches, number of knowledge workers online looking for information in the web, and the ICT development index
Demand of a medium to consume information	Demand of medium (digital or physical) to display/manage/consume the relevant digital information

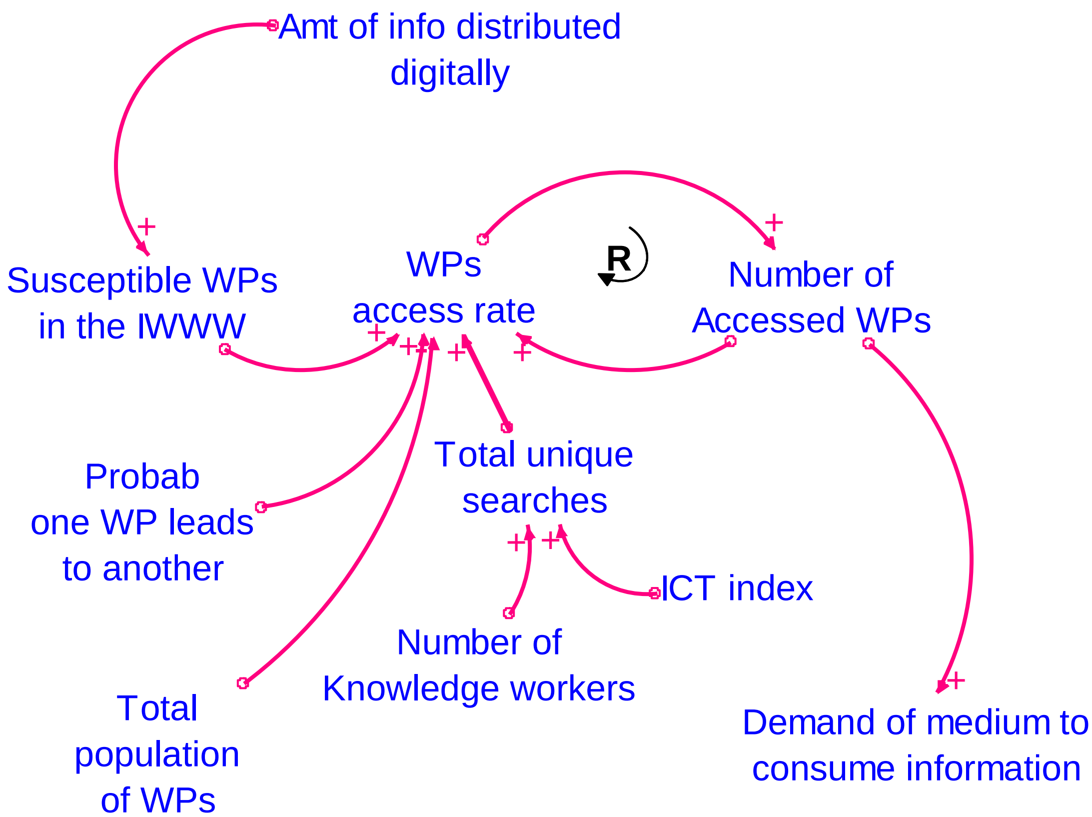


Figure 4-5. Information Access Loop

Given the lack of data for some of the exogenous variables, some feedback loops were omitted on purpose. Specifically, the feedback loops that govern ICTs' and the IWWW's growth rate are not included given the fact that modeling these dynamics represent a very complex problem by themselves. Consequently, given the lack of data to further quantitatively model these loops in the SFD, the ICT and IWWW variables were considered exogenous. At this point it is good to remember that an effective modeling process, attempts to model a well defined problem instead of the whole system (Sterman, 2000).

The drawback of this decision is that this subsystem could be considered oversimplified. Further details on how this qualitative representation of the model was translated into a stock and flow structure will be given in the "Paper Consumption quantitative SD model" (section 4-5).

4.3.2.2 AUTHORING WORK PRODUCTION SUBSYSTEM CLD

This part of the CLD captures the main feedback loop of how original information is produced by knowledge workers. There are two main concepts to be understood before the mental model that is represented in this sector is presented and discussed. These two concepts are *Knowledge* and *Learning.* Knowledge is intangible, it is a concept that, like gravity, one cannot see but just experience its effects (Hunt, 2003). Knowledge can be tacit or explicit. Tacit or implicit knowledge which is based on common sense, is "…the know-how and judgment that comes from experience, intuition, tricks, [and] rules of thumb" (O'dell & Jackson Grayson); on the other hand, explicit knowledge "is the one that comes in form of books and documents, white paper, data bases and online policy manuals" (O'dell & Jackson Grayson). The process of acquiring and retaining knowledge is *learning (Hunt, 2003)* and it is the interaction between tacit knowledge and explicit knowledge that creates *learning (Nonaka, 1994).*

The hypothesis behind this part of the system is that the more a person learns, the more his or her potential is to create new information. Along the same lines, the greater the explicit knowledge a person is exposed to, in addition with the level of tacit knowledge of that person, the greater will be the rate of original authoring work production.

The identified variables for this subsystem are presented in table 4-4. The capacity a knowledge worker has to create original knowledge or information, in other words, his/her potential to challenge, modify or improve existent knowledge, or his/her potential to create original knowledge, will be influenced depending on how much implicit and explicit knowledge that person has been exposed to. The more contact and access people have with content and technology, the more likely they are to modify that content or create new content.

Table 4-4. Information Production Subsystem Variables Description

Variable	Description
Amt of consumed info	Amount of information that is accessed and consumed (information that can be read or modified in printed or digital format)
Level of acquired implicit and explicit knowledge	Amount of new information learned by the knowledge worker
Potential to create original info or knowledge	Capacity that the knowledge worker has to create original information. The more contact and access people have with content and technology, the more likely they are to modify that content or create new content
Amt of original paper reprod info created	Total amount original paper reproducible information that is produced

Figure 4-6 depicts the main reinforcing feedback loop that characterizes the dynamics of this system. It is important to note that the variables *Amt of info distributed digitally, Susceptible WPs in the IWWW, WPs access rate, Demand of medium to consume info, and Number of accessed WPs* are the same ones from the Information Access subsystem, and therefore are described in table 4-3. How these two subsystems are connected can be observed in the complete CLD on figure 4-6.

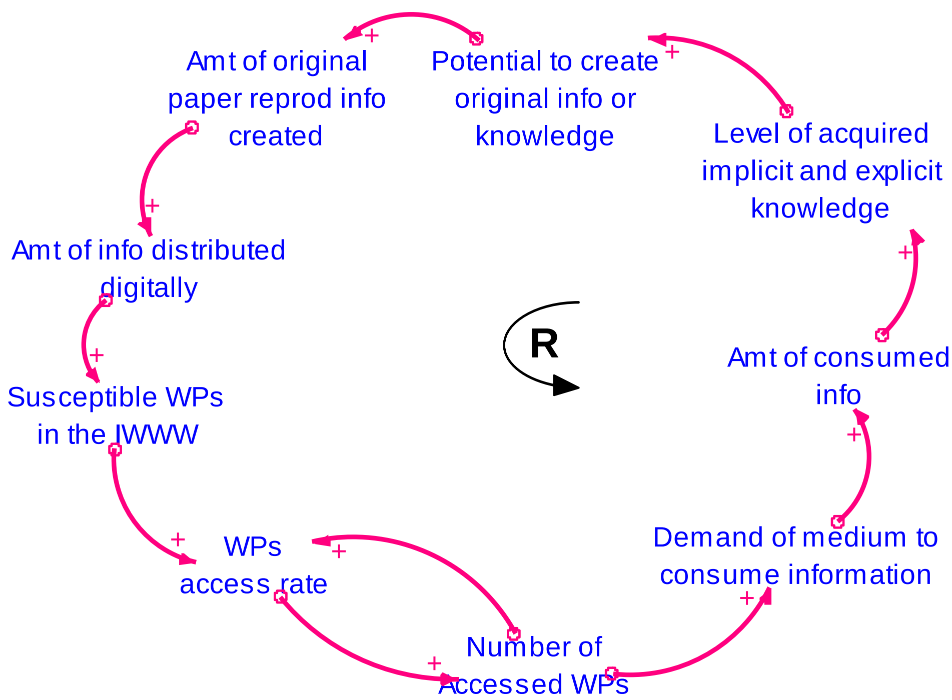


Figure 4-6. Information Production Loop

4.3.2.3 Information Consumption Subsystem CLD

Once information is accessed and determined to be relevant, people consume or manage that accessed information. They make annotations on and from the accessed information, they read it, cross-refer to it, print it, modify it, and review it, just to mention a few activities. Similarly, once original information has been produced, the need for a medium, digital or print, to distribute that information arises. The decision of which medium is to consume or distribute the relevant information is determined depending on the functionality and the affordances of each medium, paper or digital.

The development of the Information Consumption Subsystem CLD was based on principles of *Path dependence theory* and *network effects*. There are many systems, in the human and natural

world, that exhibits path dependence and lock in patterns of behavior (Sterman, 2000), and it is assumed in this study that the PW paper consumption system is one of them.

Path dependence, as defined by Sterman (2000), is “a pattern of behavior in which the ultimate equilibrium depends on the initial conditions and random shocks as the system evolves […] once a dominant design or standard has emerged, the cost of switching becomes prohibitive, so the equilibrium is self-reinforcing: the system has locked in” (Sterman, 2000). The key explanatory variable in this type of behavior is the presence of network effects (Barnes, Gartland, & Stack). Besanko et al. (2004), as cited in Barnes et al. (2004), states that "Consumers often place higher value on a product if other consumers also use it. When this occurs, the product is said to display network effect". Consequently, compatibility and network effects boost product attractiveness and thus expand the total size of the market (Sterman, 2000).

In our PW paper consumption model, network effect principles can help to understand how advances in interconnectivity and print technology have made the ownership of computers and printers more attractive and thus have led more and more people to have access to a larger volume of information which can be printed at a low cost in their jobs or homes.

Also, paper can then be seen as a technology that is locked-in, principally because it was the first one to emerge and is a relatively accessible and easy-to- use technology, but also because so far alternative technologies haven’t been able to dominate the role of paper in certain activities for the already discussed affordances of paper. Paper is a relatively cheap technology that, in contrast to alternative digital technologies, does not need any sophisticated infrastructure to be used.

The simple structure for a simple model of network effects and path dependence developed by Sterman (2000) is used as a basis in this work to develop a model that explains the battle of dominance between paper and digital technologies. This type of model is useful to explain typical standard formation of new products where the utility of the product depends on its installed base and the network of users (Sterman, 2000). Figure 4-7 shows the CLD of this type of structure developed by Sterman (2000).

Figure 4-7 provides the basic structure to capture the feedback typical of systems where the attractiveness of a product based on a given standard depends on its installed base, and where the market share depends on the relative attractiveness of the relative competitive standards (Sterman, 2000). The model presented in figure 4-7, only includes the most basic positive feedback, represented through the installed base of each product. Other determinants of attractiveness such as price, availability, quality, service, features, are excluded from this model on purpose for the sake of simplicity.

The model can be written as follows:

$$Installed\ Base\ of\ Product\ i = INTEGRAL(sales\ of\ product\ i, Initial\ installed\ base\ of\ Product\ i) \tag{4-6}$$

$$Sales\ of\ Product\ i = Total\ Demand * Market\ Share\ Product\ i \tag{4-7}$$

$$Adoption\ from\ Word\ of\ Mouth = ciPA/N \tag{4-8}$$

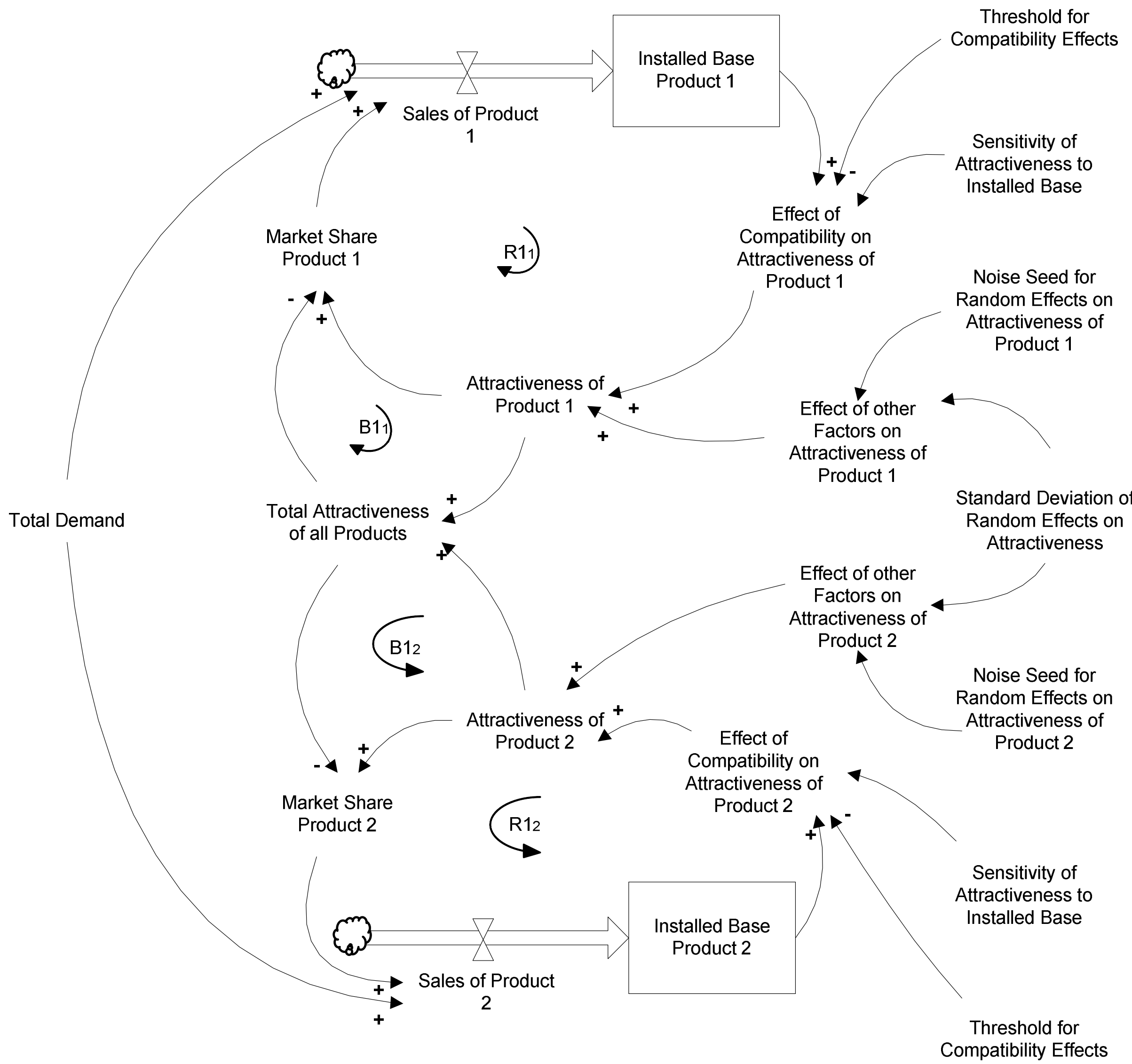


Figure 4-7: Structure for Simple Model of Network Effects (Sterman, 2000)

In the formulation for the *Market Share*, several constraints must be met: market share should increase as the attractiveness of the firm's product increases, and decrease as the attractiveness of the competitors' products rises; also, market share must be bounded between 0 and 100%, and the total market share must be equal to 100% (Sterman, 2000).

Then, market share can be formulated as:

$$Market\ Share\ Product\ i = \frac{Attractiveness\ of\ Product\ i}{Total\ Atrractiveness\ of\ All\ Products} \quad (4\text{-}9)$$

$$Total\ Attractiveness\ of\ All\ Products = \sum_{j=1}^{n} Attractiveness\ of\ Product\ j \quad (4\text{-}10)$$

Attractiveness in this simple model only depends on two factors: the Effect of Compatibility on Attractiveness (network effect) and the effect of all other factors of attractiveness (assumed exogenous).

$$Attractiveness\ of\ Product = \text{Effect of Compatibility on Attractiveness of Product i} \times$$
$$\text{Effect of Other Factors on Attractiveness of Product i} \quad (4\text{-}11)$$

The larger the installed base of the product being considered in this model, the greater the attractiveness of that product. In the following formulation for the Effect of Compatibility on Attractiveness of product i, attractiveness rises exponentially as the installed base grows relative to the Threshold for Compatibility Effects. The threshold is a scaling factor that represents the size of the installed base above which network effect become significant (Sterman, 2000).

$$Effect\ of\ Compatibility\ on\ Attractiveness\ of\ Product\ i =$$
$$\text{EXP [Sensitivity of Attractiveness to Installed Base} \times (\frac{\text{Installed Base of Product i}}{\text{Threshold for Compatibility Effects}})] \quad (4\text{-}11)$$

Based on this simple structure the battle of dominance of digital and paper, and the important feedback loops of network effects of both technologies was modeled and can be seen in figure 4-8. The CLD of this subsystem describes the important feedback loops of information consumption. This subsystem represents how the affordances of paper and digital, in addition to network effects of each technology take place and influence communication medium choice decisions.

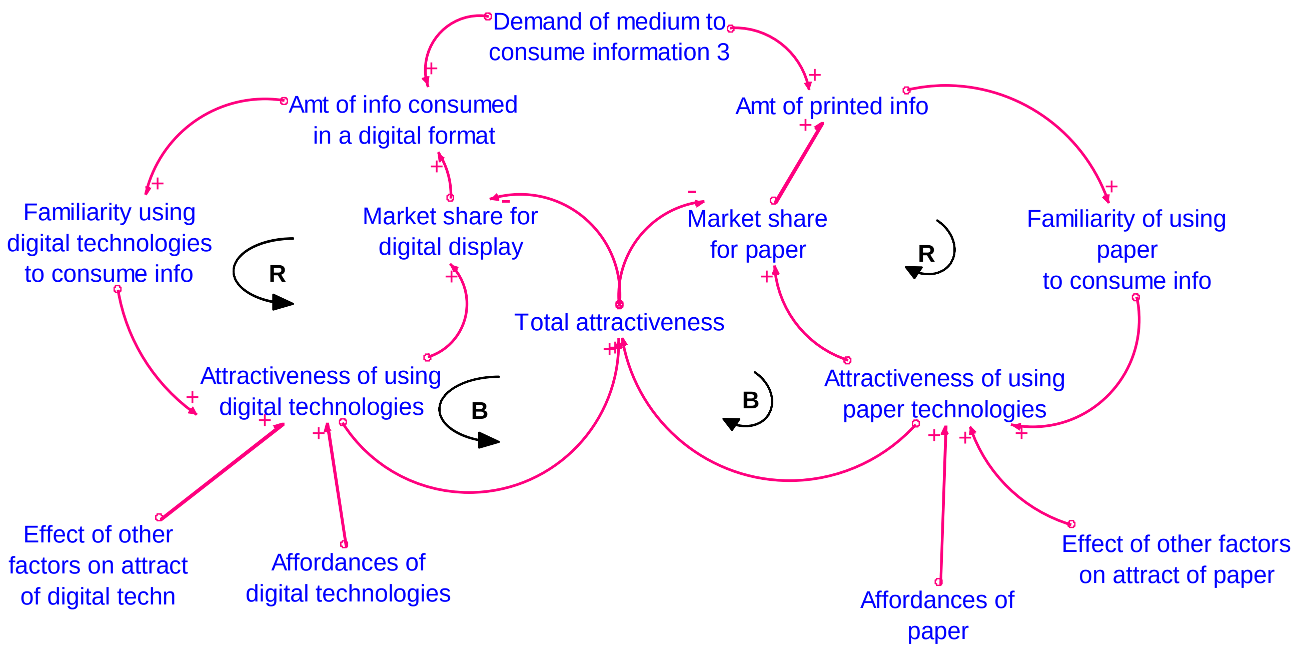


Figure 4-8. Information Consumption Loops

Figure 4-8 shows how the total market share for information increases as the quantity of accessed relevant and paper reproducible information, and consequently the demand for a medium to display that information, increases as well. The two reinforcing feedback loops describe the positive effect the familiarity of using each technology, the affordances, and effect of other factors on attractiveness of each technology have on the market share for each technology. Effects of other factors on attractiveness includes price, availability, quality, service, features and so on (Sterman, 2000). The two balancing loops illustrate how market share for each technology (paper and digital) decreases as total attractiveness of using both technologies increases. Table 4-5 provides the list of variables for the Information Consumption Subsystem used in the CLD. A description for each variable is also provided.

Table 4-5. Information Consumption Sector Variables

Variable	Description
Familiarity using digital technologies to consume info	Level familiarity a knowledge worker has with using digital media. The larger this level, the greater the preference or attractiveness of using digital display media is
Amt of info consumed in digital format	Total amount of digital displayed paper reproducible information
Market share for digital display	Percentage of the market share of Digital Display (this percentage increases as the attractiveness Digital Display technologies also does)
Attractiveness of using digital technologies	Attractiveness of consuming the information digitally which is a product of the network effect of digital display, and the effect of all other factors of attractiveness (aggregated effects of price, features, availability, and so on)
Affordances of digital technologies	Human actions that are enabled by using digital technologies such as remote access, access to a vast amount of information, editing tools, and so on
Effect of other factors on attract of digital tech	Aggregated effects of price, features, availability etc on the attractiveness of using digital display media
Total attractiveness	Sum of the attractiveness levels of printing and digital display
Market share for paper	Percentage of the market share of Printing (this percentage decreases as the attractiveness of the competitor's product rises)
Amt of printed information	Total amount of printed Paper Reproducible Information (PRI)
Familiarity of using paper to consume info	Level familiarity a knowledge worker has with paper. The larger this level, the greater the preference or attractiveness of using printed information
Attractiveness of using paper technologies	Attractiveness of printing is the product of the network effect and the effect of all other factors of attractiveness (aggregated effects of price, features, availability)
Affordances of paper	Human actions that are enabled with the use of PW paper, such as annotation, spatial layout, tangibility and so on
Effect of other factors on attract of paper	Aggregated effects of price, features, availability etc on the attractiveness of using PW paper

4.4 Limitations of CLDs and Omitted loops

The CLD helped to understand the basic dynamics and feedback loops of the problem under study. However, CLDs have several limitations. The two central concepts of system theory are:

first, stock and flow structures; second, feedback loops. However, stock and flow structures can't be captured in causal loop diagrams, not to mention that some loops could be specified in more detail (Sterman, 2000). Omitted dynamics and feedbacks are considered exogenous in this model. Specifically, the ICT development index and the IWWW growth rate are two variables that are considered exogenous in the modeling process.

The next step in this study involved the mathematical translation of the identified dynamic structure and feedback loops in the CLD. The quantitative model includes significant stock and flow structures that are not distinguished in the CLD. Some of the loops identified in the CLD are constructed in more detail in the Stock and Flow Diagram (SFD) in order to translate the subjective description of our heuristic mental models into an algorithmic one.

The previous sections of this chapter described in detail the dynamic hypothesis of this research. Also, a theoretical system dynamics model for PW paper consumption, using CLD as a system thinking tool, was developed and described. The following sections of this chapter describe how the theoretical model developed in this chapter was translated to an empirical one.

4.5 Paper Consumption quantitative SD model

Modeling paper consumption is a complex and dynamic problem which is affected by the decisions and behaviors of various stakeholders. The subsystem diagram (figure 4-2) and the CLD (figure 4-3) helped to identify the key stakeholders of the system and the main feedback loops that characterize its dynamic behavior. However, these representations are qualitative and conceptual models with certain limitations (discussed in section 4.4). In order to quantitatively understand the dynamics of this system, these qualitative representations were converted into a

quantitative model. The focus of this chapter is to translate these dynamics into stock and flow structures. Stocks characterize the state of the system and generate information that constitute the basis for action and decisions (Sterman, 2000).

The paper consumption model contains the three identified and previously discussed subsystems: the *information access, authoring work production, and information consumption* subsystems. As discussed previously in section 4-9, the remaining sectors identified in the subsystem diagram are either omitted or considered exogenous. Figure 4-9 summarizes the key stocks for each subsystem.

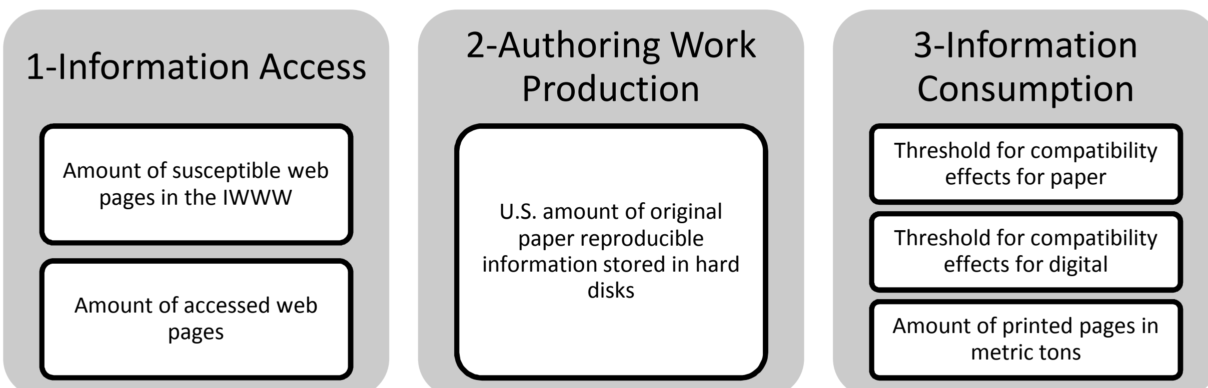


Figure 4-9. Paper Consumption SD Model Subsystems and Important Stocks

The main stocks of the information access subsystem are two: the first one tracks the amount of pages that can be accessed in the IWW, and the second one tracks the number of WPs that are actually accessed by a knowledge work population. This first subsystem is modeled based on the BDM. The second subsystem, authoring work production, represents the amount of original textual information that is stored in hard disks in the U.S. The information consumption subsystem includes the stocks threshold for compatibility effects for paper, threshold for compatibility effects for digital display, and the amount of printed pages measured in metric tons. This last subsystem is modeled following principles of network effect theory, and path

dependence patterns of behavior also discussed in Sterman (2000). Modeling details for each specific model are fully discussed in sections 4.5.1, 4.5.2, and 4.5.3.

4.5.1 Information Access Subsystem SFD

The information access subsystem tracks the amount of susceptible WPs in the IWWW and the actual number of WPs that are accessed by the total population of knowledge workers per year. This sector was modeled based on principles of the epidemic and innovation diffusion (Bass diffusion model) S-shaped growth patterns described by Sterman (Sterman, 2000) which is explained in section 4.3.2.1. Figure 4-10 depicts the stock and flow structure of the subsystem as simulated in Stella.

While this subsystem captures the basic process of how WPs are being accessed, it contains many simple and restrictive assumptions. First, this subsystem assumes that the IWWW grows exponentially. Second, the population of WPs is assumed to be homogenous: all WPs are assumed to be accessed at the same rate. For example, a social networking web page, such as Facebook, Twitter and social blogs, is assumed to be accessed at the same rate as a research electronic journal, when in fact this is not the case. Also, this model does not take into account the Deep Web[3], which is estimated to be at least 400 to 550 times larger than the Surface Web (Lyman & Varian, 2003). For instance, private WPs that require registration and log in (such as user name and passwords or some sort of subscription to access), are part of the Deep Web and are thus not considered in this model. The omission of the Deep Web in this model is based on the complexity in quantifying the content in this part of the web, reason why there aren't any accurate estimations of the approximate size of it.

---

[3] Deep Web: database driven websites that create web pages on demand; Surface Web: fixed web pagesLyman, P., & Varian, H. R. 2003. HOW MUCH INFORMATION 2003?: School of Information Management and Systems at the University of California at Berkeley.

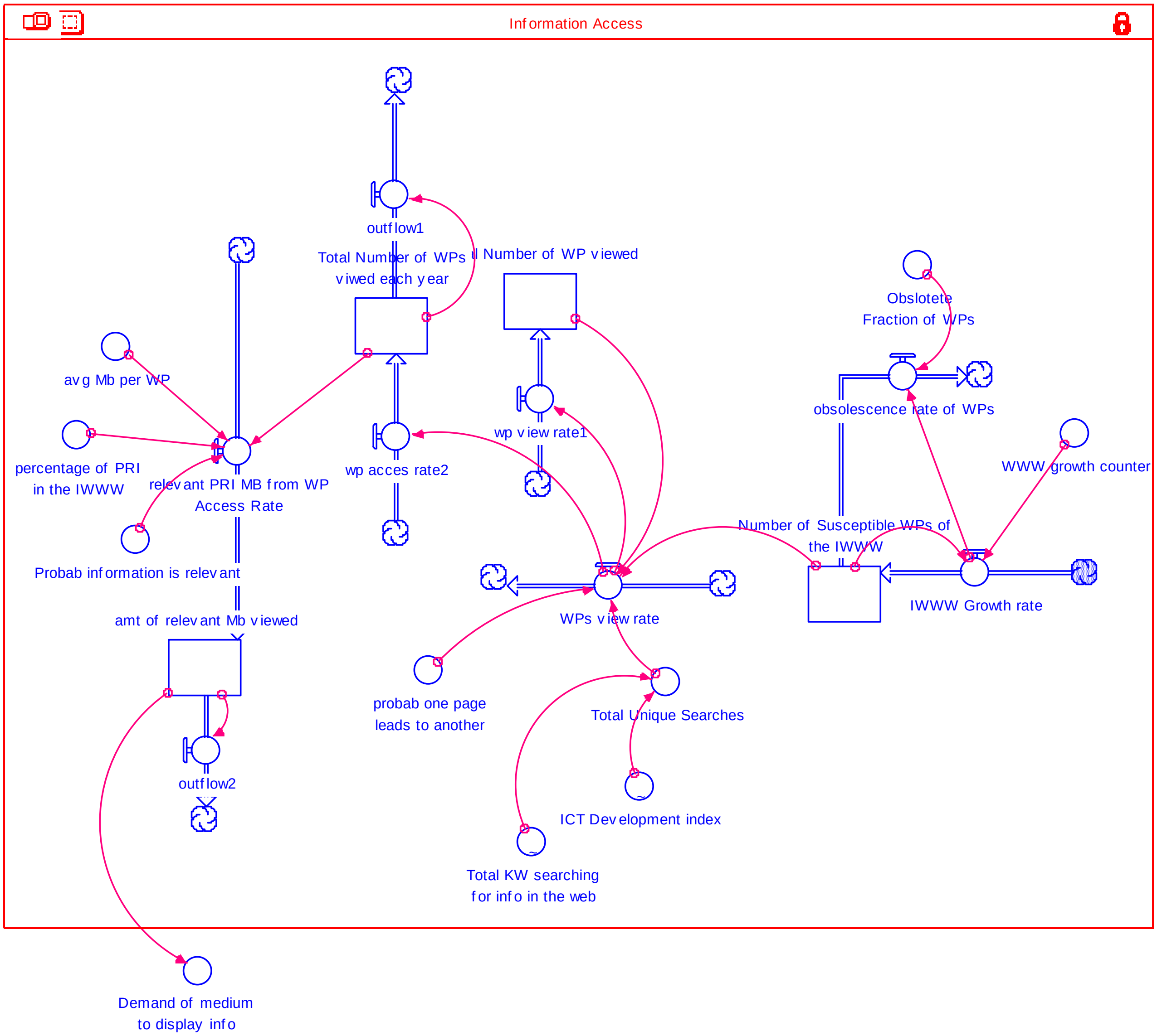


Figure 4-10. Information Access Subsystem: Stock and Flow Structure

Tables 4-6 and 4-7 are the Model Boundary Chart for this subsystem. These tables include the full description, the type of variable (stock, flow, converters, or graph), the initial value, and the equations.

Table 4-6. Model Boundary Chart: Stocks with Inflows and Outflows for the Information Access Subsystem

STOCKS WITH INFLOWS AND OUTFLOWS				
Type	**Name**	**Equation**	**Initial Value**	**Description**
STOCK	Number of susceptible s of the IWWW	Number of Susceptible s of the IWWW(t - dt) + (IWWW Growth rate + s flow - obsolescence rate of s) * dt	1	Number in million of WPs from the Indexable World Wide Web that have the potential of being accessed
INFLOWS	IWWW growth rate	= if (IWWW growth counter<1994) then (Number of Susceptible s of the IWWW*0.0002) else(if(1994<IWWW growth counter<2018) then(Number of Susceptible s of the IWWW*0.02) else(Number of Susceptible s of the IWWW*0.005))	N/a	Per year compound growth for the Amount of Susceptible s of the Indexable World Wide Web (IWWW) stock
OUTFLOWS	Obsolescence rate of s	= IWWW Growth rate*Obsolescence Fraction of s	N/a	Rate in which WPs get obsolete
STOCK	Total number of s viewed each year	= Total Number of s viewed each year(t - dt) + (access rate2 - outflow1) * dt	0	Total number of s viewed per year
INFLOWS	Access rate2	= Total Unique Searches*probab one page leads to another*Total Number of WP viewed*(1-(Total Number of WP viewed/(Number of Susceptible WPs of the IWWW+Total Number of WP viewed)))	N/A	Wps viewed rate in million per year
OUTFLOWS	Outflow1	= total number of s viwed each year	N/A	Outflow that drains the stock total number of s viewed each year, to keep it in a per year basis
STOCK	Total Number of WP viewed	= Total Number of WP viewed(t - dt) + (wp view rate1) * dt	1	Total number of web pages viewed in million in the whole time horizon
INFLOW		wp view rate1 = WPs view rate		Web pages view in million per year
STOCK	Amt of relevant Mb viewed	= amt of relevant Mb viewed(t - dt) + (relevant PRI MB from WP Access Rate - outflow2) * dt INIT amt of relevant Mb viewed = 0	0	Total Megabytes of relevant information viewed per year
INFLOW	relevant PRI MB from WP Access Rate	= Total Number of WPs viewed each year*avg Mb per WP*percentage of PRI in the IWWW*Probability information is relevant	N/A	Relevant paper reproducible (printable) Mega bytes from wps in million per year
OUTFLOW	outflow2	= amt of relevant Mb viewed	N/A	Outflow that drains the stock Amt of relevant Mb viewed

Table 4-7. Model Boundary Chart: Unattached Variables for the Information Access Subsystem

UNATTACHED VARIABLES				
Type	**Name**	**Equation**	**Initial Value**	**Description**
CONVERTER	IWWW growth counter	= counter(1979,2050)	N/A	Year counter
GRAPH	Obsolescence Fraction of WPs	= GRAPH(TIME)= (1970, 0.00), (1978, 0.00), (1986, 0.00), (1994, 0.00), (2002, 0.00), (2010, 0.00), (2018, 0.00), (2026, 0.0175), (2034, 0.0825), (2042, 0.21), (2050, 0.5)	N/A	Until 1994 obsolescence rate is zero. Then, the ratio at which WPs get obsolete per year increases (until 1/2) as the number of new wps per year also increases
GRAPH	Total knowledge workers searching for info in the web	= GRAPH(TIME)= (1970, 37.0), (1971, 39.0), (1972, 41.0), (1973, 43.0), (1974, 45.0), (1975, 46.0), (1976, 48.0), (1977, 51.0), (1978, 53.0), (1979, 55.0), (1980, 57.0), (1981, 59.0), (1982, 61.0), (1983, 63.0), (1984, 65.0), (1985, 67.0), (1986, 69.0), (1987, 71.0), (1988, 74.0), (1989, 76.0), (1990, 78.0), (1991, 80.0), (1992, 82.0), (1993, 84.0), (1994, 86.0), (1995, 88.0), (1996, 90.0), (1997, 93.0), (1998, 95.0), (1999, 98.0), (2000, 101), (2001, 103), (2002, 105), (2003, 108), (2004, 109), (2005, 112), (2006, 115), (2007, 118)	N/A	Total number of knowledge workers that are online searching for information for their job, in million per year
GRAPH	ICT Development index	= GRAPH(TIME)= (1970, 0.101), (1971, 0.401), (1972, 0.501), (1973, 0.601), (1974, 0.601), (1975, 0.601), (1976, 0.601), (1977, 0.701), (1978, 0.751), (1979, 0.901), (1980, 0.951), (1981, 0.951), (1982, 0.95), (1983, 1.10), (1984, 1.10), (1985, 1.15), (1986, 1.15), (1987, 1.15), (1988, 1.15), (1989, 1.20), (1990, 1.20), (1991, 1.20), (1992, 1.20), (1993, 1.30), (1994, 1.30), (1995, 1.40), (1996, 1.70), (1997, 2.20), (1998, 3.58), (1999, 4.04), (2000, 4.42), (2001, 4.90), (2002, 5.35), (2003, 5.64), (2004, 6.00), (2005, 6.25), (2006, 6.45), (2007, 6.70), (2008, 6.86), (2009, 7.55), (2010, 10.0)	N/A	ITU's new ICT Development Index (IDI) compares developments in information and communication technologies (ICT) in 154 countries over a five-year period from 2002 to 2007.
CONVERTER	Total Unique Searches	= Total KWs searching for info in the web*ICT Development index	N/A	Average number of actual searches run on the internet
CONVERTER	probability one page leads to another	= random(0.05,0.10)		Probability that after entering one page, the user goes to another page related to something in the content of the web page accessed.
CONVERTER	avg Mb per WP	= normal((33100/9800),1)	N/A	average Megabytes per web page
CONVERTER	percentage of PRI in the IWWW	N/A	14	Percentage of paper reproducible information in the Indexable World Wide Web (IWWW). This includes: Microsoft Excel, Word, and Power Point , Files, Text, Adobe PDF, Other listed files
CONVERTER	Probability information is relevant	= normal(0.33,0.1)	N/A	Probability the information viewed is relevant to the user
CONVERTER	Demand of medium to display info	= (amt of relevant Mb viewed +US prod\tion of org PRI stored in PC DD per year)*0.30	N/A	Demand of medium (digital or physical) to consume the relevant information in Megabytes per year
CLOUD TO CLOUD FLOW	WPs viewed rate	= Total Unique Searches*probab one page leads to another*Total Number of WP viewed*(1-(Total Number of WP viewed/(Number of Susceptible WPs of the IWWW+Total Number of WP viewed)))	N/A	Total number of web pages that are accessed per year, given a number of unique searches, number of knowledge workers online looking for information in the web, and the ICT development index in that year

4.5.2 Authoring Work Production Subsystem SFD

The Authoring Work Production Subsystem (figure 4-11) models the amount of new information that is being produced and distributed each year by knowledge workers. This sector was modeled independently of the information access subsystem based on the premise that in order to create a digital document, the knowledge worker does not necessarily have to be connected to the internet. Excel spread sheets and documents in MS Word are an example of the type of documents a knowledge worker is likely to produce in a knowledge work environment (such as office, schools and so on). The authored information is assumed to be produced and edited in an electronic device, e.g. a personal computer, and the decision of whether to distribute it digitally or in paper format is made in the *Information Consumption* subsystem.

A limitation of this subsystem is that it does not take into account the amount of pages that are printed in several stages of the knowledge work-flows. Collaboration and team work for instance, are very common in knowledge work and paper is often the preferred analytic resource to draft and manage information while these activities are taking place (Sellen & Harper, 2002).

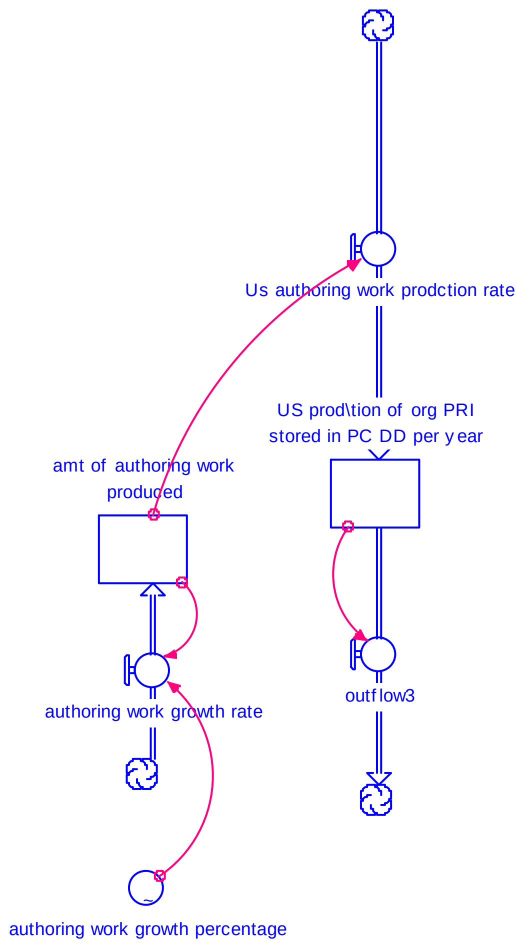


Figure 4-11. Information Production Stock and Flow Structure

The following section describes the Information Consumption Subsystem SFD.

Tables 4-8 and 4-9 are the Model Boundary Chart for this subsystem. These tables include the full description, the type of variable (stock, flow, converters, or graph), the initial value, and the equation.

Table 4-8. Model Boundary Chart: Stocks with Inflows and Outflows for the Authoring Work Production Subsystem

STOCKS WITH INFLOWS AND OUTFLOWS				
Type	**Name**	**Equation**	**Initial Value**	**Description**
STOCK	US prod\tion of org PRI stored in PC DD per year(t)	= US prod\tion of org PRI stored in PC DD per year(t - dt) + (Us authoring work production rate - outflow3) * dt	1	United States production of original Paper Reproducible Information (PRI) stored in PC disk drives in Megabytes per year
INFLOWS	Us authoring work production rate	= amt of authoring work produced	N/A	US authoring work production in Megabytes per year
OUTFLOWS	Outflow 3	outflow3 = US prod\tion of org PRI stored in PC DD per year	N/A	outflow that drains the stock US prod\tion of org PRI stored in PC DD per year, to keep it in a per year basis
STOCK	amt of authoring work produced	= amt of authoring work produced after 2006(t - dt) + (authoring work growth rate) * dt INIT amt of authoring work produced after 2006 = 6000	6000	Total amt of authoring work produced
INFLOWS	Authoring work growth rate	= amt of authoring work produced*authoring work growth percentage	N/A	Total amt of authoring work produced per year

Table 4-9. Unattached Variables for the Authoring Work Production Subsystem

UNATTACHED VARIABLES				
Type	**Name**	**Equation**	**Initial Value**	**Description**
GRAPH	Authoring work growth percentage	= GRAPH(TIME)= (1970, 0.00), (1978, 0.0075), (1986, 0.21), (1994, 0.05), (2002, 0.0175), (2010, 0.01), (2018, 0.0075), (2026, 0.005), (2034, 0.005), (2042, 0.0075), (2050, 0.01)	N/A	Growth rate at which authoring work production increases per year

4.5.3 INFORMATION CONSUMPTION SUBSYSTEM

As already discussed in section 4.3.2.3, the information Consumption Subsystem is based on principles of Path dependence theory and network effects. Figure 4-12 depicts the stock and flow structure of this subsystem as simulated in Stella.

There are three key stocks that this sector tracks: the first two are the stock *threshold for compatibility effects of paper*, and the stock *threshold for compatibility effects of digital technologies*. The third stock this included in this subsystem tracks the amount of *metric tons of printed paper*. The stocks threshold for compatibility effects represent the amount in Megabytes (Mb) of the installed base of paper and digital above which network effects, for a technology to dominate, become important. The threshold for compatibility effects for paper starts with a small amount of Mb compared to the threshold for compatibility effects for digital, and increases while the threshold of compatibility effects for digital decreases over time with the advent of newer *paper-like* digital technology.

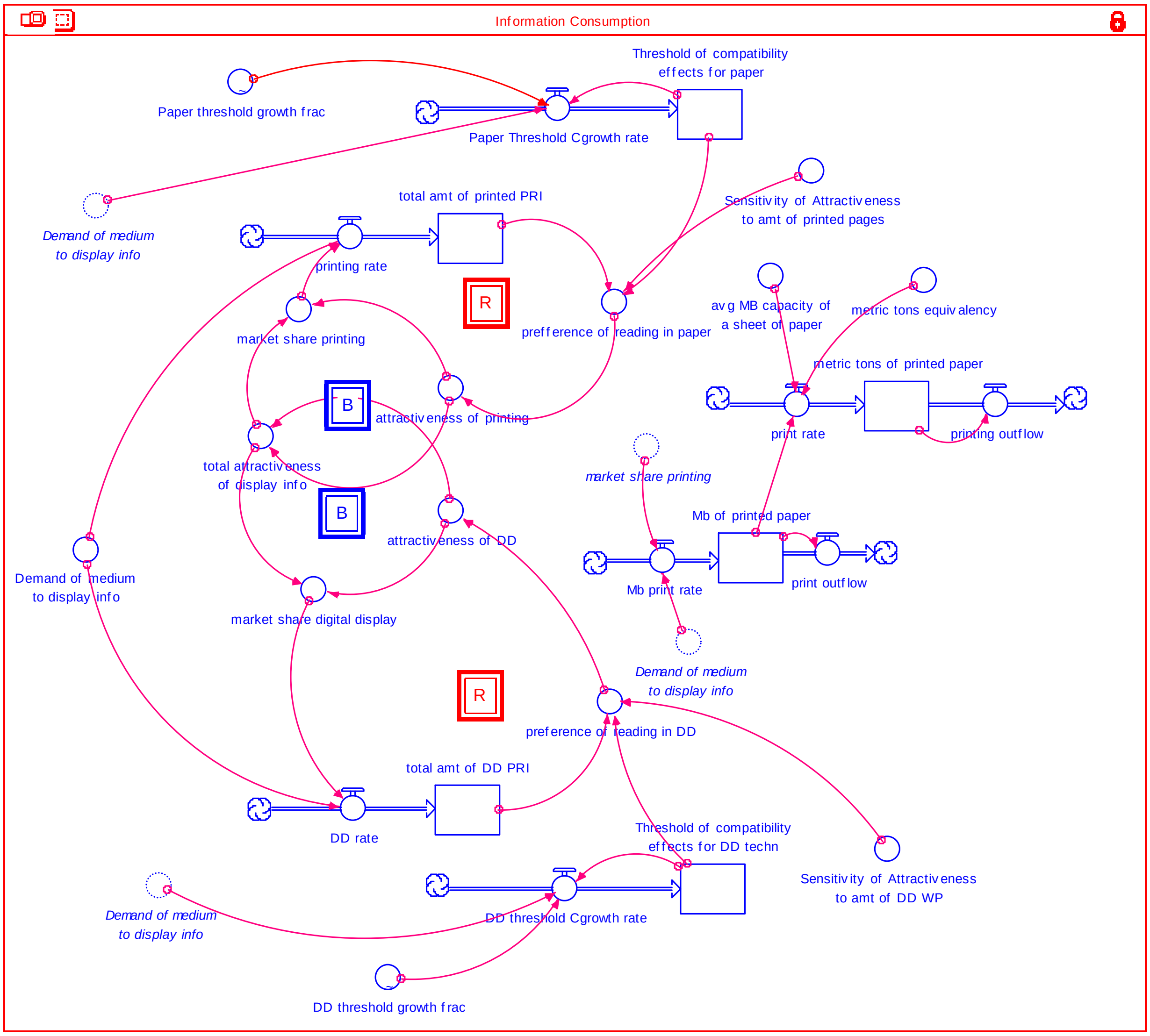


Figure 4-12: Stock and Flow Structure of the Information Consumption Sector

The variable *demand of a medium to display information* is fed by the variable *amount of relevant information accessed from the Information Access Subsystem*, and the variable *amount of original produced information* from the *Authoring Work Production Subsystem*. The variables *preference of reading in paper* and *preference of reading in digital display* are influenced by the scale of the *threshold for compatibility effects of paper* and *threshold for compatibility effects of digital* respectively. That is, the smaller the threshold for compatibility effects for paper, the

stronger will be the network effect and therefore, the greater will be the preference to use paper, and vice versa. A critical feedback in the system is the one represented by the network effect on the attractiveness of each technology. The more familiar an individual is with one technology, the more attractive it will be for that person to continue using that technology. The market share for each technology increases as its attractiveness on the product rises and decreases when the opposite happens.

Although the affordances of paper and digital technologies are vital to understand paper consumption and are captured in the qualitative CLD, they were not explicitly simulated in the SFD. It is important to remember that paper afford several human actions such as grasping, carrying, folding, and writing (Sellen & Harper, 2002) while digital devices affords others such as immediate and remote access to huge amount of information, access to a diverse set of experiences, not to mention that they have made possible new forms of dialogue and communication (Conole & Dyke). Most of these characteristics are too subjective and qualitative in nature to model in a quantitative manner, which makes it difficult to simulate, test, and validate them (Barlas, 1996). For the variables *sensitivity of attractiveness to amount of printed pages* and *sensitivity of attractiveness to amount of digital displayed pages*, the greater the sensitivity, which is a dimensionless number that goes from 1 to 20, the sharper and steeper the logistic curve that represents the growth of the market share will be, and the more rapidly share approaches its extreme values as installed base varies.

Tables 4-10 and 4-11 are the Model Boundary Chart for this subsystem. These tables include the full description, the type of variable (stock, flow, converters, or graph), the initial value, and the equations. The following section provides a description of how the simulation model was populated.

Table 4-10. Model Boundary Chart: Stocks with Inflows and Outflows for the Information Consumption Subsystem

STOCKS WITH INFLOWS AND OUTFLOWS				
Type	**Name**	**Equation**	**Initial Value**	**Description**
STOCK	Threshold for compatibility effects of paper	= Threshold of compatibility effects for paper(t - dt) + (Paper Threshold Cgrowth rate) * dt	45	Scaling factor that represents the size of the installed base of printing above which network effects become important (Megabytes per year)
INFLOWS	Paper Threshold Cgrowth rate	= Demand of medium to display info+(Threshold of compatibility effects for paper*(CGROWTH(Paper threshold growth frac)))	N/A	Compound growth rate at which the threshold of compatibility effects for paper increases
STOCK	Threshold of compatibility effects for DD techn	= Threshold of compatibility effects for DD techn(t - dt) + (DD threshold Cgrowth rate) * dt	80000	Scaling factor that represents the size of the installed base of Digital Display above which network effects become important (Megabytes per year)
INFLOWS	DD threshold Cgrowth rate	DD threshold Cgrowth rate = Demand of medium to display info+((CGROWTH(DD threshold growth frac))*Threshold of compatibility effects for DD techn)	N/A	Compound growth rate at which the threshold of compatibility effects for digital display increases
STOCK	Total amt of printed PRI	= total amt of printed PRI(t - dt) + (printing rate) * dt	200	Total amount of printed Megabytes of Paper Reproducible Information (PRI)
INFLOW	Printing rate	= demand of medium to display info*market share printing	N/A	Printed reproducible information rate (megabytes per year)
STOCK	Total amt of DD PRI	= total amt of DD PRI(t - dt) + (DD rate) * dt	1	Total amount of digital displayed Megabytes of paper reproducible information
INFLOW	DD rate	= Demand of medium to display info*market share digital display	N/A	Digital Displayed PRI rate (Megabytes per year)
STOCK	Mb of printed paper	= Mb of printed paper(t - dt) + (Mb print rate - print outflow) * dt	0	Total amount of printed Mega Bytes of information per year
INFLOWS	Mb print rate	= Demand of medium to display info*market share printing	N/A	Rate at which information is printed per year
OUTFLOWS	Print outflow	= mb of printed paper	N/A	Outflow that drains the stock Mb of printed paper to keep it in a per year basis
STOCK	Metric tons of printed paper(t)	= metric tons of printed paper(t - dt) + (print rate - printing outflow) * dt	0	Total amount of printed paper in metric tons per year
INFLOWS	Print rate	= (mb of printed paper/avg mb capacity of a sheet of paper)*metric tons equivalency	N/a	number of sheets of paper per year
OUTFLOWS	Printing outflow	= metric tons of printed paper	n/a	Outflow that drains the stock metric tons of printed paper to keep it in a per year basis

Table 4-11. Unattached Variables for the Information Consumption Subsystem

UNATTACHED VARIABLES				
Type	**Name**	**Equation**	**Initial Value**	**Description**
GRAPH	Paper threshold growth frac	= GRAPH(TIME)= (1970, 0.00), (1975, 1.00), (1980, 4.50), (1985, 12.5), (1990, 23.5), (1995, 32.0), (2000, 41.5), (2005, 55.0), (2010, 73.5), (2015, 89.5), (2020, 100)	N/A	Rate at which the threshold of paper will be increasing
CONVERTER	Demand of medium to display info	= (amt of relevant Mb viewed+US prod\tion of org PRI stored in PC DD per year)*0.30	N/A	Demand of medium (digital or physical) to display/manage/consume the relevant information in Megabytes per year
GRAPH	DD threshold growth frac	= GRAPH(TIME)= (1970, 30.0), (1975, 30.0), (1980, 30.0), (1985, 20.7), (1990, 13.2), (1995, 7.35), (2000, 5.10), (2005, 3.90), (2010, 2.70), (2015, 1.35), (2020, 1.20)	N/A	Rate at which the threshold of digital display will be increasing
CONVERTER	Market share digital display	= attractiveness of dd/total attractiveness of display info	N/a	Percentage of the market share of digital display (this percentage increases as the attractiveness digital display technologies rises)
CONVERTER	Market share printing	= attractiveness of printing/total attractiveness of display info	N/a	Percentage of the market share of printing (this percentage decreases as the attractiveness of the competitor's product rises)
CONVERTER	Total attractiveness of display info	= attractiveness of dd+attractiveness of printing	N/a	Sum of the attractiveness levels of printing and digital display
CONVERTER	Attractiveness of DD	= preference of reading in DD	N/A	Attractiveness of digital display which is the product of the network effect of digital display and the effect of all other factors of attractiveness (aggregated effects of price, features, availability)
CONVERTER	Attractiveness of printing	= prefference of reading in paper	N/a	Attractiveness of printing is the product of the network effect and the effect of all other factors of attractiveness (aggregated effects of price, features, availability)
CONVERTER	Preference of reading in DD	= EXP(Sensitivity of Attractiveness to amt of DD WP*(total amt of DD PRI/Threshold of compatibility effects for DD techn))	N/A	Preference of reading in digital display is the effect of compatibility of attractiveness of digital display that captures the network and compatibility effects: the larger the installed base, the greater the preference or attractiveness of digital display
CONVERTER	Prefference of reading in paper	= exp(sensitivity of attractiveness to amt of printed pages*(total amt of printed pri/threshold of compatibility effects for paper))	N/a	Preference of reading in paper is the effect of compatibility of attractiveness of printing that captures the network and compatibility effects: the larger the installed base, the greater the preference or attractiveness of printing
CONVERTER	Sensitivity of Attractiveness to amt of printed pages	N/A	15	Sensitivity of attractiveness to the installed base (printed paper reproducible information). The greater this sensitivity (which is a dimensionless number), the sharper and steeper the logistic curve, and the more rapidly share approaches its extreme values as installed base varies
CONVERTER	Sensitivity of Attractiveness to amt of DD WP	N/A	1	Sensitivity of attractiveness to the installed base (digital displayed paper reproducible information). The greater this sensitivity (which is a dimensionless number), the sharper and steeper the logistic curve, and the more rapidly share approaches its extreme values as installed base varies
CONVERTER	Avg MB capacity of a sheet of paper	= 2/1000	N/A	Average mega bytes capacity of a sheet of paper
CONVERTER	Metric tons equivalency	= 4.08233133*10^(-6)*10^6	N/a	Equivalency to convert Mb of printed paper into metric tons

4.6 POPULATING THE MODEL

This section discusses the different sources of data that were used to populate the model. In addition, the assumptions and decisions that were made for those variables where data was not available are discussed in this section.

One of the goals of the model is to explain the role that ICTs have had on past and current paper consumption patterns and behavior. However, for the simulation model, there are three specific outcomes that are of special interest:

- How the market share for paper and digital technologies varies over time and when the crossover point for both market shares is likely to occur. This will inform if a total substitution of paper for digital technologies can happen and if it is possible, when it will likely occur if nothing changes in the system.

- If a peak in paper consumption is possible. Of special interest is also how dramatic this peak might be depending on how the parameters vary. In addition, the possibilities of paper consumption peaking and leveling off at a certain level, or reaching a peak to then start decreasing until it is completely substituted by digital technologies are investigated.

- The numerical value of the paper consumption peak. This value will inform how far away current paper consumption is from the calculated peak value. This can theoretically tell if paper consumption is already reaching a peak.

The assumptions and decisions made, as well as the sources of data that was used to populate the variables in the model were:

- The model uses United States data. This was the most available free data.

- The time horizon goes from 1970-2050. This way important feedback that arises with the time and delays can be captured.

- The growth of IWWW is very dynamic. The internet began in the late 80s, however, the actual commercialization and exploitation of the WWW began to occur early in 1994 with the release of the Mosaic web browser (Kogut, 2004). Before 1994, for this model the growth rate of the IWWW is assumed to be zero. Then it is assumed to double every 5 years.

- Information is accessed and produced digitally.

- Paper starts fully dominating the information market share. In other words it starts with 100 percent market share while digital display market share starts with 0 percent.

- The threshold for compatibility effects of paper is assumed to be very small in the first decades before the commercialization of the internet; after 1994, it is assumed to start decreasing. The opposite is assumed for the threshold for compatibility effects of digital devices.

- The parameter sensitivity of attractiveness to amount of printed pages and sensitivity of attractiveness to amount of digital displayed web pages is a factor that goes from 1 to 20 and controls the strength of the network effect. It was assumed a value of 15 for sensitivity of attractiveness of paper and 1 for sensitivity of attractiveness to digital initially.

- The affordances of paper and digital devices are not included in the SFD. In other words, although these factors are a central concept in this thesis, given their qualitative nature and the difficulty in modeling them quantitatively, there are only described qualitatively in the CLD.

- Although it is a very interest point of discussion, the sustainability of the alternative technology to paper is not considered as a factor of preference.

4.7 SUMMARY

This chapter presented a theoretical and empirical model of the system under study. Three main subsystems to be included in the model were identified: *Information Access*, *Authoring Work Production*, *and Information Consumption* subsystems. The key variables for the theoretical model were identified and described. Then, the CLD for each subsystem was generated and the principles of the Bass Diffusion Model and Path Dependence Theory, as explained by Sterman (2000), where used to develop the *Information Creation* and *Information Consumption* subsystem respectively. Finally, a discussion of the limitations of CLD and omitted loops were discussed.

Furthermore, description of the stock and flow diagram of the print media paper consumption patterns was developed and described. For each of the three identified subsystems a description of the stocks and variables was provided. The assumptions, decisions, and type of data that was used to populate the model were also discussed. Once the model was populated based on the available data and the researcher's assumptions and decisions, a *Base Run* and *Test Run* of the model were generated. Both runs are compared against real available data for the year 2002 and are presented in Chapter 5.

5. TESTING

This section describes the results of the first run of the model based on the initial decisions and assumptions. We call this first run the “Base Run”. Then, a “Scenario 2002” is developed based on available real data. This data is used to create a test scenario at a specific point in time to check the order of magnitude of the model results. The section continues discussing the results of a performed experiment (or sensitivity analysis) to test the most influential and sensitive parameters of the model. Finally, based on the results from sensitivity analysis, a *Test Run* is developed and compared with both, the *Base Run* and the *Scenario 2002*.

5.1 BASE RUN RESULTING BEHAVIOR

Figure 5-1 shows the base run results for paper consumption behavior from 1970 to 2050 using the initial assumptions of the modeler. The results indicate that although paper consumption slightly decreases from 1990 to 2009, a drastic peak in paper consumption never occurs. On the contrary, after 1994 paper consumption continues increasing, at least until 2050.

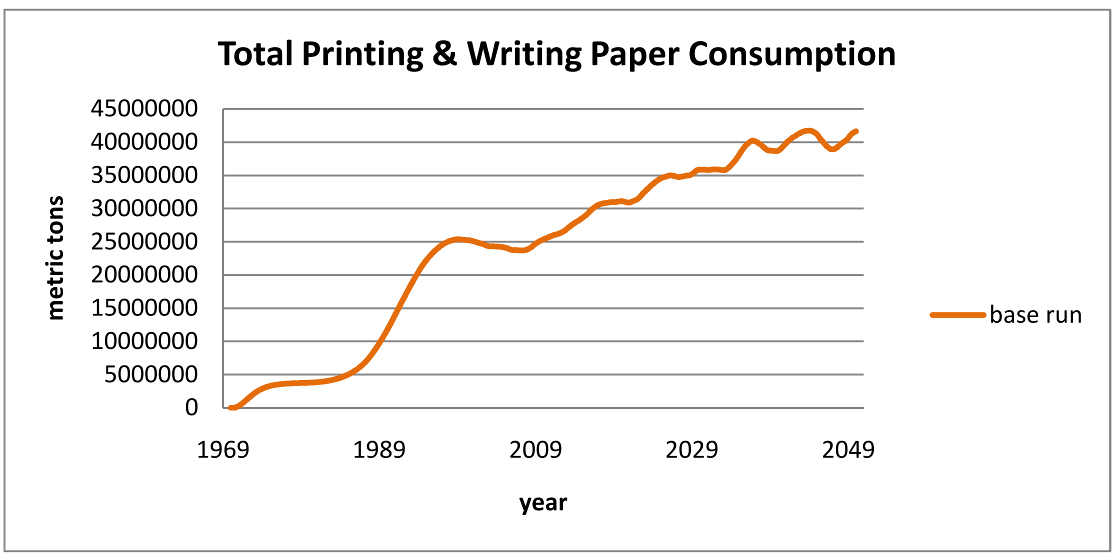


Figure 5-1. Base Run: Total Printed Paper Consumption

Because one of the assumptions is that all accessed and produced information has a digital origin, it only makes sense to compare the model results with real data after 1994, when greater proportion of the population actually started to have internet access, which in turn, made the ownership of personal computers more attractive. Figure 5-2 depicts a comparison of both trends; the ones resulting from the simulation against the real ones.

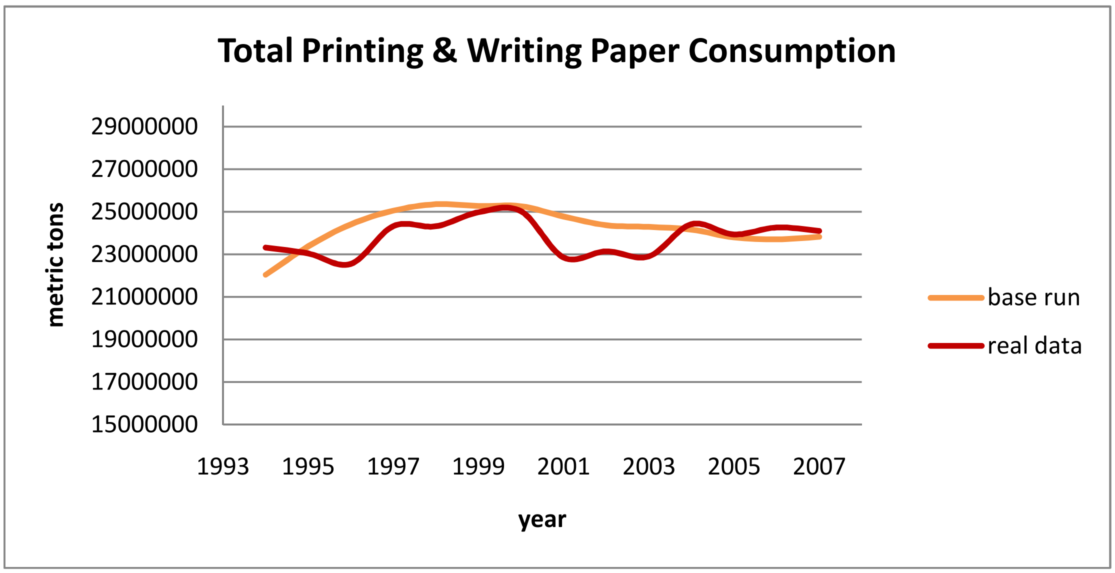


Figure 5-2. Printed Paper Consumption, Base Run vs. Real Data

After 1994, the real data's curve seems to be flattening, which can explain why current wisdom suggests that paper consumption might have been starting to level off Also, the model results' curve has a similar shape to the real one for the same time frame. Although the curve does not fit the real one exactly, it can be argued that the base run curve appears to be a good approximation for paper consumption patterns from 1994 to 2007.

Under the assumptions discussed in section 4.6, the market share for PW paper starts with 100 percent of the market share of information consumption. As shown in figure 5-3, PW paper starts with 100 percent of the market share and digital display with 0 percent of the market share but

then both market shares meet around 2010 to continue sharing equal portions of the total market share. Neither one of the markets appear to dominate after 2010.

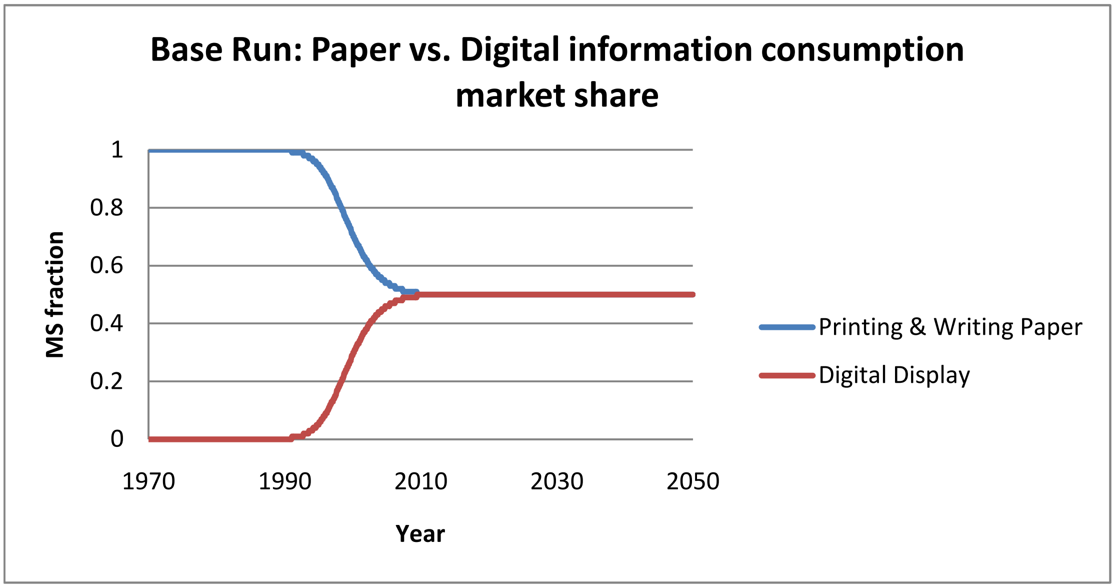


Figure 5-3. Base Run: Paper vs. Digital Information Consumption Market Share

In order to test the model market share results, an understanding of how the real market share distribution for paper vs. digital devices, was needed. The next section discusses how the market share for the year 2002 (the only year for which most of the meaningful data was available) was calculated.

5.2 SCENARIO 2002

In this section how the market share for the year 2002 was calculated is discussed. This was done in order to have a base line comparison for the Base and Test Run results.

Annually, on average per capita paper consumption for the U.S. is 11,916 sheets of paper, and at least half of this paper is used in printers and copiers to produce office documents (Lyman & Varian, 2003). Assuming that one sheet of printing and writing paper weights approximately 0.009 pounds, and knowing that one metric ton is equivalent to 2,204.62 lbs, it can be estimated

that annually, an average knowledge worker consumes at least 54 lbs or 0.024 metric tons of PW paper used in office documents. Using the conversion of 6 GB of data per metric ton of paper (Lyman & Varian, 2003), a knowledge worker in the U.S. is estimated to consumes on average 0.147 GB, or the same as 150.5 MB of printed information each year.

Based on data from the *Bureau of Labor Statistics* (Statistics) and from *How much information? 2003 (Lyman & Varian, 2003)* the knowledge workers population with internet access for 2002 was estimated to be 60,961,570. In order to calculate the total amount of printed information consumed by the knowledge work population in 2002, the total number of knowledge workers was multiplied by the average amount of printed information each knowledge worker consumes. The total amount of printed information by knowledge workers with internet access was estimated to be approximately 8, 621 Terabytes (calculated based on(Lyman & Varian, 2003)).

In order to calculate the amount of information that was consumed digitally in 2002 the same formula that was used in the model to calculate the *amount of WPs viewed rate* (Table 4-6 was used, but this time using real data. This formula is the BDM Adoption from Word of Mouth (Eq. 4-4). *WPs viewed rate* was estimated to be 2,308 Terabytes

$$WPs\ viewed\ rate = \text{Total Unique Searches} \times \text{probability one page leads to another} \times \text{Total Number of WP viewed} \times \left(1 - \frac{\text{Total Number of WP viewed}}{(\text{Number of Susceptible WPs of the IWWW} + \text{Total Number of WP viewed})}\right) \quad (5\text{-}1)$$

Then,

$$Total\ Unique\ Searches = Total\ KW\ population \times ICT\ Development\ Index \quad (5\text{-}2)$$

The total KW population was estimated to be 61 million. The number that resulted for the *Unique Searches* calculations was 119,043 x 10^6 per yr.

Probability one page leads to another was assumed to be 0.5. This number was picked assuming that every time a KW enters a specific WP, he or she will be likely to go to another related WP at least half of the times.

The *Total number of WP viewed* for 2002 was calculated to be 629 M. Considering that KWs represent only a fraction of the total internet users that access WPs, the assumption that 20% of the total amount of susceptible WPs was viewed was made.

The *number of susceptible WPs of the IWWW* was calculated to be 3,143 M for the year 2002. This number was estimated from http://www.worldwidewebsize.com/ (2009) assuming the IWWW doubles every 5 years.

$$Total\ market\ share\ of\ information =$$

$$Total\ amount\ of\ printed\ information + Total\ accessed\ web\ pages \qquad (5\text{-}3)$$

The *total market share of information* was estimated to be 11,269 Tb

To calculate the market share of information for printing and digital display equation 5-4 was used:

$$Market\ Share\ Printing = \frac{\text{Total amount of printed inform}}{(\text{Total accessed WPs} + \text{total amt of printed information})} \qquad (5\text{-}4)$$

And,

$$Market\ Share\ Digital\ Display = \frac{\text{Total amount of digital display}}{(\text{Total accessed WPs} + \text{total amt of printed information})} \qquad (5\text{-}5)$$

The resulting market share of information for printing for the year 2002 was 80 percent, and for digital display 20 percent. These numbers, although very rough estimates, can give a general idea of how much digital information could have been accessed electronically in 2002.

The market share results from the base run of the model can be observed in figure 5-3. The market share (MS) distribution resulted from the simulation model differs greatly from the estimated results for 2002. The results suggest that the MS for 2002 was of 59% for printing and writing paper, and 41% for digital devices vs. the real data ones that were estimated to be 80% and 20% respectively.

In conclusion, the base run of the model, based on the initial assumptions of the modeler, fits in a good manner the historical trends for paper consumption from 1994 to 2007, but does not fit well the estimated MS distribution for the 2002 snapshot. A formal mechanism to understand how the assumed values should be set up was needed. Design of Experiment was identified as a powerful approach to identify the most influential model parameters to set the model parameters at values that best represent U.S. data.

5.3 Testing and Design of Experiments

Experimentation and testing is a vital part of the scientific or engineering method (Montgomery, 2005). In addition, through experimentation the performance and robustness of processes and systems can be studied and assessed. In this section, the details of a fractional factorial experiment are described.

5.3.1 Goal of the Experiment

The goal this experiment is to test the parameters of the base run model and determine the level of influence that these parameters have on three response variables: 1) The year in which a peak

in PW paper consumption occurs, 2) The value of a peak in paper consumption, and 3) The year in which the market shares for digital and paper cross. Furthermore, a second objective is to discover how the parameters should be set up to reduce variability between the system dynamics model results and real trends, to replicate the real data in the most accurate possible way.

The strategy of experimentation selected for this study was to conduct a fractional factorial experiment to test the variables of interest. A fractional factorial experiment "is a variation of the basic factorial design in which only a subset of the runs are used" (Montgomery, 2005). Factorial designs have several advantages: they are more efficient than one-at-a-time experiments, they are necessary when interactions may be present, and they allow the effect of a factor to be estimated at several levels of the other factors (Montgomery, 2005). The main effect in a factorial design indicates the change in response produced by a change in the level of the primary factors of interest being tested (Montgomery, 2005).

5.3.2 Parameters of Interest

Several factors of the system can be considered in the DOE; however, the following exogenous variables are of primary interest:

- *ICT development index.* This variable is crucial given the critical role ICTs play in paper consumption.
- *Paper threshold growth fraction*. This variable controls the level at which the threshold for compatibility effects of paper increases with the advent of alternative technology. Because this value is assumed, it would be interesting to see how the results change when this parameter is varied.

- *Digital display threshold growth fraction.* This variable controls the level at which the threshold for compatibility effects of digital devices decreases with the advent of newer technologies. Same rationale as the *Paper threshold growth fraction* variable.

- *Sensitivity of attractiveness to amount of printed pages and Sensitivity of attractiveness to amount of digital displayed*. The effect of these parameters are of special interest because they control how fast market share approaches its extreme values, and because the assumed value is based on the researcher's mental model.

- *Percentage of paper reproducible content in the IWWW.* This variable represents the assumed percentage of the IWWW content that is printable, static or textual. Because the percentage of paper reproducible content in the web was an assumed value, it is of special interest to investigate how the results of the model vary when this parameter increases or decreases.

- *Size of the knowledge workers population*. This parameter is also interesting given the fact that our society has been increasingly turning into a knowledge based one for the past decades.

Once the critical parameters were identified, the experimental design was performed. Results are given in section 5.3.3.

5.3.3 Experimental Design

The experiment was designed using the statistical software for data analysis Minitab ® (http://www.minitab.com/en-US/default.aspx). From the above identified seven variables, which yields a 2^7 design, each factor was varied in two extreme levels: high and low, to observe its

effect on the response variables. A the one-half resolution VII fraction design containing $2^6 = 64$ runs was decided. The experimental matrix with the run order and combination of levels for each parameter can be found in Appendix 1. The results of the experiment are discussed in detail in the following section.

5.3.4 Testing and Design of Experiment Results

For each response variable a main effect plot was generated. Figure 5-4 shows the main effects plot for the *paper consumption peak year,* figure 5-5 depicts *the peak value of paper consumption*, and figure 5-6 shows the one for the *MS crossover year*. An important observation is that some of the results fall outside the time horizon. In some cases the Peak never occurs within the time horizon so an extremely far away peak year was assumed in these cases, for instance, the year 2100 was assumed for peaks that seemed to never occur in the near horizon. In other cases, even when the peak year is not obvious on the plots, the curves suggest that the crossover will happen near the year 2050. In these cases the year was decided with a best-guess approximation.

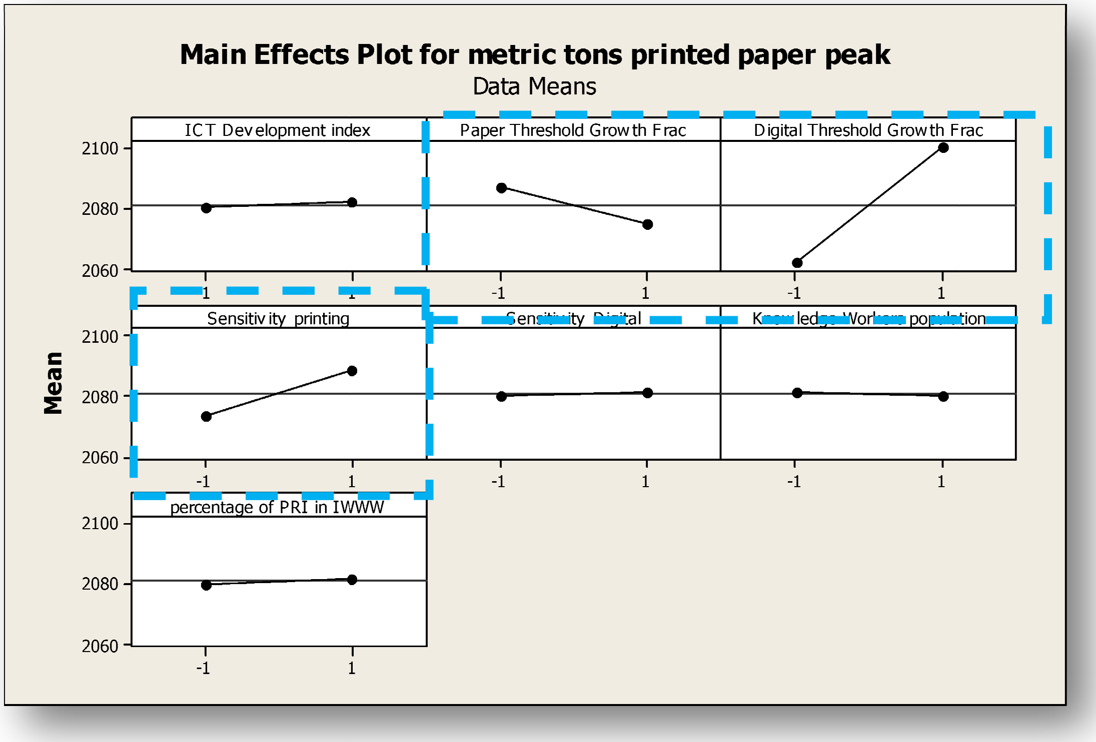


Figure 5-4. Main Effects Plot for Peak Year in Paper Consumption

The main effects plot for the *paper consumption peak year* (figure 5-4) depicts the level of effect of each parameter in the outcome as follows:

- *ICT Development Index*: this parameter does not have a major effect on the response variable.
- *Paper threshold growth fraction:* a low value for this factor moves the peak year far in time, a high value brings the peak closer in time.
- *Digital threshold growth fraction:* This parameter has an even greater effect than the previous and following one in the response outcome. A low value in this parameter means that the threshold for compatibility effects of digital will grow at a significant

lower rate and a high value means the opposite. Low value results in a sooner peak; high value results in a more distant peak.

- Se*nsitivity for amount of printed paper:* a low value for this parameter translates into a weaker network effect. Paper consumption peaks sooner with this parameter set to low.

- *Sensitivity for amount of digital displayed:* this parameter does not have an important effect on the value on the response variable.

- *Knowledge workers population:* this parameter does not have a significant effect on the response variable.

- *Percentage of paper reproducible information (PRI) in IWWW:* this parameter does not have a significant effect on the response variable.

The main effects plot for the *peak value of paper consumption* (figure 5-5) also depicts the level of effect of each parameter for this outcome:

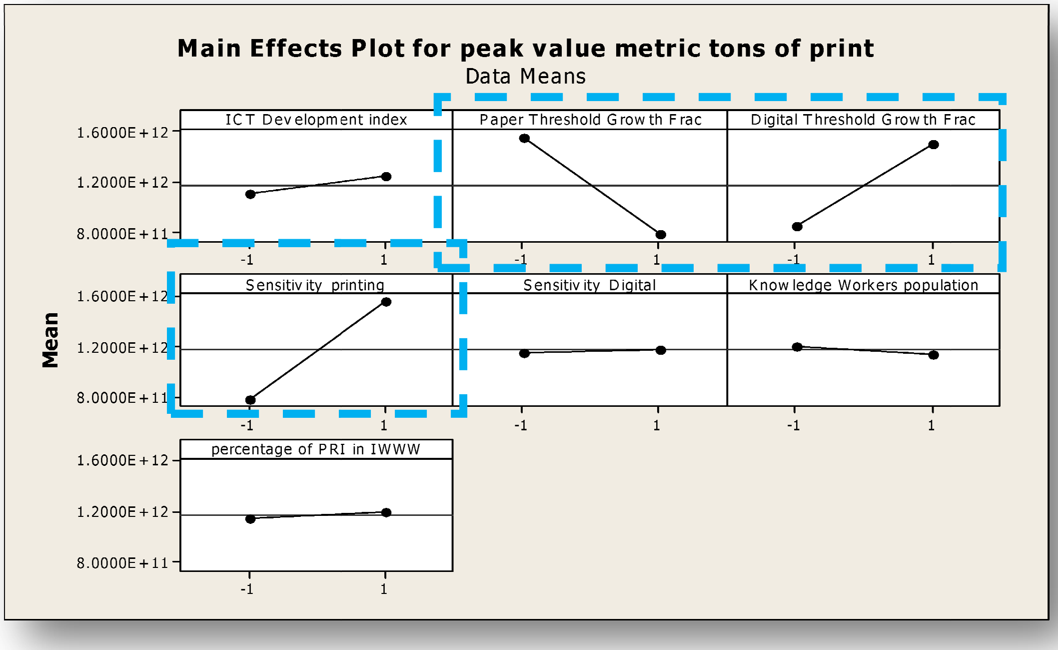


Figure 5-5. Main Effects Plot for Peak Value of Paper Consumption

- *ICT Development Index:* this parameter does not have a major effect. However, this parameter has a major effect in this response variable than in the paper consumption peak year response variable.

- *Paper threshold growth fraction:* a low value for this factor increases the value of the peak. A high value decreases the value of the peak.

- *Digital threshold growth fraction:* Low value results in lower amount for the value of the peak; high value results in the opposite.

- *Sensitivity for amount of printed paper*: the value of the paper consumption peak is lower with this parameter set to low and vice versa.

- *Sensitivity for amount of digital displayed:* this parameter does not have a major effect on the value of the paper consumption peak.

- *Knowledge workers population:* this parameter does not have a considerable effect on the value of the paper consumption peak.

- *Percentage of paper reproducible information (PRI) in IWWW:* this parameter does not have an important effect on the value of the paper consumption peak.

Note that the same previously discussed parameters resulted in having the major effect on the *paper consumption peak* response variable value. However, for this response variable, the parameters show to have a greater effect than in the previous response as can be observed in figure 5-5.

For the *MS crossover year* response outcome, just the paper threshold growth fraction and the sensitivity for attractiveness on printing have a significant effect. The effect happens in the same direction as in the previous response outcomes. Figure 5-6 illustrates these results and below is a description for each parameter:

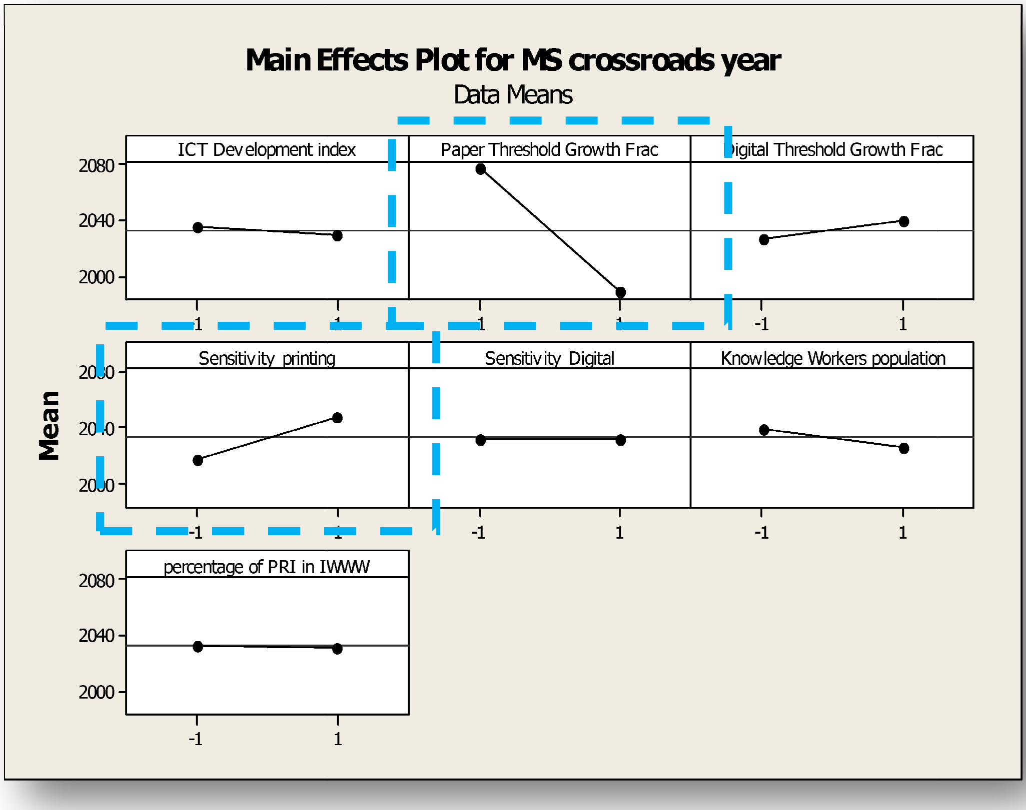


Figure 5-6. Main Effects Plot for Market Share Crossover Year

- ICT Development Index: this parameter does not have a major effect.

- Paper threshold growth fraction: this parameter has a strong effect on the year that the MS crossover occurs. A low value for this factor moves the crossover MS year far in time, a high value brings it closer.

- Digital threshold growth fraction: a low value for this parameter translates in a sooner MS crossover; a high value results in a more distant one.

- Sensitivity for amount of printed paper: this parameter does not have a major effect.

- Sensitivity for amount of digital displayed: this parameter does not have a strong effect on the value on the response variable.

- Knowledge workers population: this parameter does not have a great effect on the response variable.

- Percentage of paper reproducible information (PRI) in IWWW: this parameter does not have a major effect on the response variable.

In summary, in order to accelerate the peak in paper consumption and the MS crossover, and control the peak value, threshold paper growth fraction needs to be set up high and digital the digital threshold growth fraction needs to be set up low. Also, the sensitivity parameter needs to be set up low. Prototype plots for each response outcome of the 64 runs are given in Appendix 2.

5.3.5 TEST RUN RESULTING BEHAVIOR

Leveraging the insights from the DOE analysis a test run was constructed to fit better real paper consumption trends and the estimated 2002 MS distribution. Figure 5-7 shows the new curve for total paper consumption in the U.S. from 1970 to 2050 in which, as in the Base Run results, a drastic decrease in paper consumption does not appear to happen within the selected time horizon.

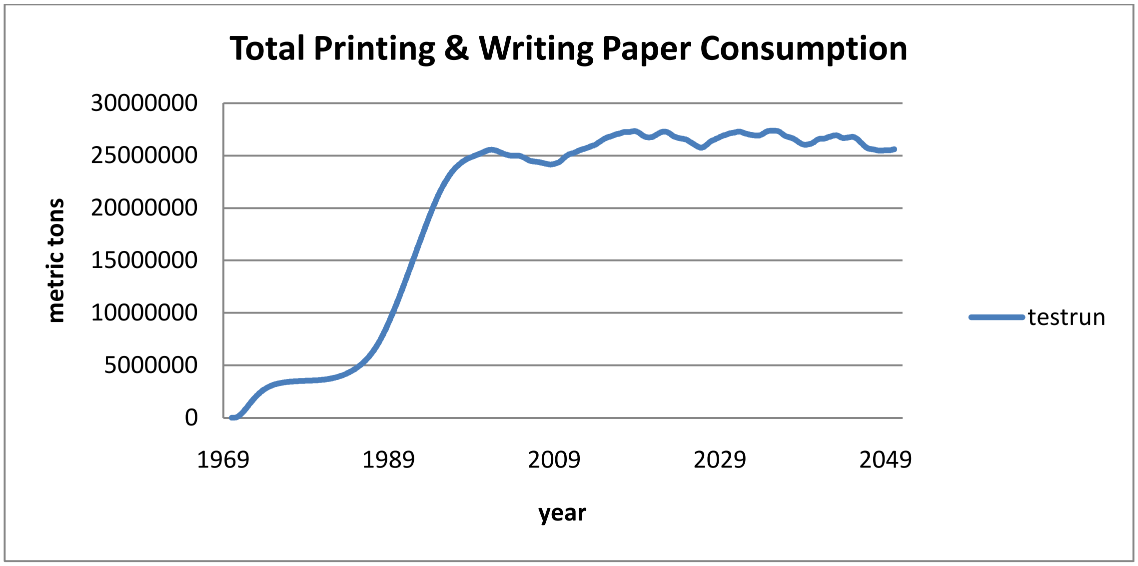


Figure 5-7. Total Printed Paper Consumption Test Run Results

Comparing the real data vs. the test run curve for paper consumption (Figure 7-8), it can be observed that the new curve does not perfectly matches the real one.

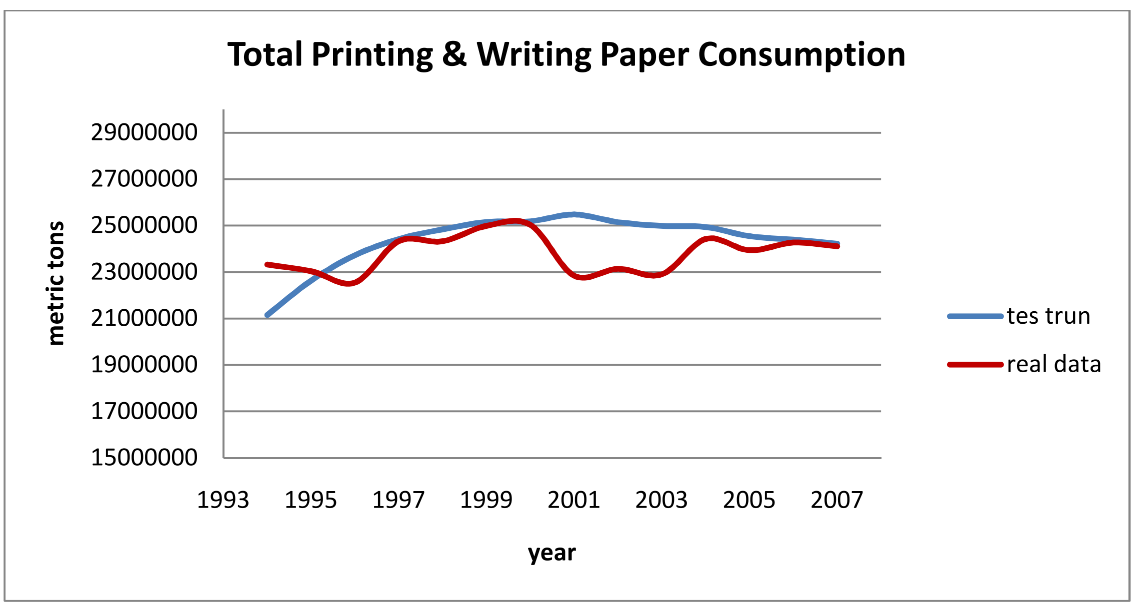


Figure 5-8. Total Printed Paper Consumption: Test Run vs. Real Data

Figure 5-9 shows the new results for the information market share distribution. In 2002 the test run MS distribution resulted in 80% for printing and writing paper and 20% for digital devices.

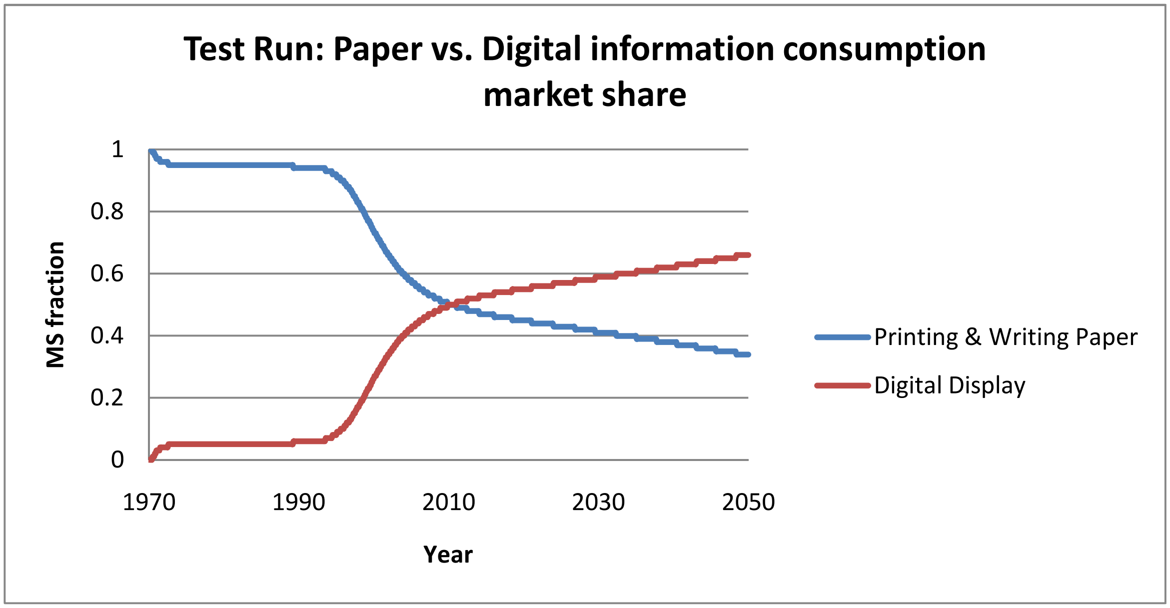


Figure 5-9. Paper vs. Digital Information Consumption Market Share Test Run Results

Again, the results do not match exactly the real estimations but it can be argued that the DOE insights helped in getting a better and more accurate approximation of results to real data, at least for the market share results. Setting the parameters based on the insights from the DOE resulted in less variability between real data and the ones from the simulation model.

5.4 Summary

Based on the one-half fraction design of experiments the parameters that resulted to influence the most the value of the three response variables *(year in which a peak in PW paper consumption occurs, value of a peak in paper consumption*, and *year in which the market shares for digital and paper cross),* are the *threshold paper growth fraction*, *digital threshold growth fraction,* and *sensitivity* parameters.

This chapter showed that, based on the insights gained from the sensitivity analysis, a better approximation to real data was achieved. The sensitivity analysis confirmed that the most influential parameters are the ones responsible for the network effects in the system. It can be concluded that in order to reduce PW paper consumption and PW paper market share, alternative technology that affords in a more efficient way the actions paper affords, but that also affords other different and exciting possibilities must take place, with the caveat that a decrease in paper consumption does not necessarily means a lower impact to the environment. In order to minimize PW paper consumption's impact to the environment, both, printing and digital cleaner technologies must be co-developed such that they don't cause negative side effects.

6. Conclusions and Future Work

This chapter summarizes the research conducted and the key observations that resulted from this study. In addition, opportunities for future work and improvement are also discussed. These research opportunities would contribute to a larger research goal which is to understand the characteristics of new alternative technology in order to decrease paper consumption, and to improve the environmental impact of information medium consumption.

This study motivated the importance of analyzing PW paper consumption patterns through a holistic approach as a first step to drive it towards a more sustainable state. Technology designers, PW paper producers, the print and ICT industry, and policy makers need to have a clear understanding of what influences paper consumption and the potential implications of the penetration of alternative digital technologies that are intended to substitute PW paper. This understanding can be used to guide their designs, decisions, and trade-offs.

A review of the literature revealed that although paper consumption and its negative environmental impacts have been well recognized by many, there is a gap in the literature in the sense that no study has so far been conducted that analytically addresses the relationships between PW paper consumption, advances in ICTs and print technology, and the effects of the increased role that knowledge work plays in our society. From this literature review, system dynamics modeling emerged as a powerful tool to analyze and understand the dynamics of the PW paper consumption.

The research methodology conducted in this study, was based on the modeling steps outlined by Sterman (2000). Also, it was argued that even though these modeling steps shouldn't be seen as a template, they can serve as general guideline for the modeling process.

The dynamic hypothesis of this thesis stated that because of endogenous feedback loops, even if PW paper consumption decreases, it is not likely that it will go down to sustainable levels. Three subsystem, *Information Access, Authoring Work Production, and Information Consumption* subsystems, were identified and developed to understand the critical dynamics of the system and test the dynamic hypothesis. Also, the key variables of the system were identified and described, and the CLD for each subsystem was generated based on the principles of the Bass Diffusion Model and Path Dependence Theory.

Moreover, a stock and flow diagram for the print media paper consumption patterns system was developed and populated based on real data and initial assumptions, which resulted in a *Base* and *Test Run* of the model. Sensitivity analysis through the use of a one-half fractional factorial experiment was performed to identify the most influential model parameters to set the model parameters at values that best represented US data. An approximation to real data was achieved based on the insights gained from the sensitivity analysis.

A simple and flexible system dynamics model was built that can be used to test different assumptions and hypotheses. . Through exercising the model and through sensitivity analysis the main parameters that influence paper consumption were identified as the ones most responsible for the network effects. These are the *threshold paper growth fraction, digital threshold growth fraction,* and *sensitivity* parameters. This suggests that in order for alternative digital technology to dominate and break society's lock-in to paper, there must be an effective diffusion of green alternative paper-like technologies. These insights stress the need to develop green technology that meets the affordances of PW paper, in order to reduce PW paper consumption and PW paper market share. However, a decrease in paper consumption does not necessarily mean a lower impact to the environment.

An important challenge for sustainability is how to shift from unsustainable patterns of consumption to more sustainable ones. Different strategies and combinations of strategies can be used to promote more sustainable consumption patterns. For instance, developing product service systems, also called functional sales, to maximize the utilization of goods, can help us to move from our current consumption model to a service one, in which the function that the product provides is emphasized rather than the product itself. Also, consumption of innovative green products, such as alternative paper-like technologies that are designed to have a minimal or at least lower impact to the environment on every stage of their lifecycle, can also help to alleviate the burdens placed on the Earth's ecosystem when these green products replace the consumption of non-green ones.

However, one of the most critical needs of sustainability is the redesign of cultural structure and habits such that everyone becomes conscious of the implications of overconsumption and their individual decisions, so that they can move toward sustainable habits and choices when they find themselves in "unsustainable patterns of addiction" (EHRENFELD, 2008). For these challenges to be overcome, an "epidemic" of green innovation driven by educators, policy makers, the government, and the industry, needs to take place.

This research has shown that historic trends of PW paper consumption can be replicated using system dynamics. However, it should be stressed that in order to model how PW paper consumption trends might evolve in the future, a more endogenous structure of the model should be considered, although a more endogenous structure would add complexity to the model.

The insights generated from this study could be used to visualize why the demand for PW paper has been growing as opposed to what has been predicted. This study has shown the effects that

the exponential growth of available and easy-to-access information has had on PW paper consumption. Even when the ratio of digital to hard copy consumed information has increased, because the total amount of accessed information has also increased, the volume of consumed paper has also increased. This is due largely to the fact that PW paper is still the preferred medium for several knowledge work activities. However, paradoxically, even when advances in ICTs are one of the most important factors that have fueled PW paper consumption, as the advent on ICTs permits more affordances, new digital or *paper-like* technology could potentially lead to a decrease in paper consumption.

As discussed previously, insights from this study are only the first steps towards a bigger goal. In order to accomplish this goal, future work should be targeted to:

- Work on a more sophisticated and endogenous structure for the model and/or break the system into several individual subsystems and then connect them into a larger one. For instance, creating a system dynamics model that explains the role of progress in ICTs has had on how information is created, accessed, and distributed could be used to understand how these dynamics influence PW paper consumption behavior.

- The sustainability of each technology as a factor that can improve the attractiveness of each medium should be taken into account for future work. ICTs are often seen as a greener technology over paper just because they have a slower rate of waste production (paper is discarded much faster and easier than a PC for instance). This belief and the fact that green technology alternatives to paper might be developed could start leading people to consume less paper, as the awareness of our ecological

footprint increases. On the other hand, if new and greener paper and print technology and practices are developed and marketed, paper consumption could continue increasing. Both scenarios should be considered for future work.

- As it was argued in this study, one story is for developed countries and a different one is for developing ones. Paper consumption is a global problem that should be treated as that, global. Understanding what behavior models are possible for developing countries, whether they will continue the same patterns of consumption of developed nations or whether they will leap frog to newer technologies and the effects that will have on their paper consumption patterns would be of interest to study.

Although the results of this study are preliminary, they can help to start learning about the system in a holistic manner, which will lead to better results and can guide us towards sustainable development. Donella Meadows explains it in an exquisite manner in one of her articles: “while we are waiting for perfection, fisheries are collapsing, greenhouse gases are accumulating, species are disappearing, soils are eroding, forests are overcut, and people are suffering. So it is important to get some preliminary indicators out there and into use, the best we can do at the moment” (Meadows, 1998).

This study was an effort to build better understanding about a system that has been traditionally a theme of controversy and debate. Only a few studies, however, have been targeted to formally understand the printing and writing paper consumption and its relationship with ICTs in a holistic manner. The intention of the present study was to contribute a systematic analysis of a PW paper consumption system and create knowledge about its present state and possible future

behavior. Knowing where we are and how we got here brings us just half way to our overall goal: determining where we want to go, and what efforts are needed to get there.

WORKS CITED

Abbasi, G. Y., & Abbassi, B. E. 2004. Environmental assessment for paper and cardboard industry in Jordan -- a cleaner production concept. ***Journal of Cleaner Production***, 12(4): 321-326.

AFPA. 2000. American Forest & Paper Association facts.

Ayres, R. U., & Kneese, A. V. 1969. Production, Consumption, and Externalities. ***The American Economic Review***, 59(3).

Barlas, Y. 1996. Formal aspects of model validity and validation in system dynamics %J System Dynamics Review. 12(3): 183-210.

Barnes, W., Gartland, M., & Stack, M. Old habits die hard: path dependence an behavioral lock in. ***Journal of Economic Issues***, 38.

Bhushi, U. M., & Javalagi, C. M. 2004. System Dynamics application to Supply Chain Management: A review. ***IEEE International Engineering Management Conference***, 3: 1244-1248.

Bossel, H. 1999. Indicators for Sustainable Development:Theory, Method, Applications. A Report to the Balaton Group: INTERNATIONAL INSTITUTE FOR SUSTAINABLE DEVELOPMENT.

Cairns Jr., J. 2009. Is Homo sapiens Just Another Stochastic Event in the History of Life. ***Asian J. Exp. Sci.***, 23(1).

Cavana, R. Y., & Clifford, L. V. 2006. Demonstrating the utility of system dynamics for public policy analysis in New Zealand: the case of excise tax policy on tobacco. ***System Dynamics Review***, 22(4): 321-348.

Clean-Energy-Ideas. 2008. Recycling paper.

Conole, G., & Dyke, M. What are the affordances of information and communication technologies? ***Research in Learning Technology***, 12(2): 114-124.

Cost, F. 2005. ***The new medium of print : material communication in the Internet age***. Rochester, NY: RIT Cary Graphic Arts Press.

EHRENFELD, J. R. 2008. ***Sustainability by Design***.

EIA. 2000. Energy Use: Forest Products Industry Analysis Brief. Energy Information Association: Official Energy Statistics from the US Government.

EIA. 2006. Manufacturing Energy Consumption Survey manufacturing and industrial energy uses and costs.

EIA. 2008. Energy Information Administration: Official Energy Statistics from the U.S. Government.

EPA. 2008. SUMMARY OF THE EPA MUNICIPAL SOLID WASTE PROGRAM.

EPA. 2009. History of Sustainability.

Fairfield, H. 2008. Pushing Paper Out the Door, ***The New York Times***.

FAOSTAT. 2009. United States Printing and Writing Paper Production and Import.

Fiksel, J. 2006. Sustainability and resilience: toward a systems approach. ***Sustainability: Science, Practice, & Policy***, 2(2).

Georgiadis, P., & Besiou, M. 2008. The importance of feedback loops designing environmental policies for sustainable development.

Gonçalves, P., Hines, J., & Sterman, J. 2005. The impact of endogenous demand on push-pull production systems. ***System Dynamics Review***, 21(3): 187-216.

Hjorth, P., & Bagheri, A. 2006. Navigating towards sustainable development: A system dynamics approach. ***Futures***, 38(1): 74-92.

Hunt, D. P. 2003. The concept of knowledge and how to measure it. ***Journal of Intellectual Capital***, 4(1).

ITU. 2009. The ICT Development Index: Information Telecommunication Union.

Jones, A., RW Corell, A. B., Cummings, T., Fiddaman, T., McGlade, J., van Peter, F., Sawin, E., Siege, L., & Sterman, J. 2008. The Climate Action Initiative: deploying policy exercises and the pangaea simulation to facilitate and support long-term climate policy development, ***IOP Conf. Series: Earth and Environmental Science***.

Jones, A., Seville, D., & Meadows, D. 2002. Resource sustainability in commodity systems: the sawmill industry in the Northern Forest. ***System Dynamics Review***, 18(2).

Kogut, B. 2004. ***The global internet economy*** (1st ed.): The MIT Press.

Lumley, S., & Armstrong, P. 2004. Some of the Nineteenth Century Origins of the Sustainability Concept. ***Environment, Development and Sustainability;***, 6(3): 367-378.

Lyman, P., & Varian, H. R. 2003. HOW MUCH INFORMATION 2003?: School of Information Management and Systems at the University of California at Berkeley.
Lyneis, J. M., & Ford, D. N. 2007. System dynamics applied to project management: a survey, assessment, and directions for future research. ***System Dynamics Review***, 23(2-3): 157-189.
Marin, C. 2003 published in 2006. Paper and paperboard production. FAO, Forestry Report 2003.
Maryanne Grieg-Gran, S. B., Joshua Bishop, Sarah Roberts, Richard Sandbrook, Nick Robins, Michael Bazett, Varsha Gadhvi, Susan Subak,. 1997. Towards a Sustainable Paper Cycle: A Summary. ***Journal of Industrial Ecology***, 1(3): 47-68.
Meadows, D. 1998. Indicators and Information Systems for Sustainable Development. A Report to the Balaton Group: Sustainability Institute.
Meadows, D. 2002. Dancing with Systems, ***The System Thinker***, Vol. 13.
Meadows, D. H., Meadows, D. L., & Randers, J. 1992. ***Beyond the limits : confronting global collapse, envisioning a sustainable future***. Post Mills, Vt.: Chelsea Green Pub. Co.
Montgomery, D. C. 2005. ***Design and Analysis of Experiments*** (6th ed.).
Nonaka, I. 1994. A Dynamic Theory of Organizational Knowledge Creation. ***Organization Science***, 5(1): 14-37.
ntia. Percentage of computers and internet access for US households, US Department of Commerce, National Telecommunications and Information Administration.
O'dell, C., & Jackson Grayson, C. ***If Only We Knew What We Know: The Transfer of Internal Knowledge and Best Practice***
Randers, J. 2000. From limits to growth to sustainable development or SD (sustainable development) in a SD (system dynamics) perspective. ***System Dynamics Review***, 16(3): 213-224.
Ruth, M., & Harrington, T. J. 1998. Dynamics of Material and Energy Use in U.S. Pulp and Paper Manufacturing. ***Journal of Industrial Ecology***, 1(3): 147-168.
Sellen, A. J., & Harper, R. 2002. ***The myth of the paperless office***. Cambridge, Mass.: MIT Press.
Senge, P. M. 2006. ***The fifth discipline : the art and practice of the learning organization*** (Rev. and updated. ed.). New York: Doubleday/Currency.
Shrivastava, P. 1995. The Role of Corporations in Achieving Ecological Sustainability. ***The Academy of Management Review***, 20(5): 936-960.
Statistics, B. o. L. Employment status of the civilian noninstitutional population 16 years and over, 1970 to date.
Sterman, J. 2000. ***Business dynamics : systems thinking and modeling for a complex world***. Boston: Irwin/McGraw-Hill.
Sterman, J. D. 2002. All models are wrong: reflections on becoming a systems scientis. ***System Dynamics Review***, 18(4).
Sundin, E., Svensson, N., McLaren, J., & Jackson, T. 2002. Materials and Energy Flow Analysis of Paper Consumption in the United Kingdom, 1987-2010. ***Journal of Industrial Ecology***, 5(3): 89-105.
SystemDynamicsOrganization. 2009a. System Dynamics and Energy Modeling: The World Models.
SystemDynamicsOrganization. 2009b. What is System Dynamics?
Taylor, T., & Ford, D. N. 2006. Tipping point failure and robustness in single development projects. ***System Dynamics Review***, 22(1): 51-71.
UIS. Education Indicators: Technical Guidelines.
UnitedNations. 1987. Report of the World Commission on Environment and Development, General Assembly Resolution 42/187 ed.
Videira, N., Antunes, P., Santos, R., Lopes, R., & Tavares, F. 2009. Participatory Dynamic Modelling Framework for Integrated Sustainability Assessment.
Walmart. 2010. Sustainability Index.
Wolstenholme, E. F. 2003. Towards the definition and use of a core set of archetypal structures in system dynamics. ***System Dynamics Review***, 19(1): 7-26.
WRI. 1998, updated June 2001. NO END TO PAPERWORK: World Resource Institute.
WRI. 2008. World Resources Institute. EarthTrends.
York, R. 2006. Ecological Paradoxes: William Stanley Jevons and the Paperless Office. ***Human Ecology Review***, 13(2).

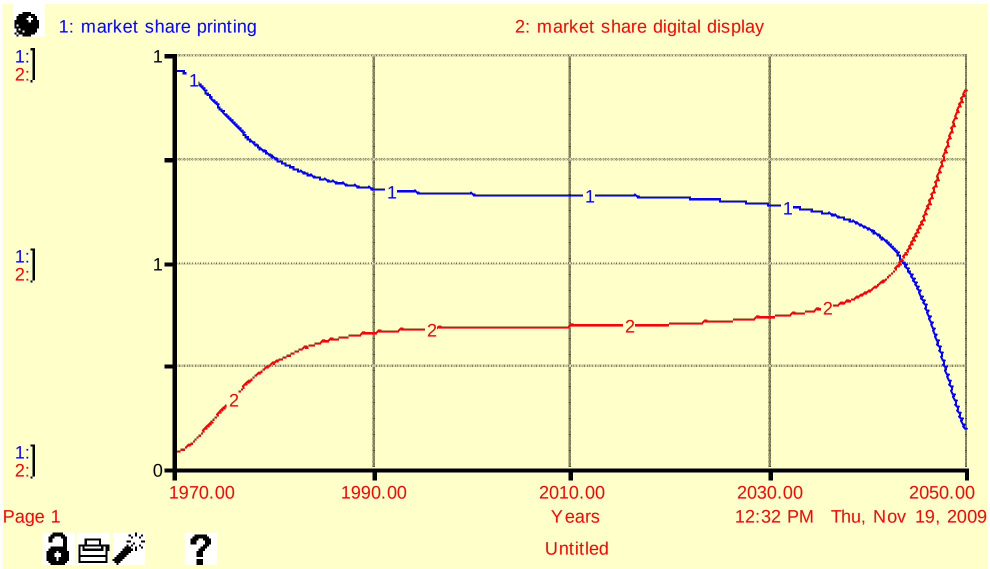
Appendix 1: Factorial Design of Experiment and Value for the Response Variables

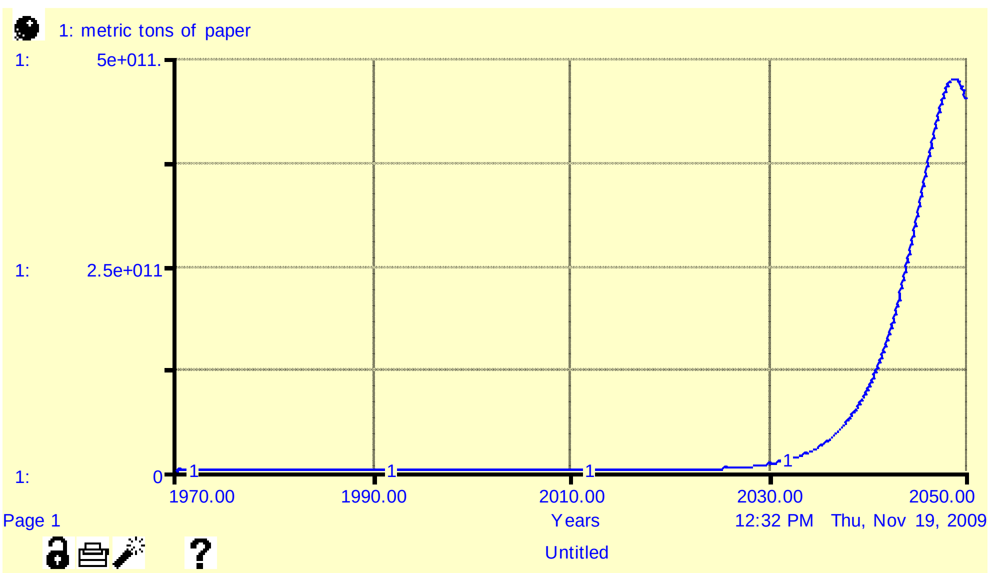
Run No.	ICT Development index	Paper Threshold Growth Frac	Digital Threshold Growth Frac	Sensitivity printing	Sensitivity Digital	Knowledge Workers population	percentage of PRI in IWWW	MS crossovers year	metric tons printed paper peak year	peak value million metric tons of printed paper
1	-	-	-	-	-	-	+	2043	2047	429885.354
2	+	-	-	-	-	-	-	2043	2049	476579.375
3	-	+	-	-	-	-	-	1983	2047	298955.997
4	+	+	-	-	-	-	+	1983	2048	306595.446
5	-	-	+	-	-	-	-	2100	2100	1330897.34
6	+	-	+	-	-	-	+	2100	2100	1356371.22
7	-	+	+	-	-	-	+	1984	2100	1116505.2
8	+	+	+	-	-	-	-	1983	2100	1114121.89
9	-	-	-	+	-	-	-	2100	2100	2216930.9
10	+	-	-	+	-	-	+	2100	2100	2216930.9
11	-	+	-	+	-	-	+	1989	2049	303814.912
12	+	+	-	+	-	-	-	1989	2048	308775.7
13	-	-	+	+	-	-	+	2100	2100	2229358.67
14	+	-	+	+	-	-	-	2100	2100	2225090.2
15	-	+	+	+	-	-	-	1991	2100	1109755.44
16	+	+	+	+	-	-	+	1990	2100	1132842.52
17	-	-	-	-	+	-	-	2041	2047	229359.915
18	+	-	-	-	+	-	+	2041	2046	243454.946
19	-	+	-	-	+	-	+	1981	2046	155359.595
20	+	+	-	-	+	-	-	1983	2045	155321.932
21	-	-	+	-	+	-	+	2100	2100	1338217.83
22	+	-	+	-	+	-	-	2100	2100	1335662.28
23	-	+	+	-	+	-	-	1983	2100	1109667.91
24	+	+	+	-	+	-	+	1984	2100	1132101.81
25	-	-	-	+	+	-	+	2100	2100	2228604.11
26	+	-	-	+	+	-	-	2100	2100	2225265.62
27	-	+	-	+	+	-	-	1990	2045	155475.006
28	+	+	-	+	+	-	+	2100	2100	2216466.83
29	-	-	+	+	+	-	-	2100	2100	2260470.18
30	+	-	+	+	+	-	+	2100	2100	2260470.18
31	-	+	+	+	+	-	+	1990	2100	1116115.78
32	+	+	+	+	+	-	-	1990	2100	2225706.05

Run No.	ICT Development index	Paper Threshold Growth Frac	Digital Threshold Growth Frac	Sensitivity printing	Sensitivity Digital	Knowledge Workers population	percentage of PRI in IWWW	MS crossovers year	metric tons printed paper peak year	peak value million metric tons of printed paper
33	-	-	-	-	-	+	-	2043	2048	476436.843
34	+	-	-	-	-	+	+	1970	20050	766147.218
35	-	+	-	-	-	+	+	1983	2047	291053.764
36	+	+	-	-	-	+	-	1972	2049	363863.85
37	-	-	+	-	-	+	+	2100	2100	1336517.83
38	+	-	+	-	-	+	-	2100	2100	1343909.94
39	-	+	+	-	-	+	-	1984	2100	1114294.9
40	+	+	+	-	-	+	+	1971	2100	1162874
41	-	-	-	+	-	+	+	2100	2100	2263262.69
42	+	-	-	+	-	+	-	2100	2100	2238006.62
43	-	+	-	+	-	+	-	1990	2048	306624.748
44	+	+	-	+	-	+	+	1984	2050	500616.945
45	-	-	+	+	-	+	-	2100	2100	2226546.27
46	+	-	+	+	-	+	+	2100	2100	2317799.73
47	-	+	+	+	-	+	+	1990	2100	1134029.03
48	+	+	+	+	-	+	-	1990	2100	1121402.68
49	-	-	-	-	+	+	+	2041	2046	242899.748
50	+	-	-	-	+	+	-	1971	2047	290901.863
51	-	+	-	-	+	+	-	1982	2046	154941.874
52	+	+	-	-	+	+	+	1971	2047	269537.846
53	-	-	+	-	+	+	-	2100	2100	1335998.34
54	+	-	+	-	+	+	+	1978	2100	1389382.11
55	-	+	+	-	+	+	+	1983	2100	1134146.95
56	+	+	+	-	+	+	-	1981	2100	1119261.83
57	-	-	-	+	+	+	-	2100	2100	2226799.33
58	+	-	-	+	+	+	+	2100	2100	2319310.98
59	-	+	-	+	+	+	+	1990	2045	152974.903
60	+	+	-	+	+	+	-	1984	2046	172993.475
61	-	-	+	+	+	+	+	2100	2100	2267727.2
62	+	-	+	+	+	+	-	2100	2100	2239043.74
63	-	+	+	+	+	+	-	1990	2100	1114543.28
64	+	+	+	+	+	+	+	1985	2100	1159772.07

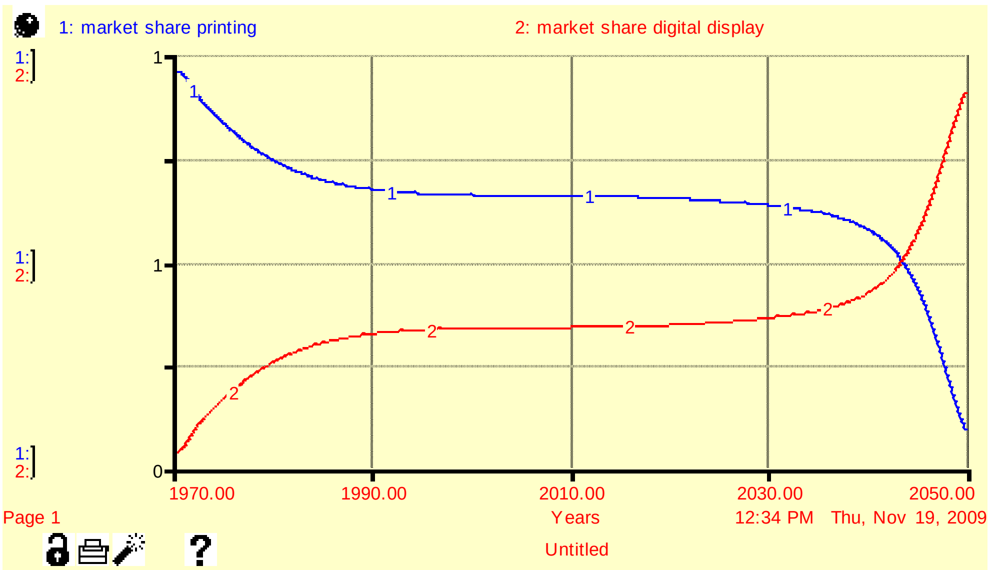
APPENDIX 2: SENSITIVITY ANALYSIS RESULTS PLOTS

Run 1

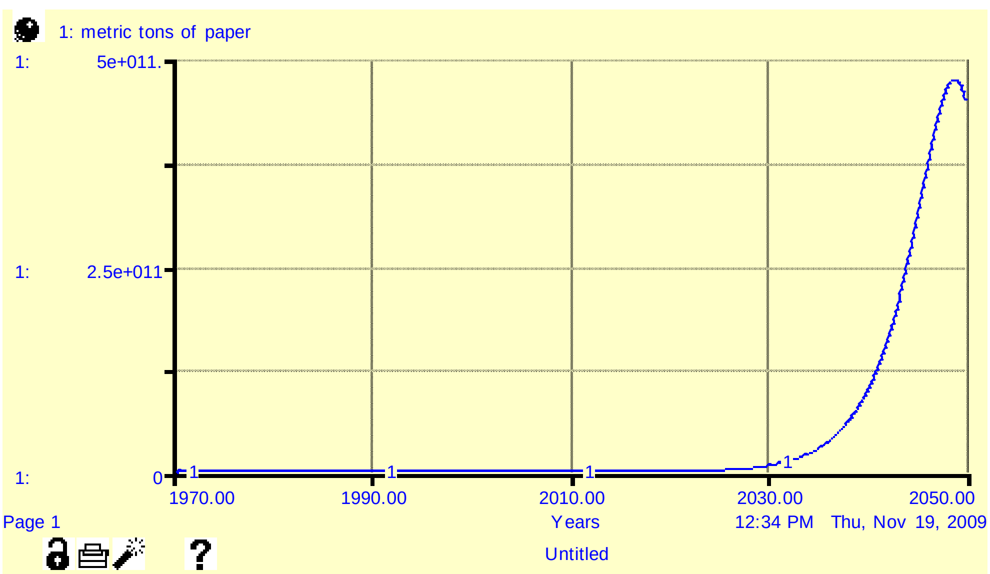




Run 2:

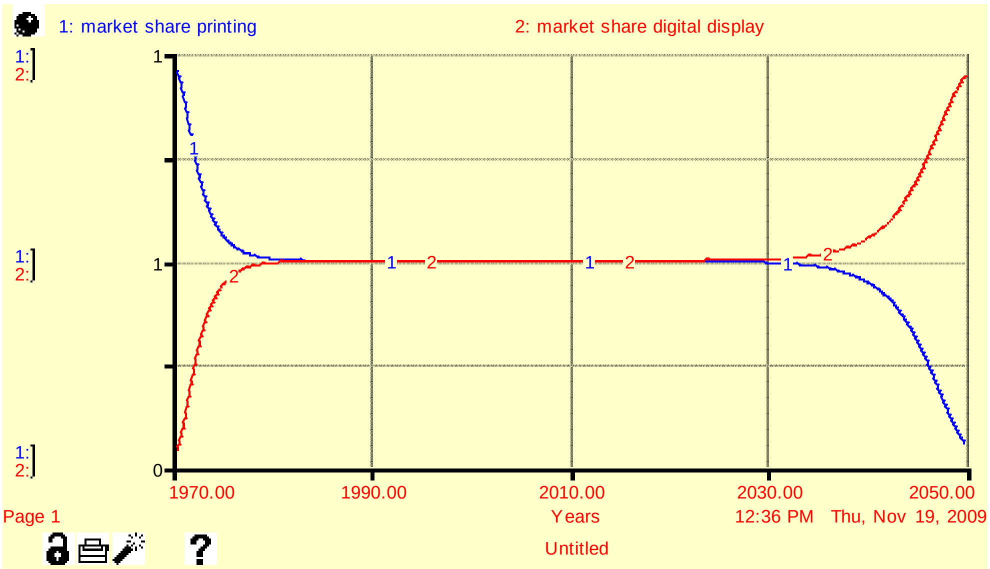


1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
12:34 PM Thu, Nov 19, 2009
Untitled

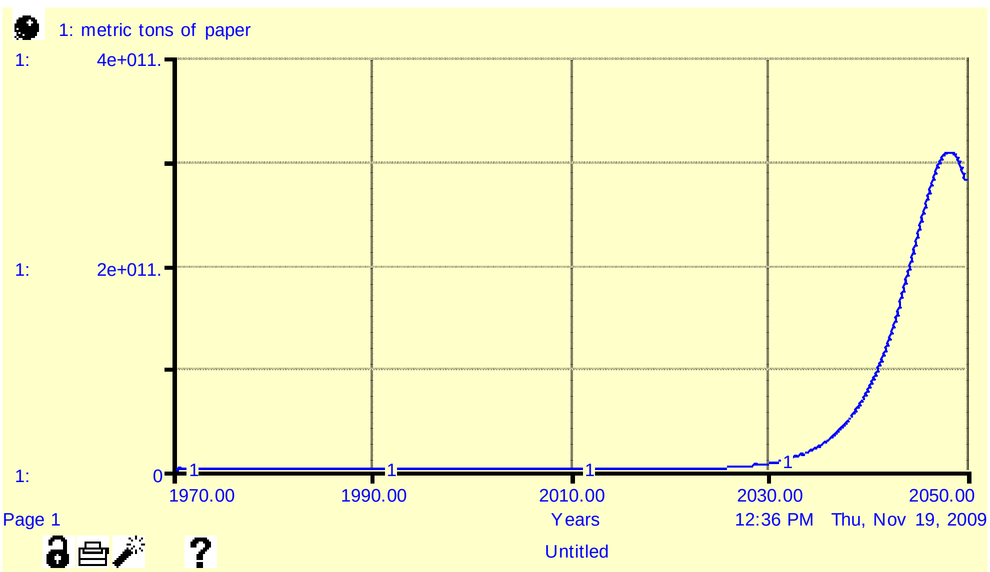


1: metric tons of paper
1: 5e+011.
1: 2.5e+011
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
12:34 PM Thu, Nov 19, 2009
Untitled

Run 3

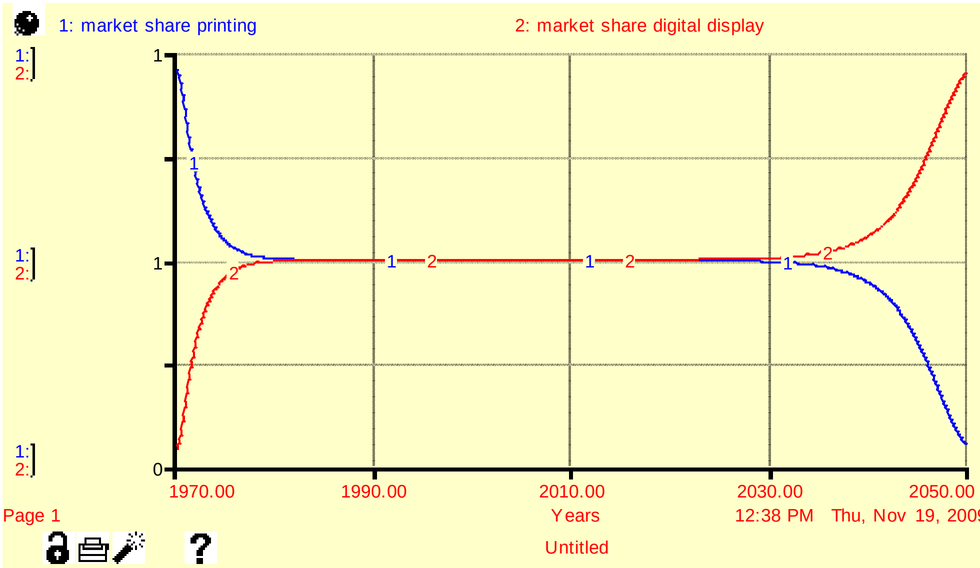


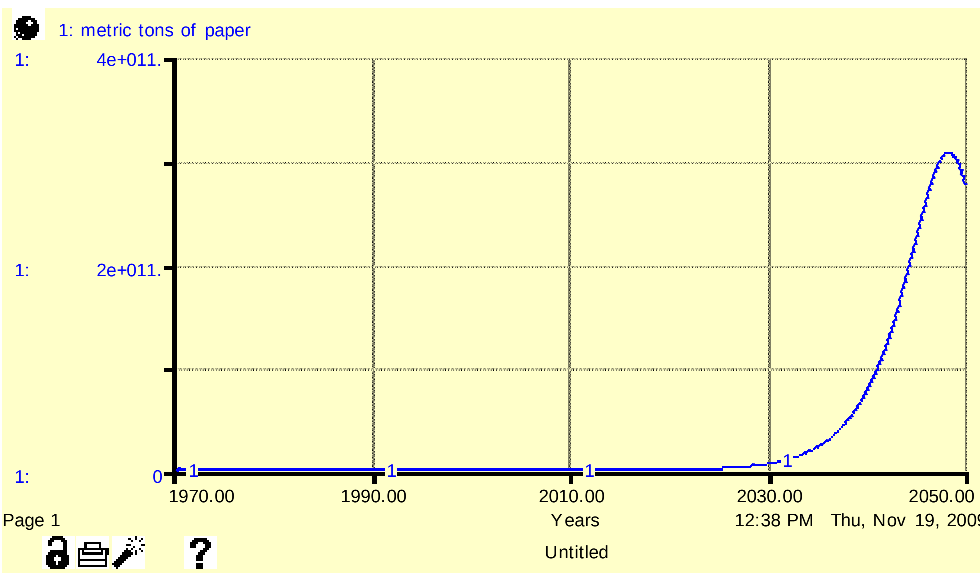
1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
12:36 PM Thu, Nov 19, 2009
Untitled



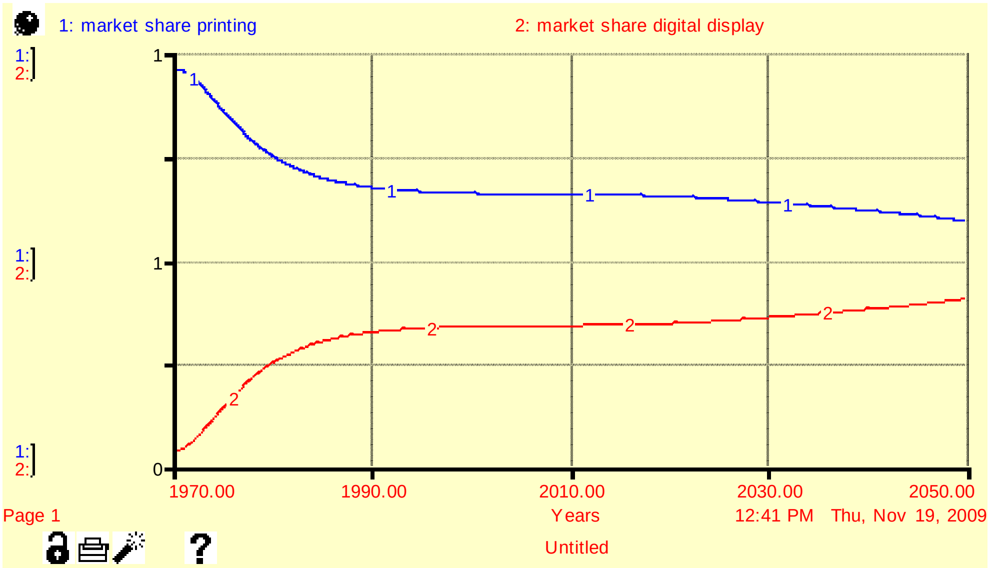
1: metric tons of paper
1: 4e+011.
1: 2e+011.
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
12:36 PM Thu, Nov 19, 2009
Untitled

Run 4

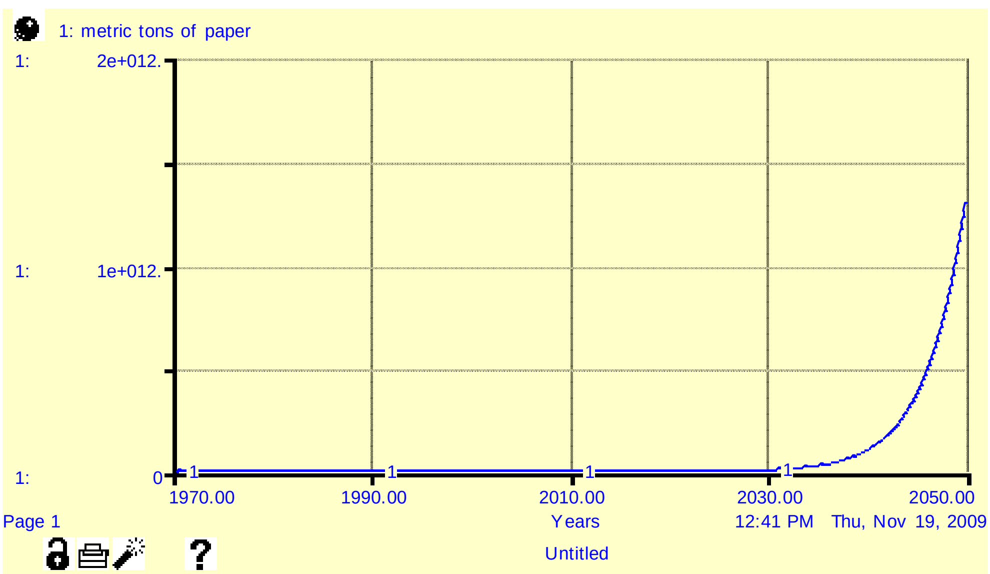

1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
12:38 PM Thu, Nov 19, 2009
Untitled


1: metric tons of paper
1: 4e+011.
1: 2e+011.
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
12:38 PM Thu, Nov 19, 2009
Untitled

Run 5

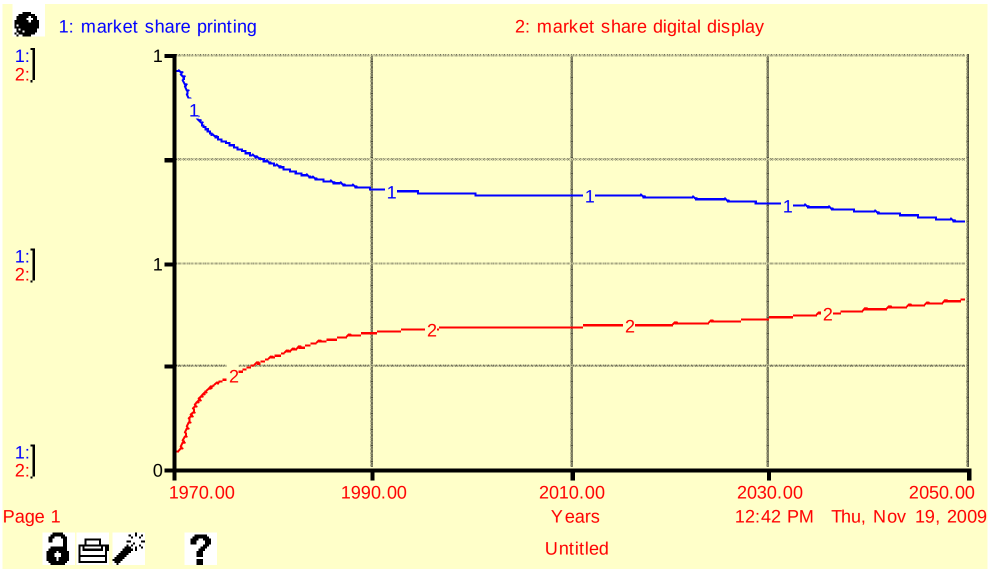


1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
12:41 PM Thu, Nov 19, 2009
Untitled

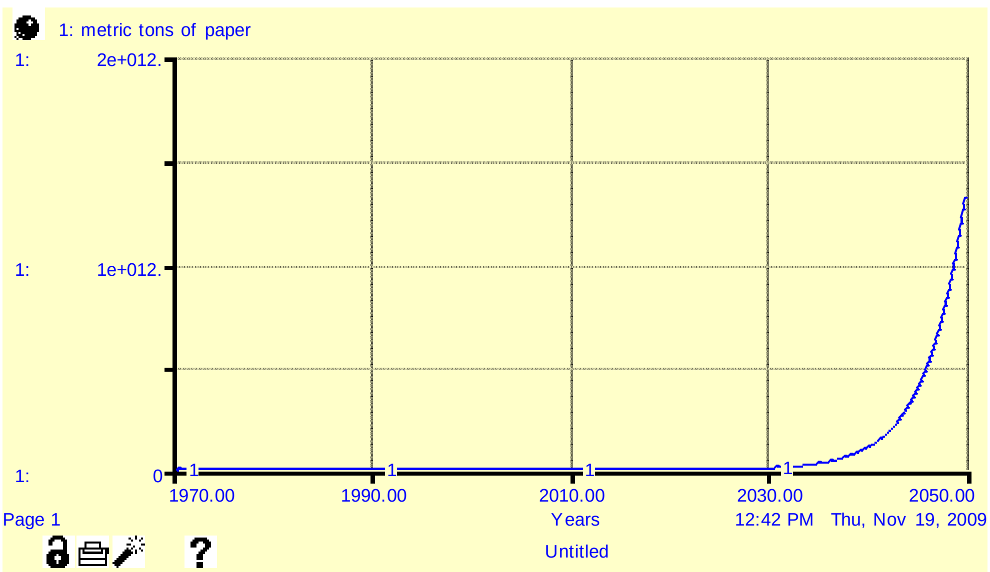


1: metric tons of paper
1: 2e+012.
1: 1e+012.
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
12:41 PM Thu, Nov 19, 2009
Untitled

Run 6:

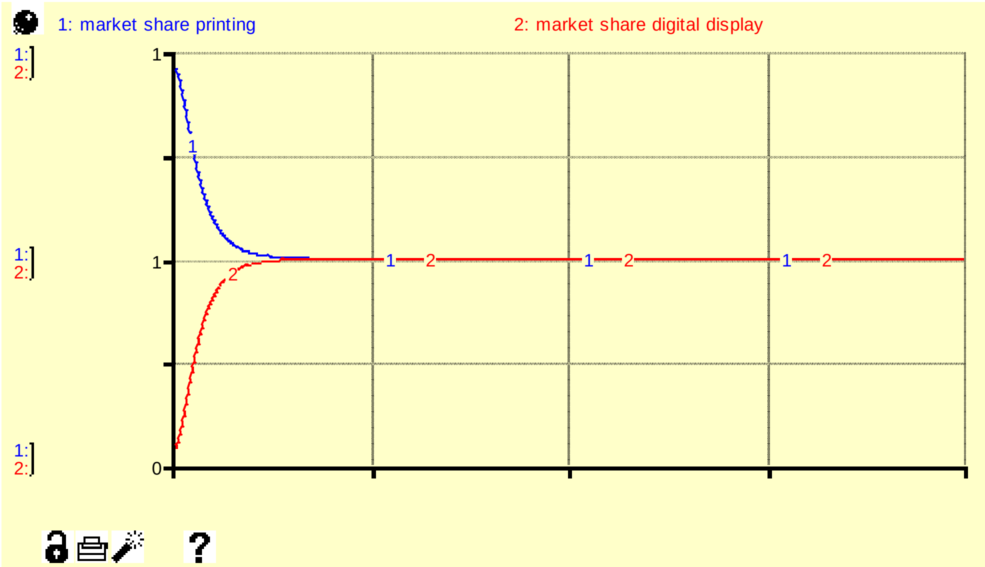


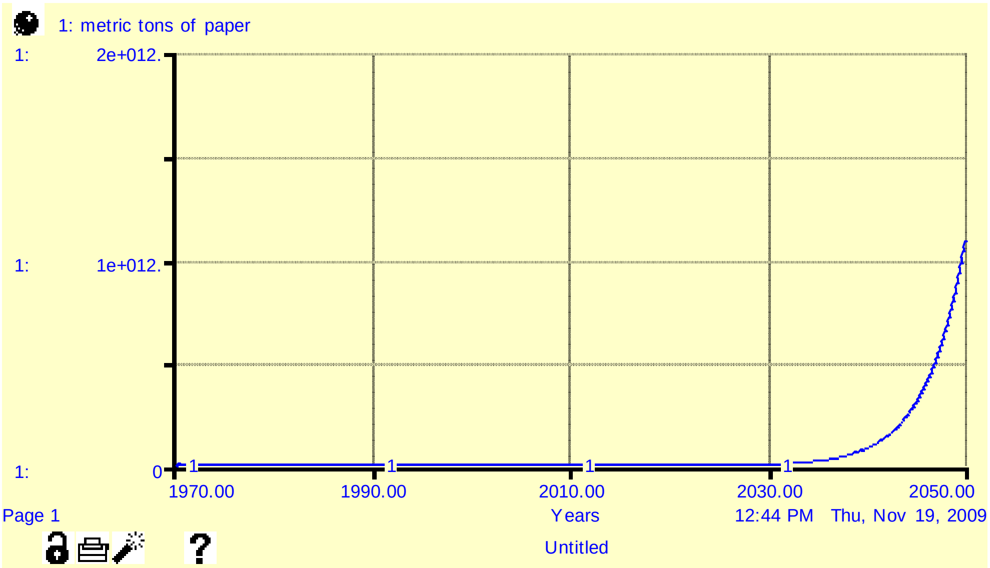
1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
12:42 PM Thu, Nov 19, 2009
Untitled



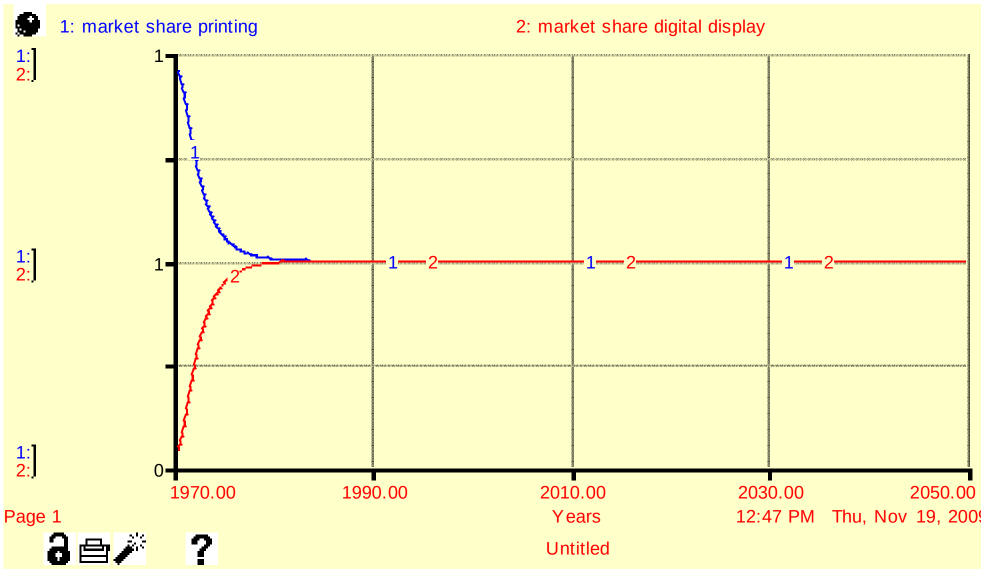
1: metric tons of paper
1: 2e+012.
1: 1e+012.
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
12:42 PM Thu, Nov 19, 2009
Untitled

Run 7:

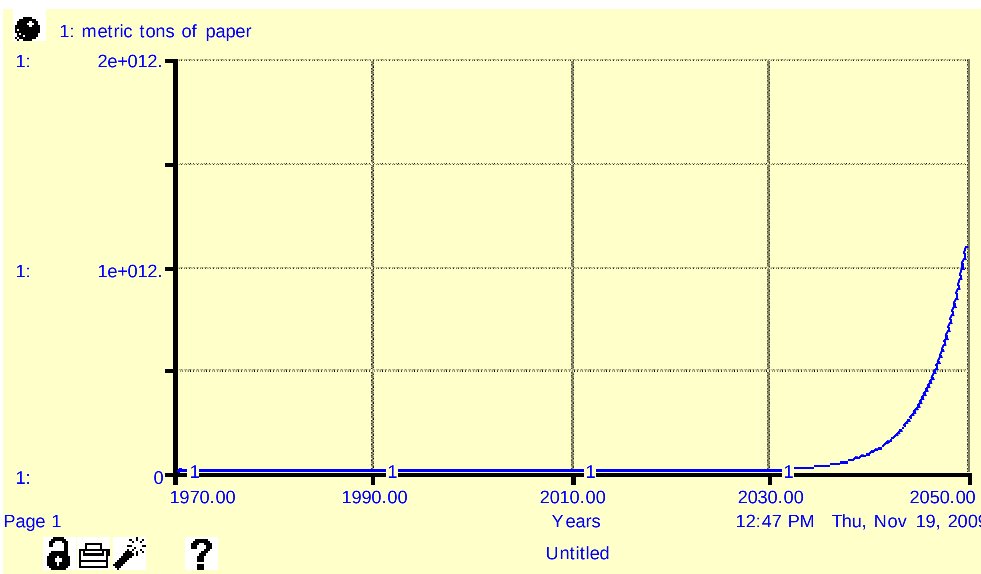

1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0


1: metric tons of paper
1:
2e+012.
1:
1e+012.
1:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
12:44 PM Thu, Nov 19, 2009
Untitled

Run 8:

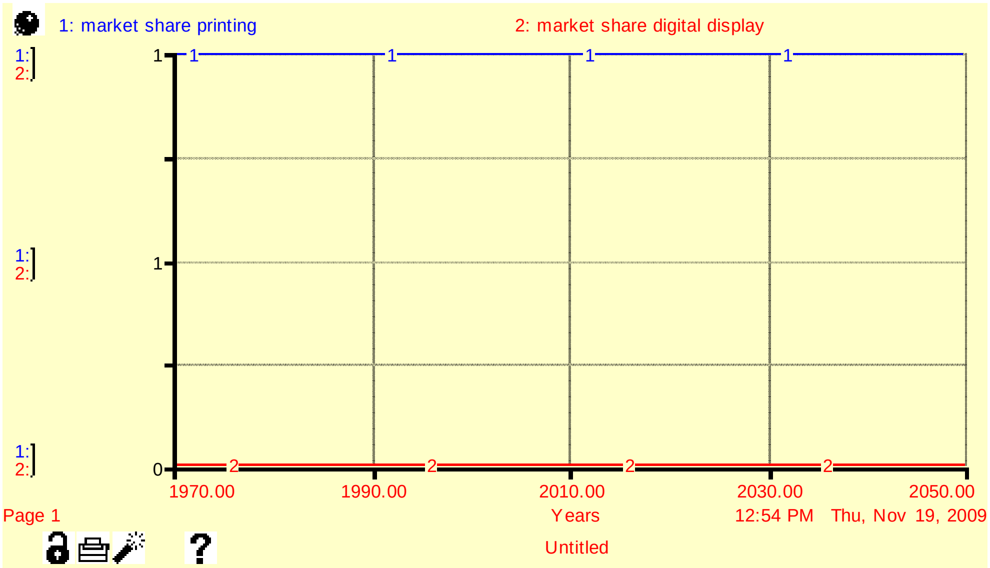


1: market share printing
2: market share digital display
1
1
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
12:47 PM Thu, Nov 19, 2009
Untitled

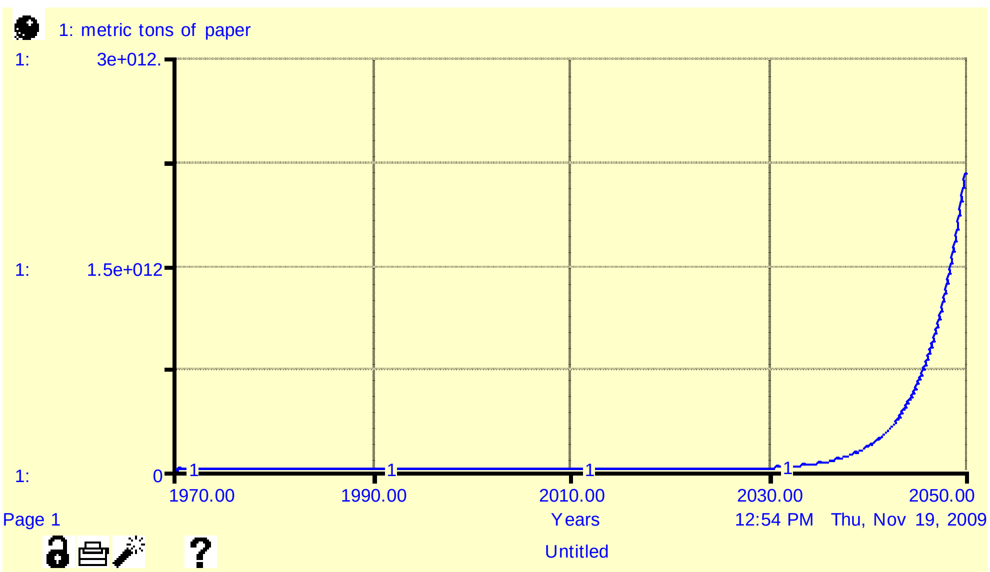


1: metric tons of paper
2e+012.
1e+012.
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
12:47 PM Thu, Nov 19, 2009
Untitled

Sensi9:

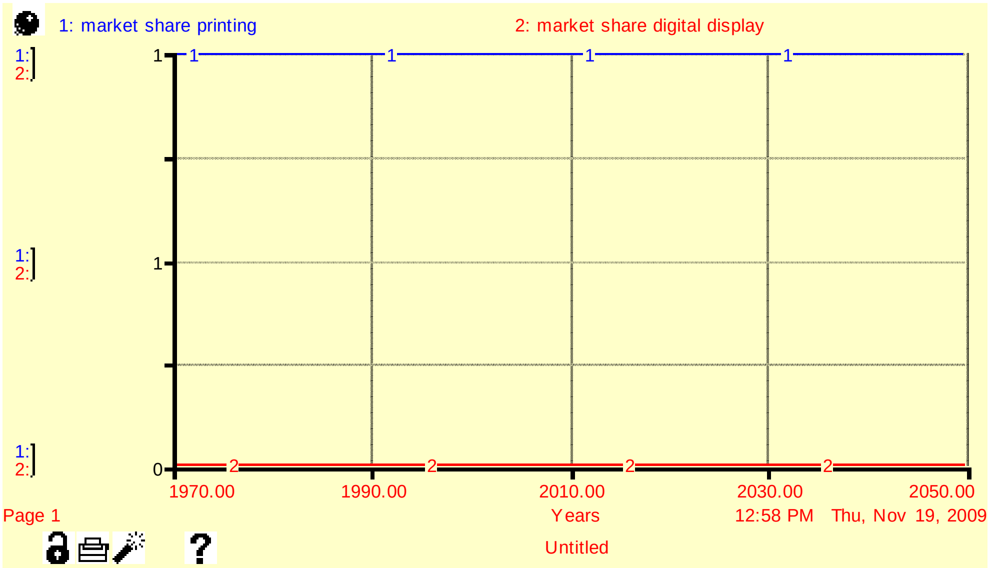


1: market share printing
2: market share digital display
1:
2:
1
1
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
12:54 PM Thu, Nov 19, 2009
Untitled

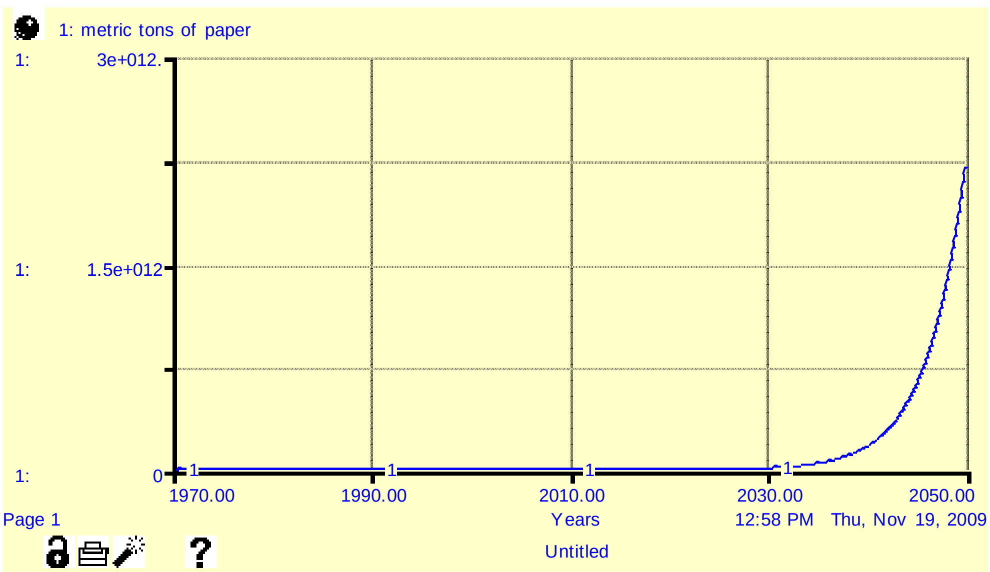


1: metric tons of paper
1: 3e+012.
1: 1.5e+012
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
12:54 PM Thu, Nov 19, 2009
Untitled

Run 10:

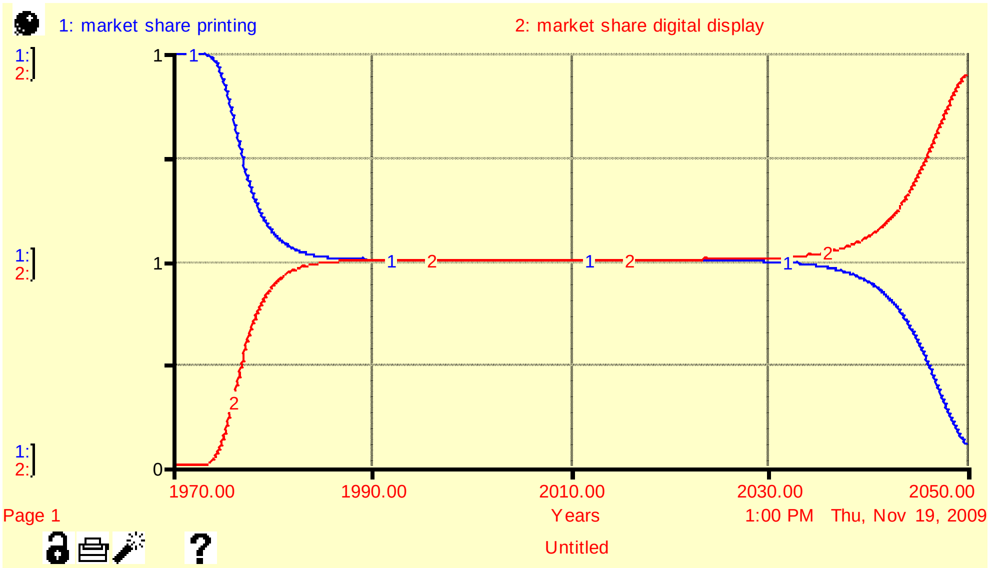


1: market share printing
2: market share digital display
1:
2:
1
1
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
12:58 PM Thu, Nov 19, 2009
Untitled

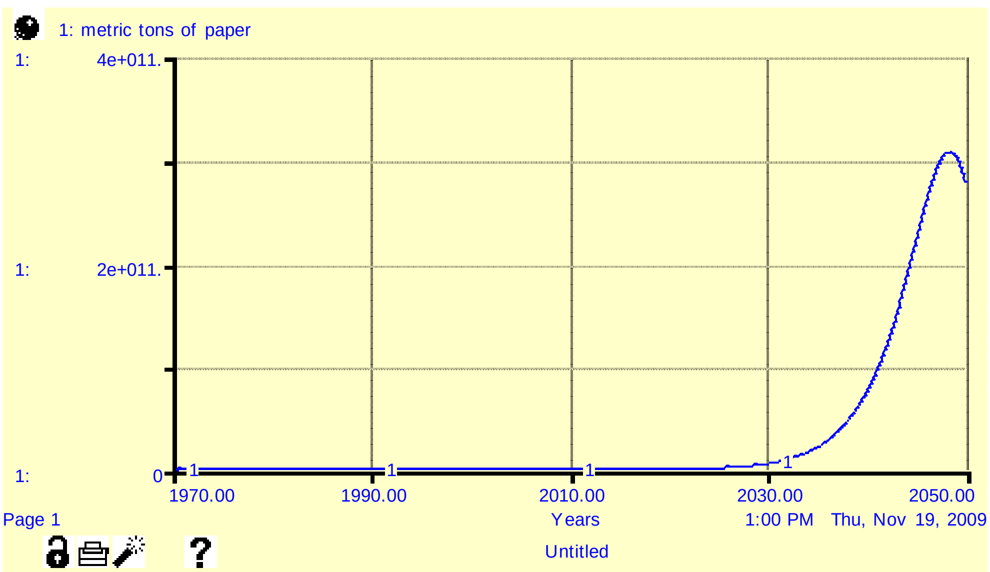


1: metric tons of paper
1: 3e+012.
1: 1.5e+012
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
12:58 PM Thu, Nov 19, 2009
Untitled

Run 11:

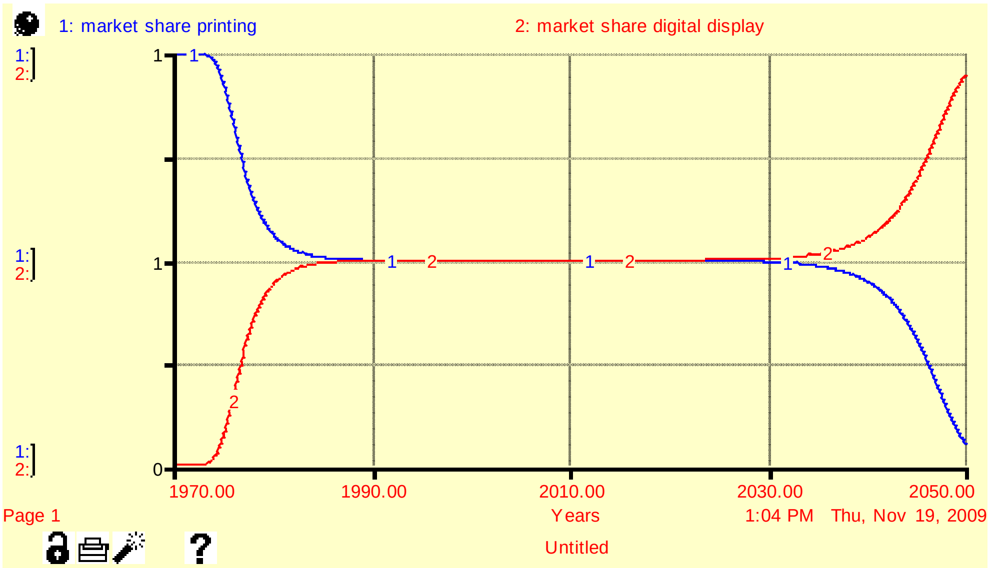


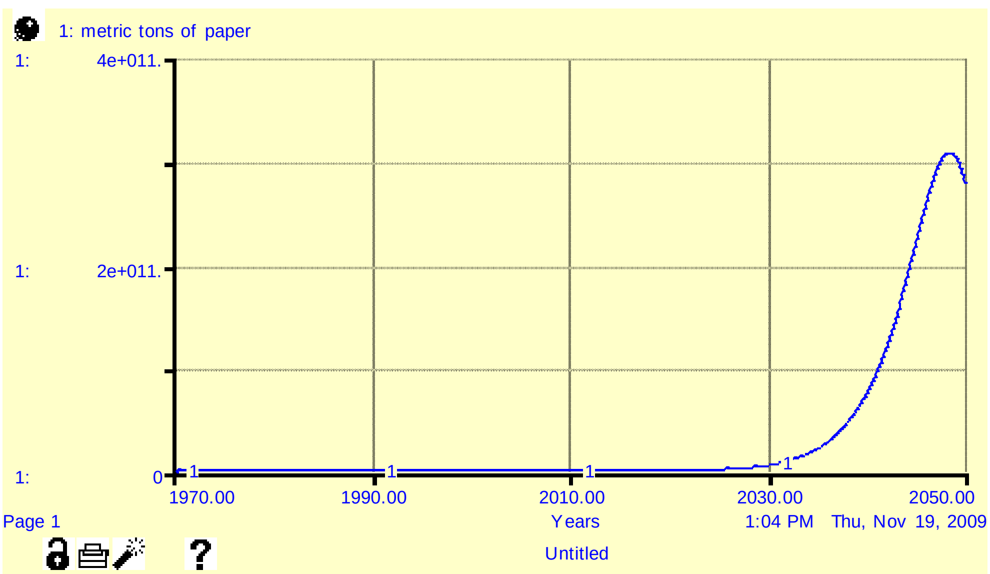
1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:00 PM Thu, Nov 19, 2009
Untitled



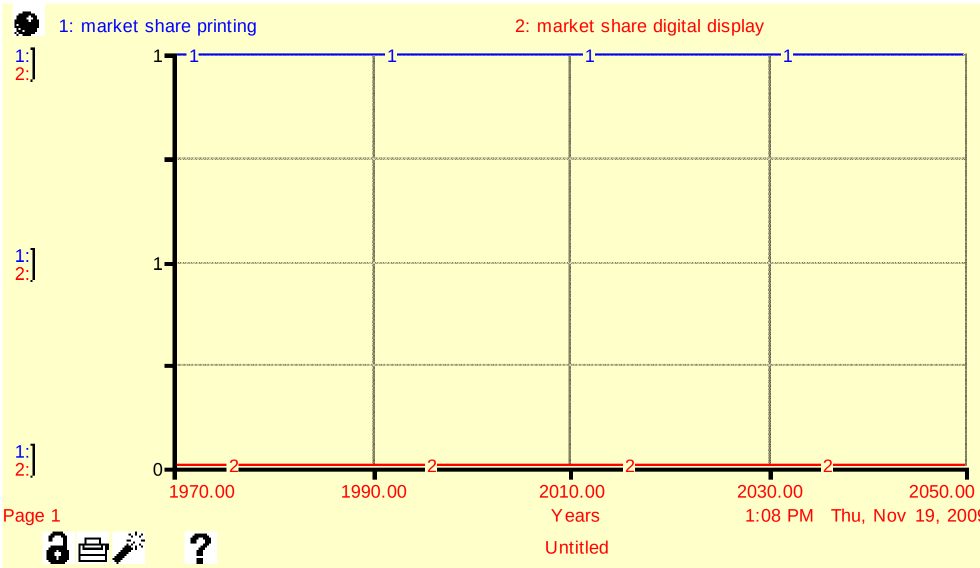
1: metric tons of paper
1: 4e+011.
1: 2e+011.
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:00 PM Thu, Nov 19, 2009
Untitled

Run 12:

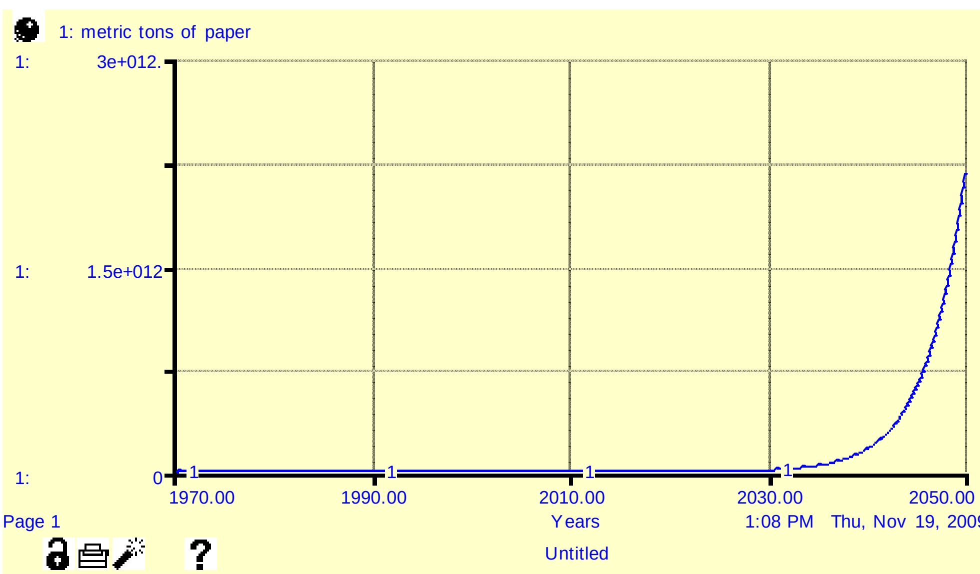

1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:04 PM Thu, Nov 19, 2009
Untitled


1: metric tons of paper
1: 4e+011.
1: 2e+011.
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:04 PM Thu, Nov 19, 2009
Untitled

Run 13:

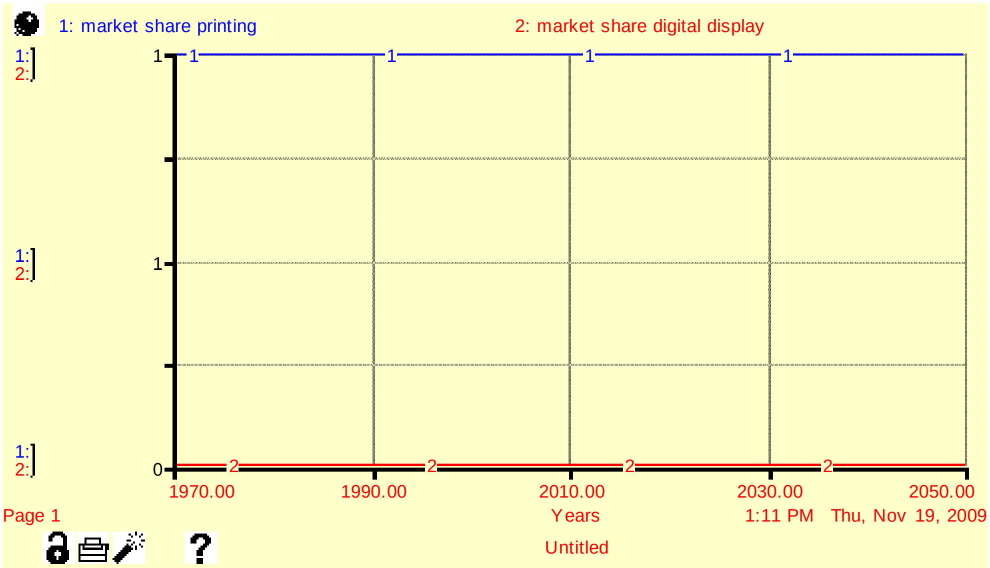


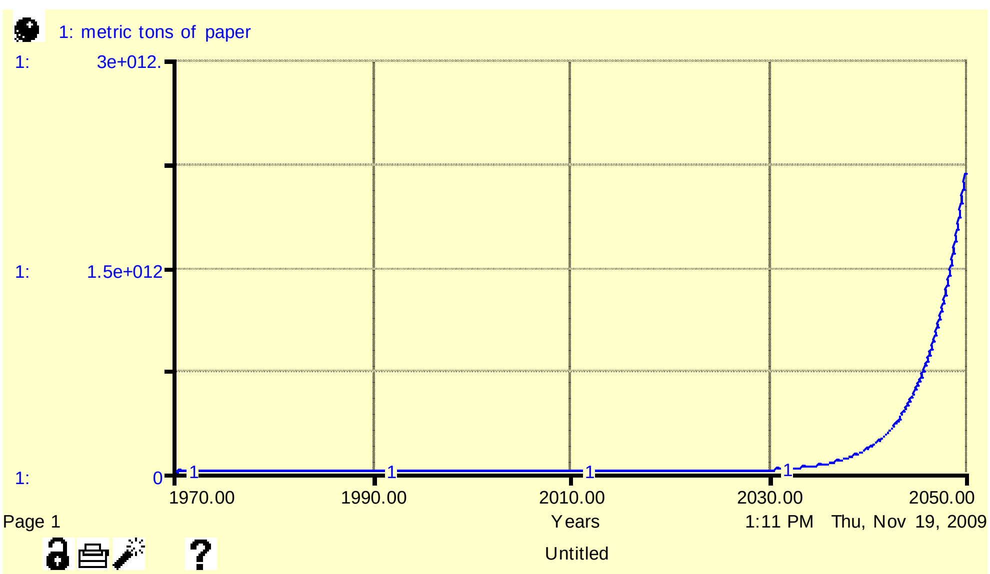
1: market share printing
2: market share digital display
1:
2:
1
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:08 PM Thu, Nov 19, 2009
Untitled



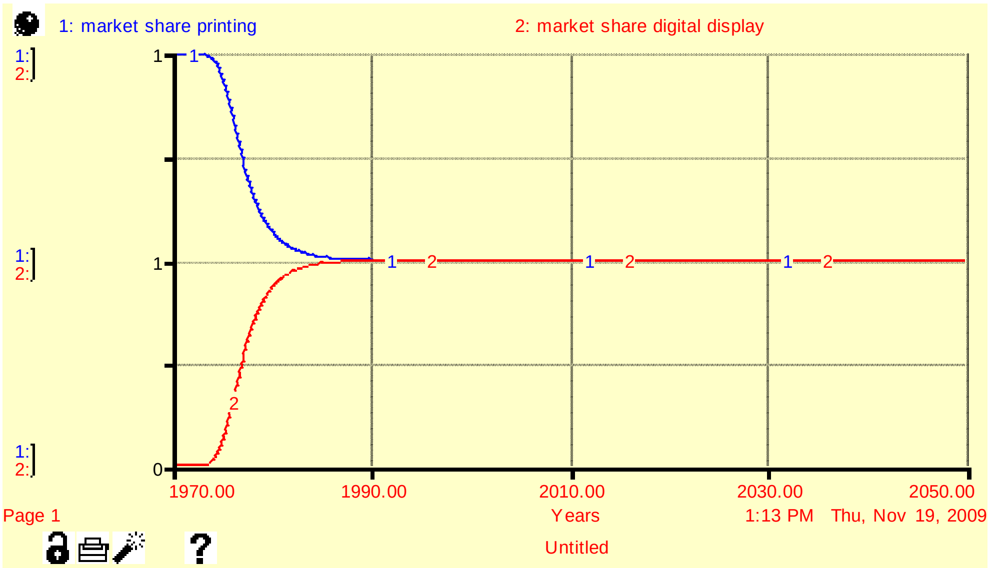
1: metric tons of paper
1: 3e+012.
1: 1.5e+012
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:08 PM Thu, Nov 19, 2009
Untitled

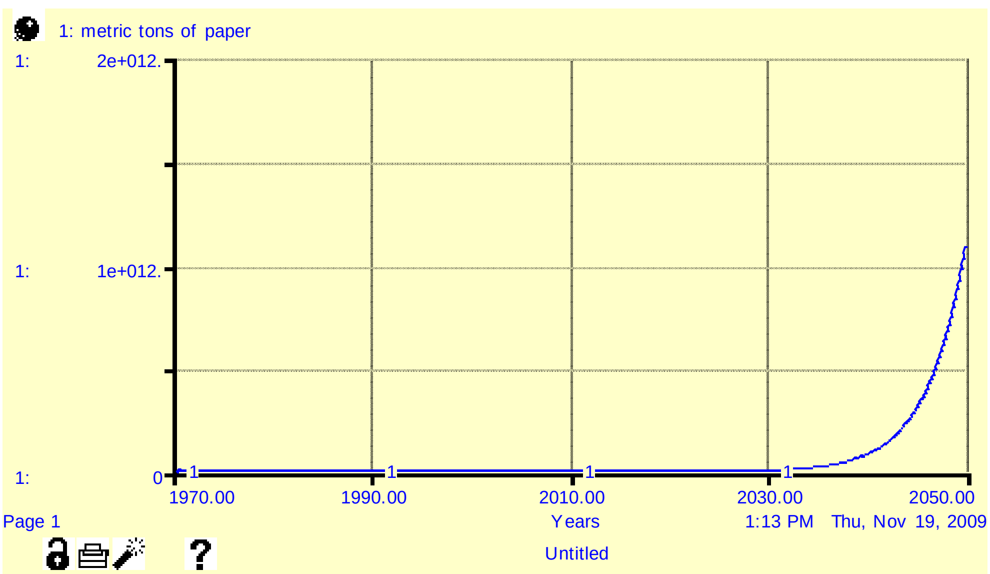
Run 14:


1: market share printing
2: market share digital display
1:
2:
1
1
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:11 PM Thu, Nov 19, 2009
Untitled

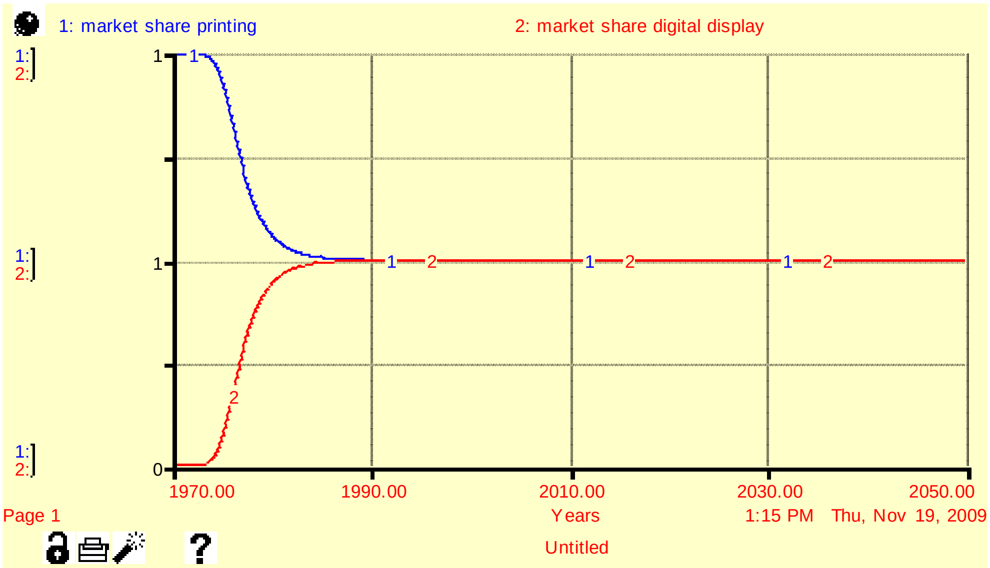

1: metric tons of paper
1: 3e+012.
1: 1.5e+012
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:11 PM Thu, Nov 19, 2009
Untitled

Run 15:

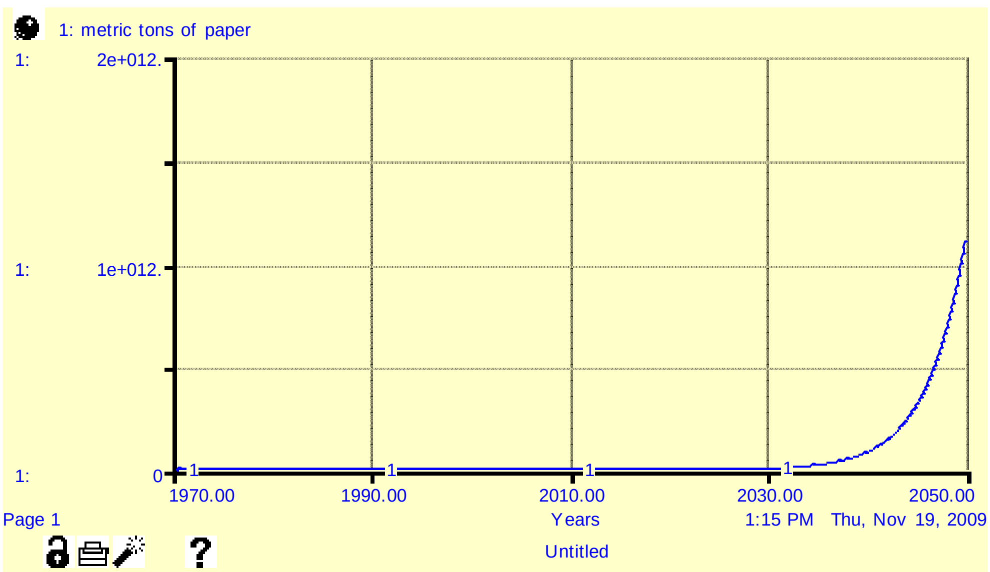

1: market share printing
2: market share digital display
1
1
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:13 PM Thu, Nov 19, 2009
Untitled


1: metric tons of paper
2e+012.
1e+012.
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:13 PM Thu, Nov 19, 2009
Untitled

Run 16:

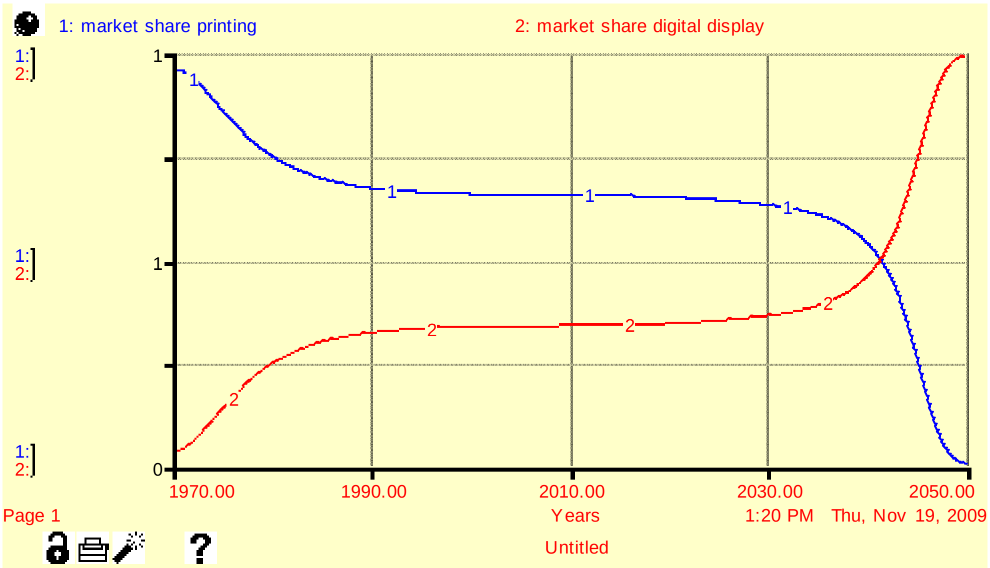


1: market share printing
2: market share digital display
1
1
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:15 PM Thu, Nov 19, 2009
Untitled

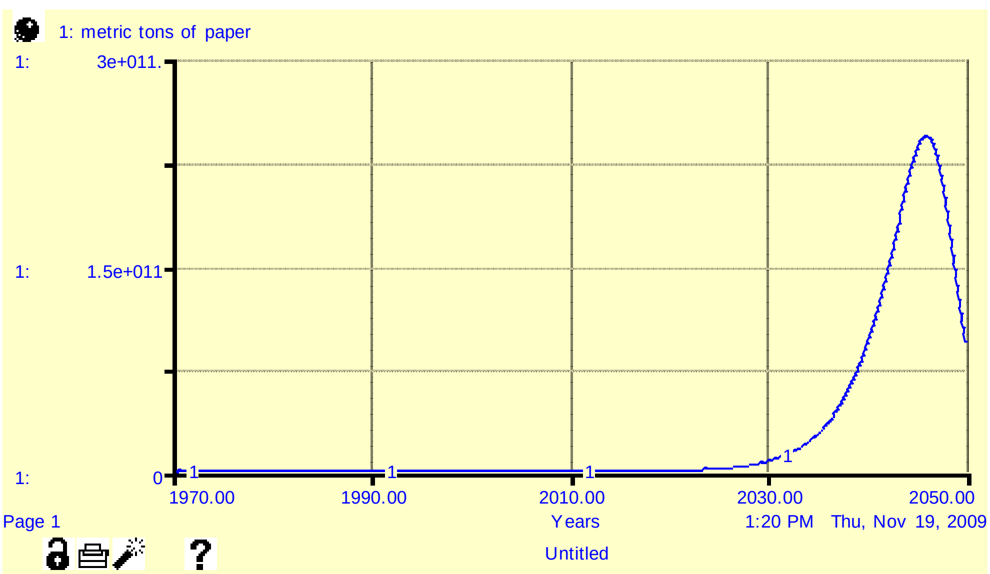


1: metric tons of paper
2e+012.
1e+012.
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:15 PM Thu, Nov 19, 2009
Untitled

Run 17:

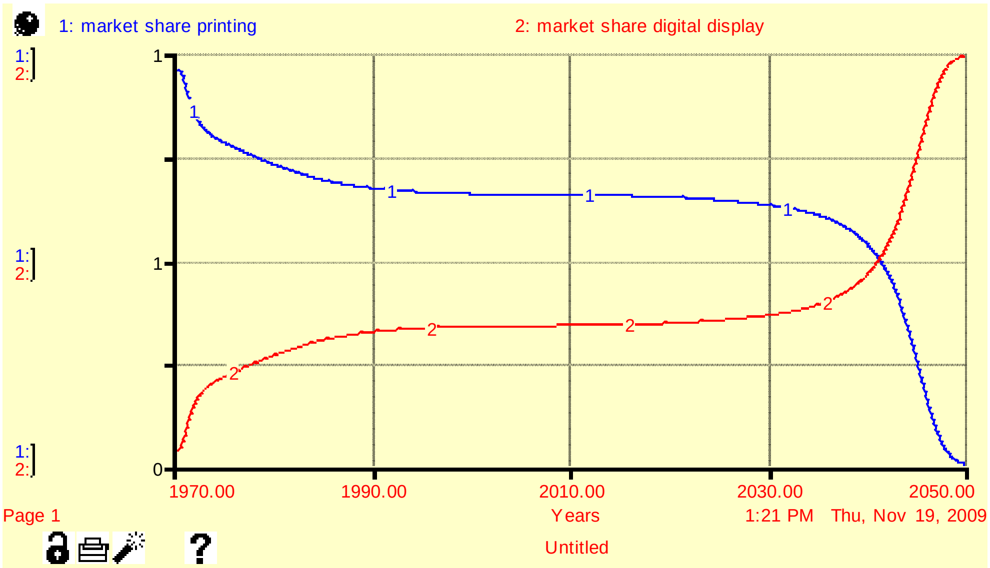


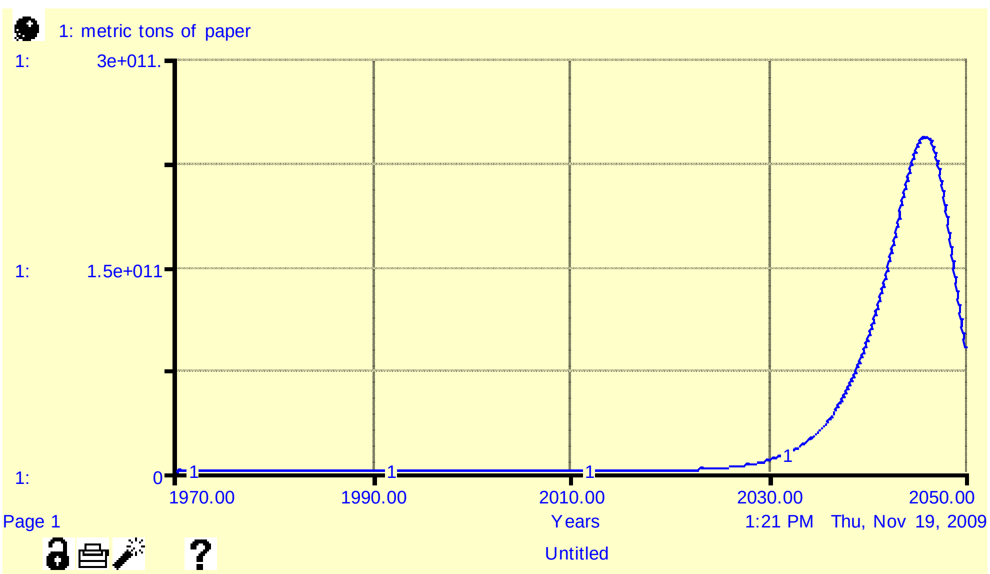
1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:20 PM Thu, Nov 19, 2009
Untitled



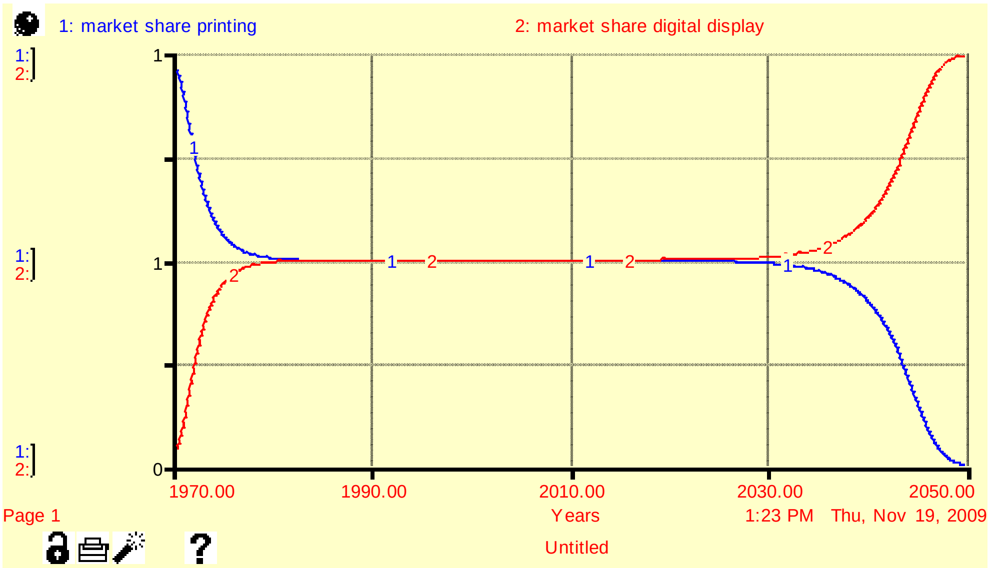
1: metric tons of paper
1: 3e+011.
1: 1.5e+011
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:20 PM Thu, Nov 19, 2009
Untitled

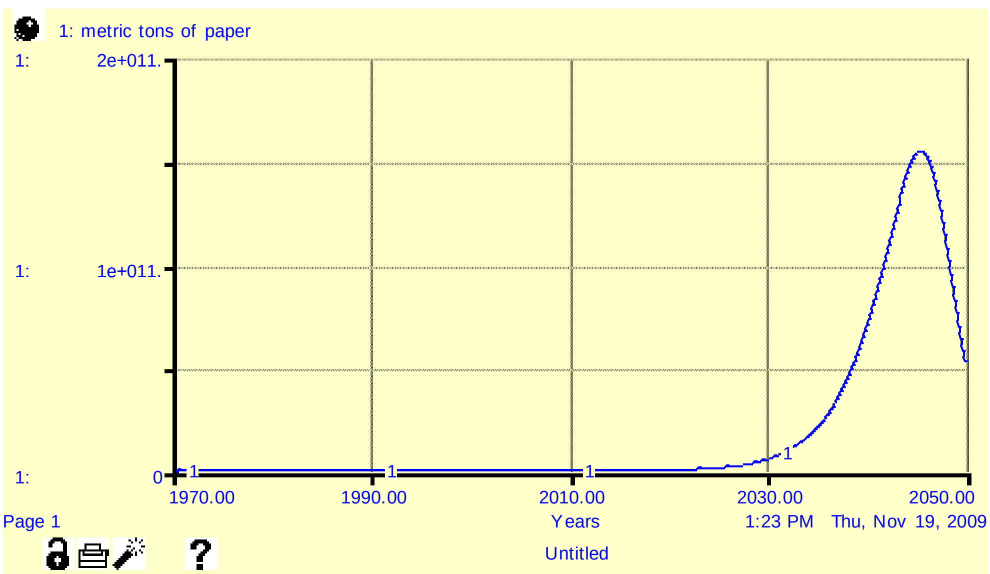
Run 18:


1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:21 PM Thu, Nov 19, 2009
Untitled

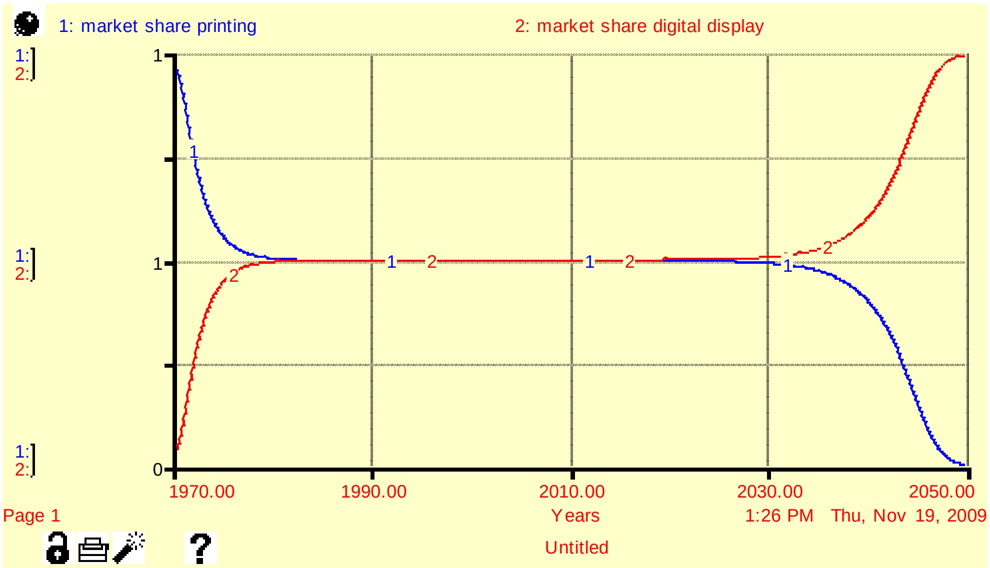

1: metric tons of paper
1: 3e+011
1: 1.5e+011
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:21 PM Thu, Nov 19, 2009
Untitled

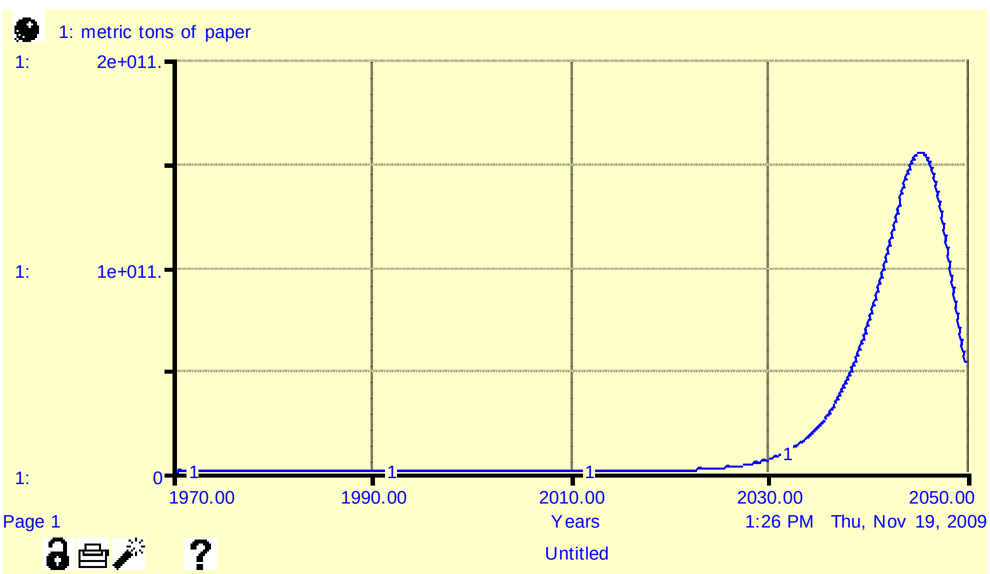
Run 19:


1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:23 PM Thu, Nov 19, 2009
Untitled

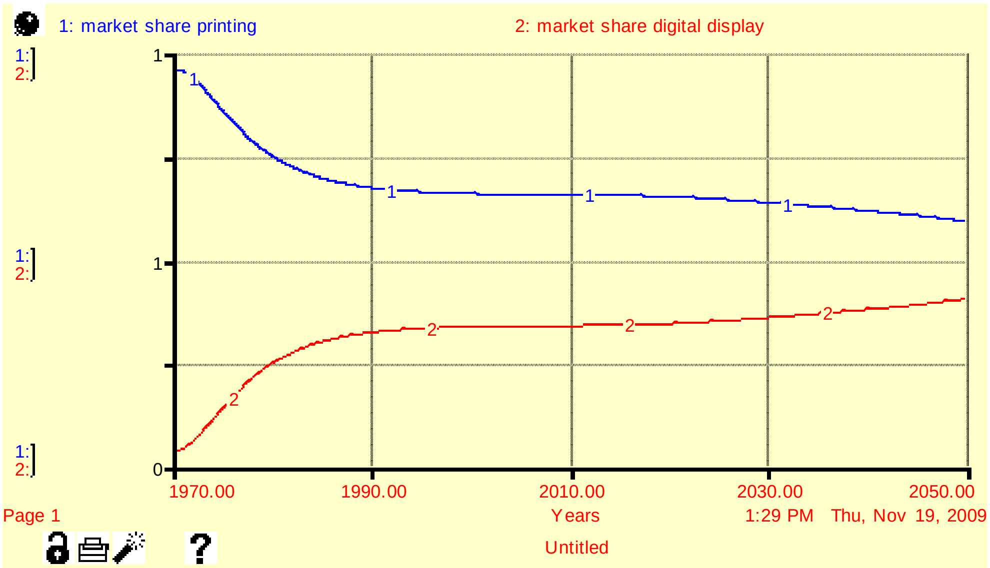

1: metric tons of paper
1: 2e+011.
1: 1e+011.
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:23 PM Thu, Nov 19, 2009
Untitled

Run 20:

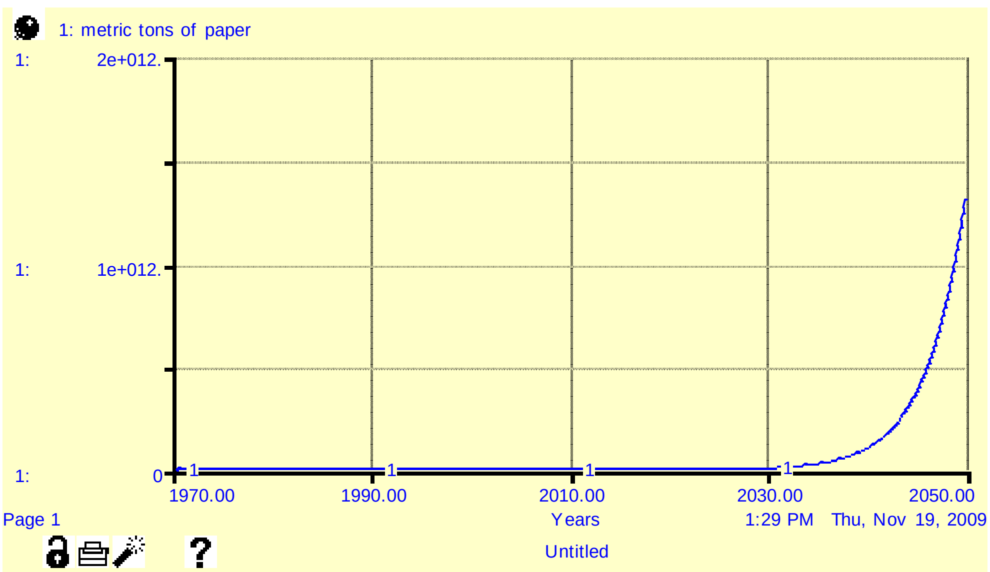

1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:26 PM Thu, Nov 19, 2009
Untitled


1: metric tons of paper
1: 2e+011.
1: 1e+011.
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:26 PM Thu, Nov 19, 2009
Untitled

Run 21:

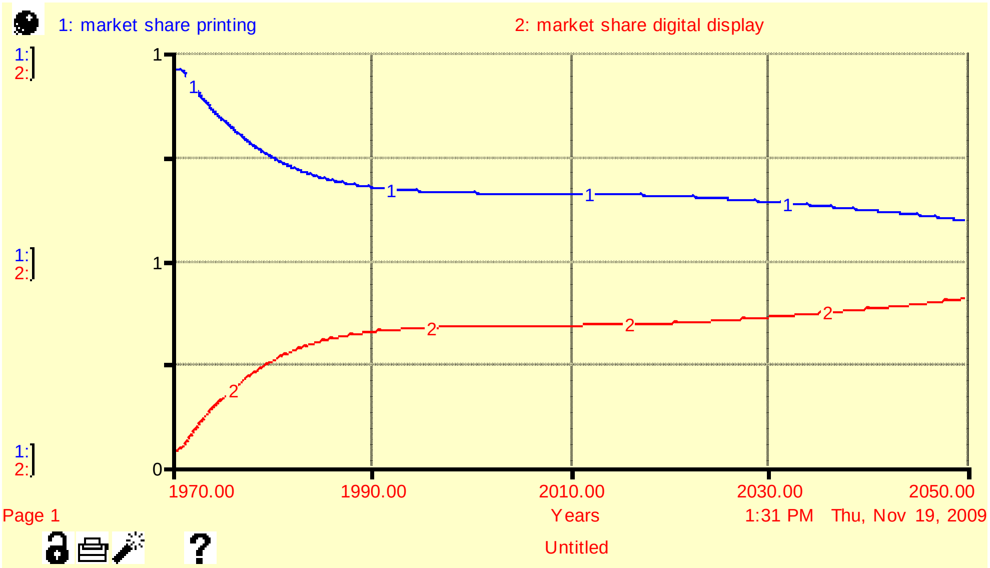


1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:29 PM Thu, Nov 19, 2009
Untitled

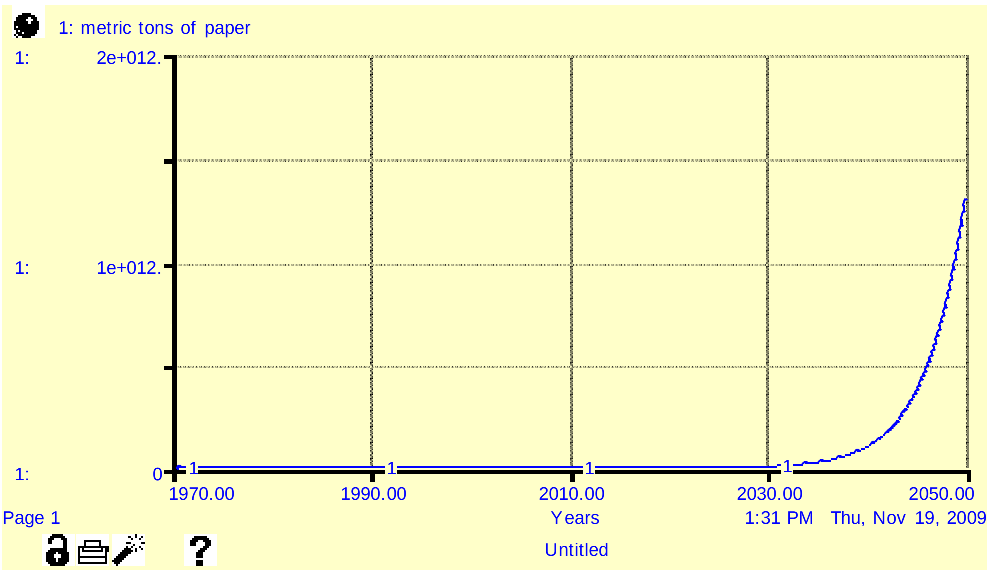


1: metric tons of paper
1: 2e+012.
1: 1e+012.
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:29 PM Thu, Nov 19, 2009
Untitled

Run 22:

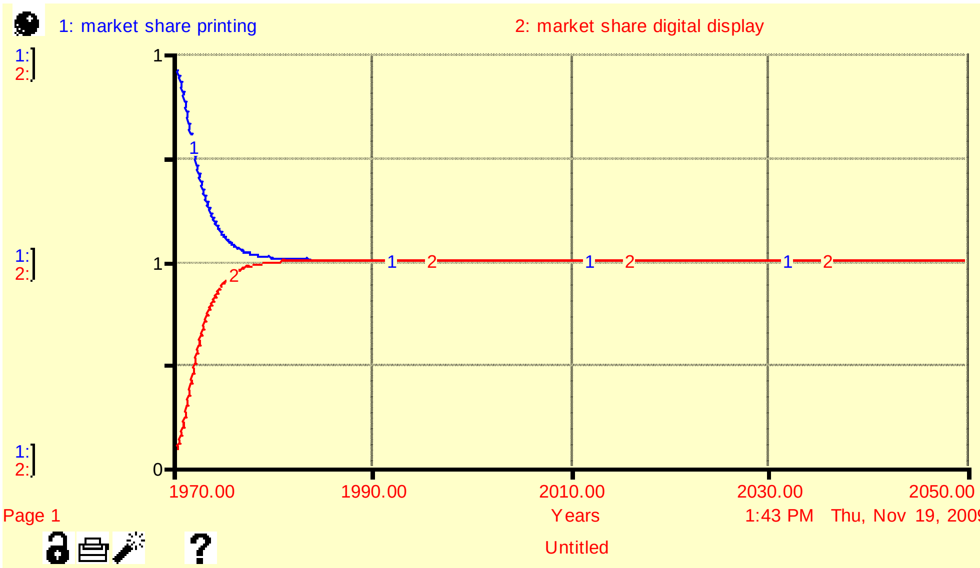


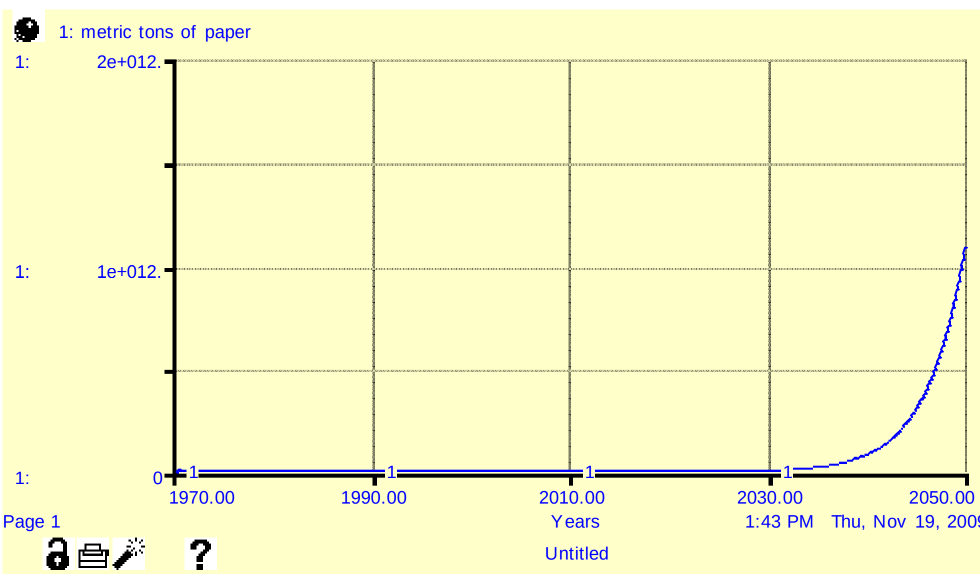
1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:31 PM Thu, Nov 19, 2009
Untitled



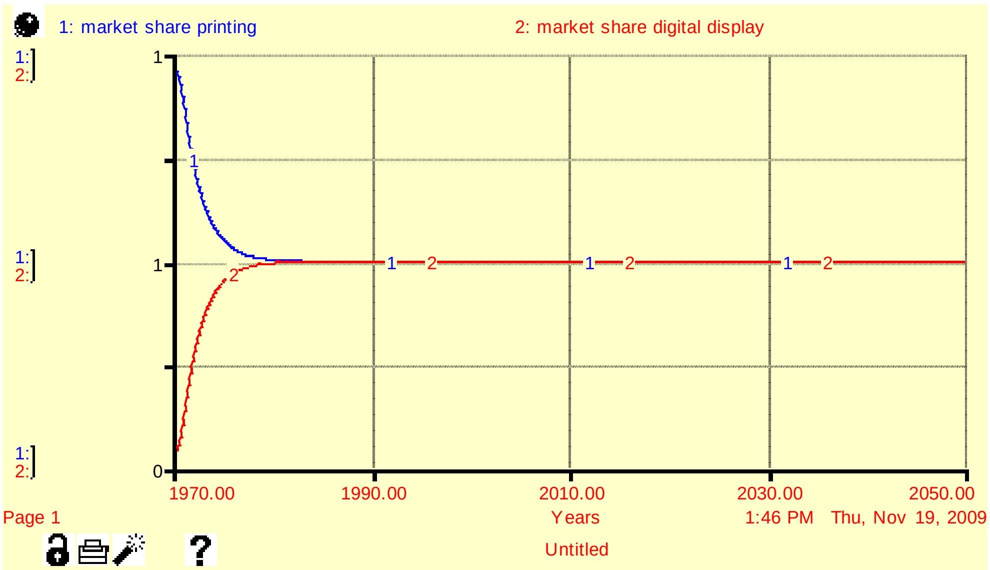
1: metric tons of paper
1:
2e+012.
1:
1e+012.
1:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:31 PM Thu, Nov 19, 2009
Untitled

Run 23:

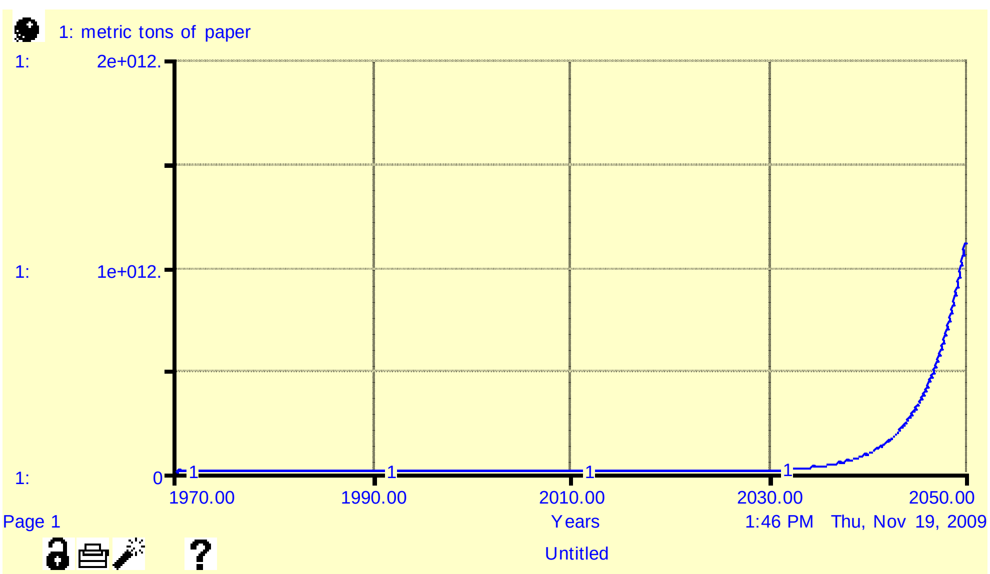

1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:43 PM Thu, Nov 19, 2009
Untitled


1: metric tons of paper
1: 2e+012.
1: 1e+012.
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:43 PM Thu, Nov 19, 2009
Untitled

Run 24:

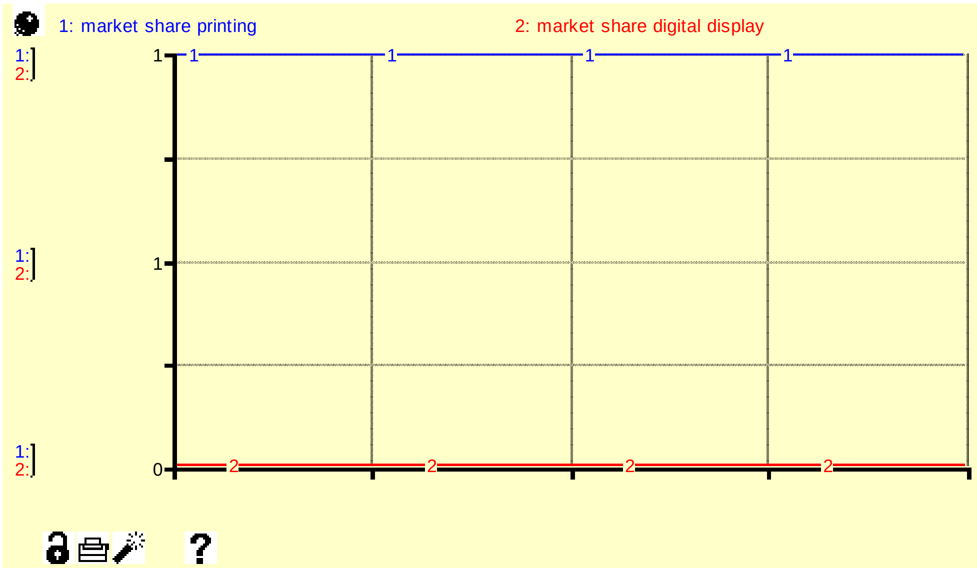


1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:46 PM Thu, Nov 19, 2009
Untitled

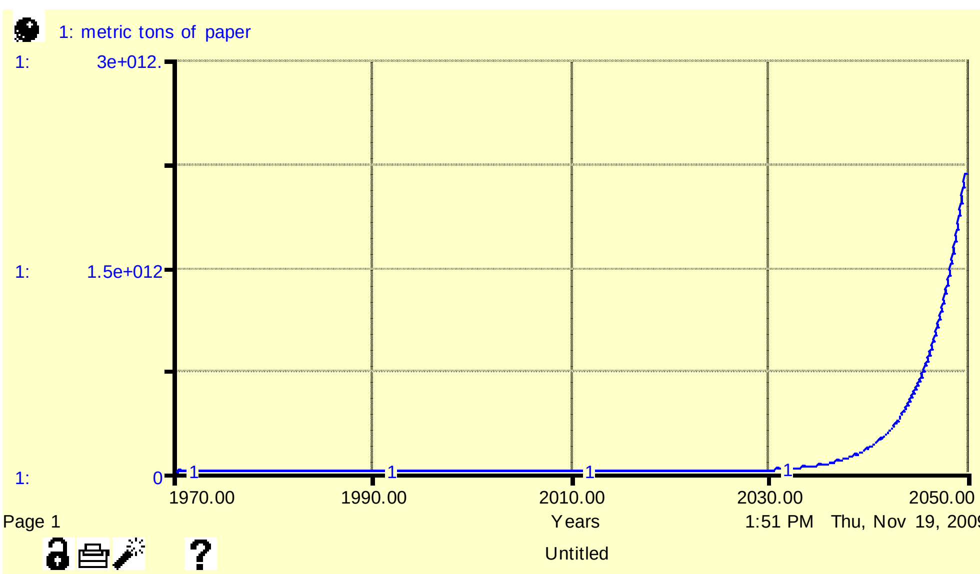


1: metric tons of paper
1:
2e+012.
1:
1e+012.
1:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:46 PM Thu, Nov 19, 2009
Untitled

Run 25:

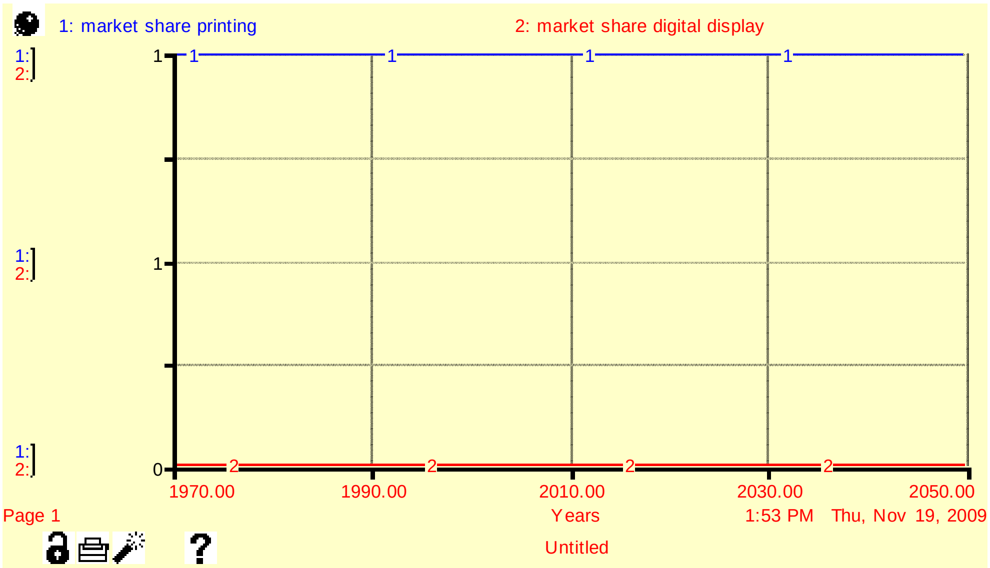


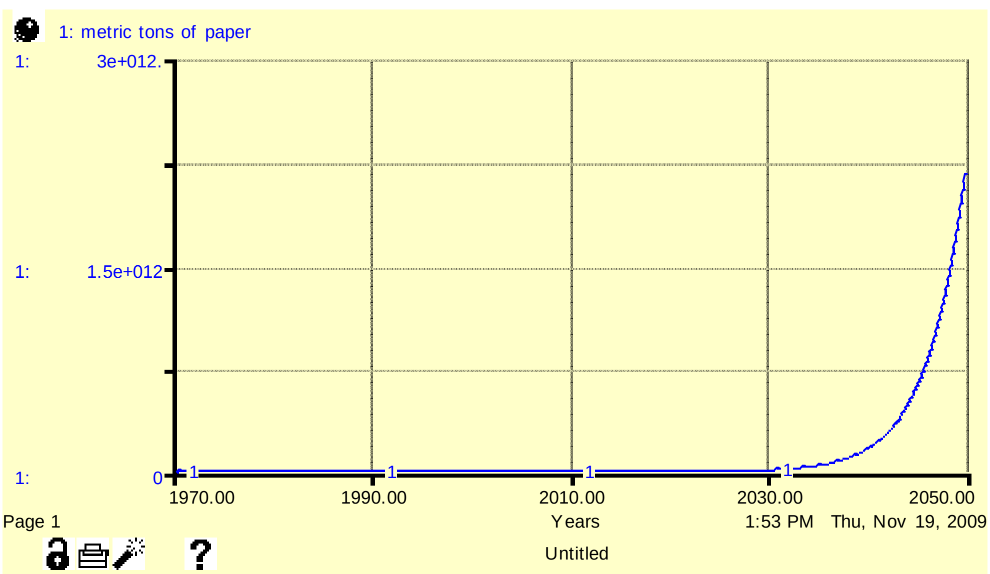
1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0



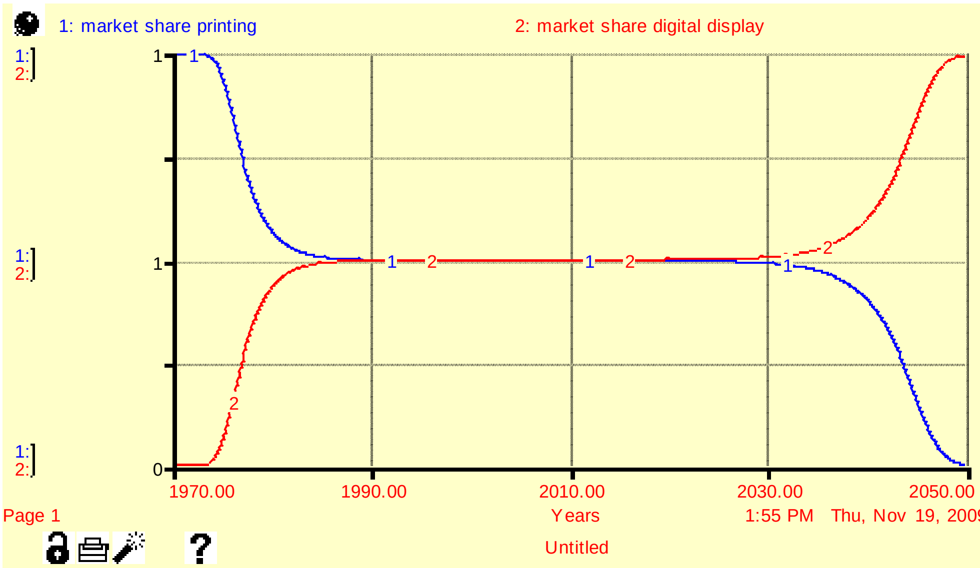
1: metric tons of paper
1: 3e+012.
1: 1.5e+012
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:51 PM Thu, Nov 19, 2009
Untitled

Run 26:

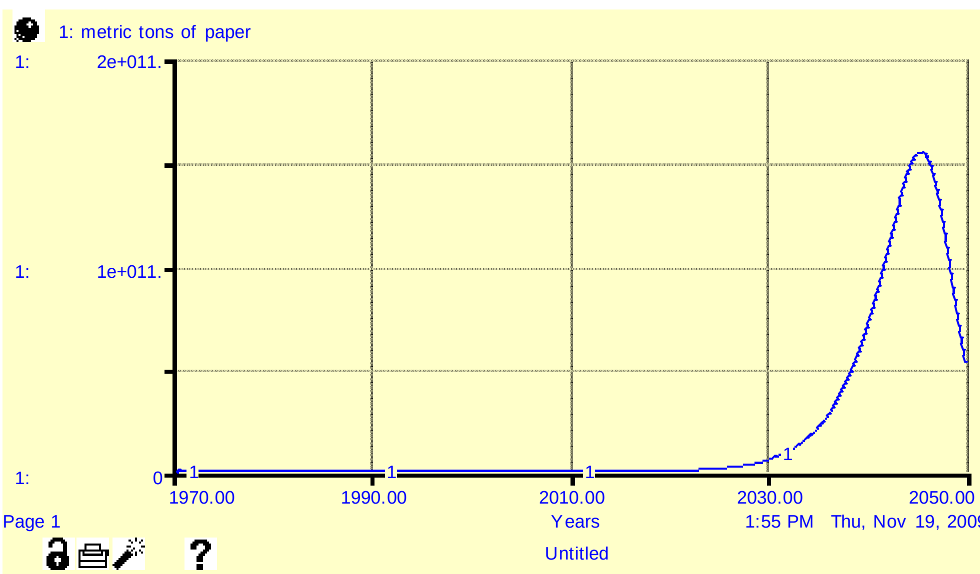

1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:53 PM Thu, Nov 19, 2009
Untitled


1: metric tons of paper
1: 3e+012.
1: 1.5e+012
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:53 PM Thu, Nov 19, 2009
Untitled

Run 28:

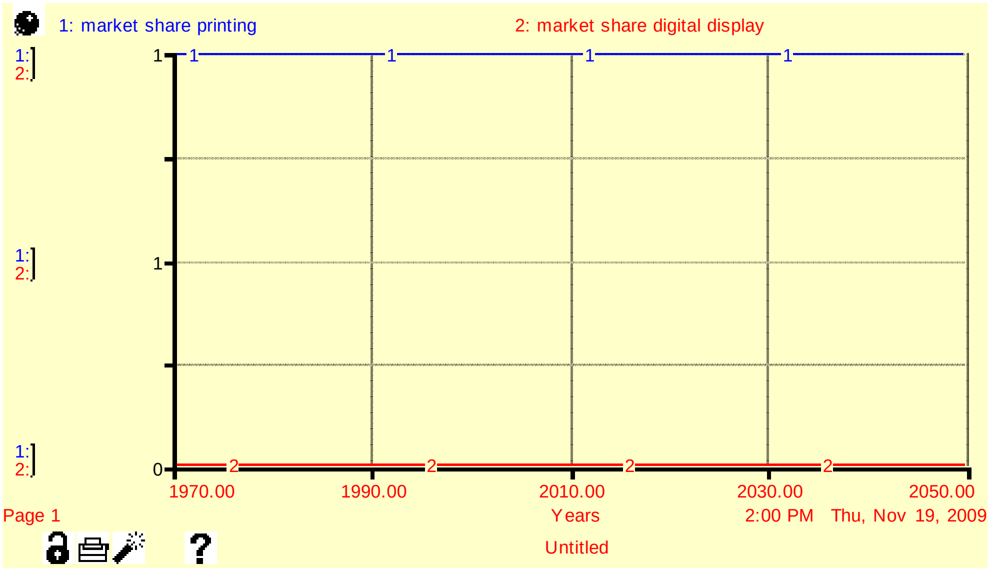


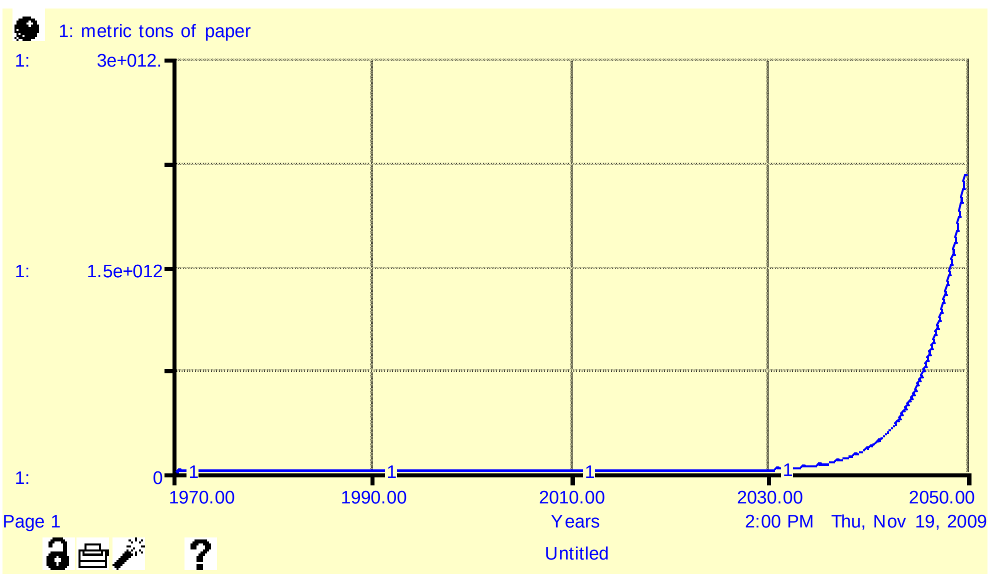
1: market share printing
2: market share digital display
1
1
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:55 PM Thu, Nov 19, 2009
Untitled



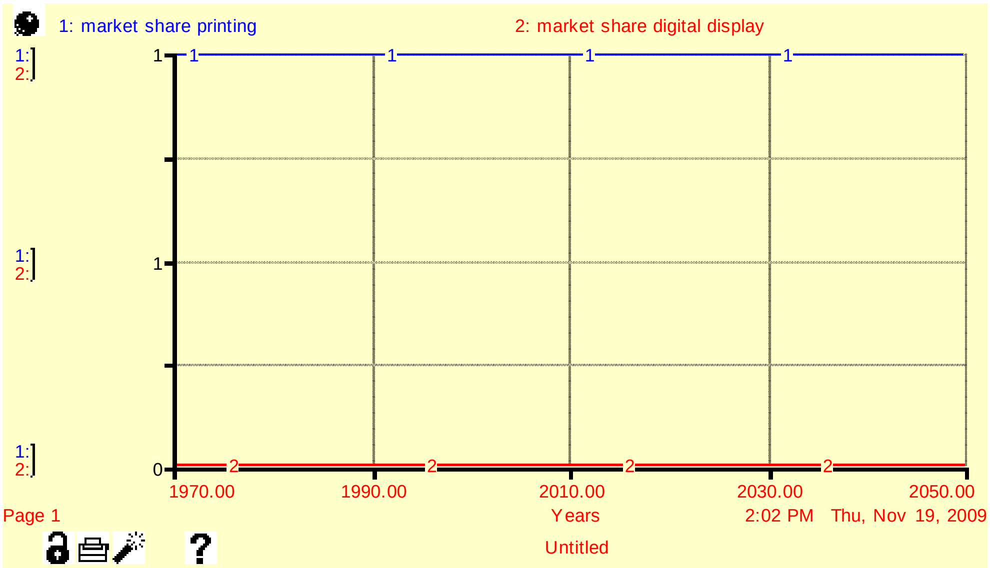
1: metric tons of paper
2e+011.
1e+011.
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
1:55 PM Thu, Nov 19, 2009
Untitled

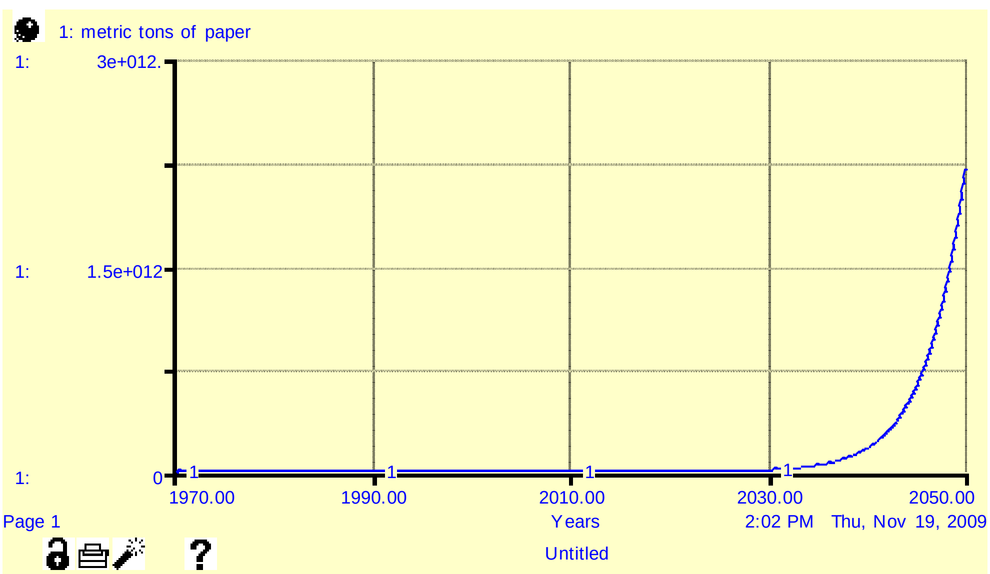
Run 29:


1: market share printing
2: market share digital display
1:
2:
1
1
0
1970.00
1990.00
2010.00
2030.00
2050.00
Years
Page 1
2:00 PM Thu, Nov 19, 2009
Untitled

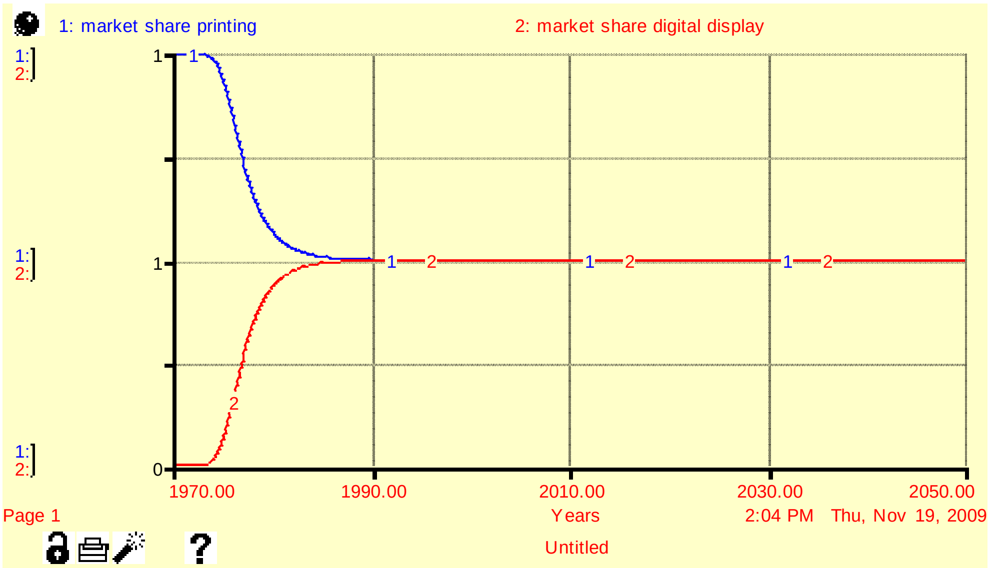

1: metric tons of paper
1: 3e+012
1: 1.5e+012
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Years
Page 1
2:00 PM Thu, Nov 19, 2009
Untitled

Run 30:

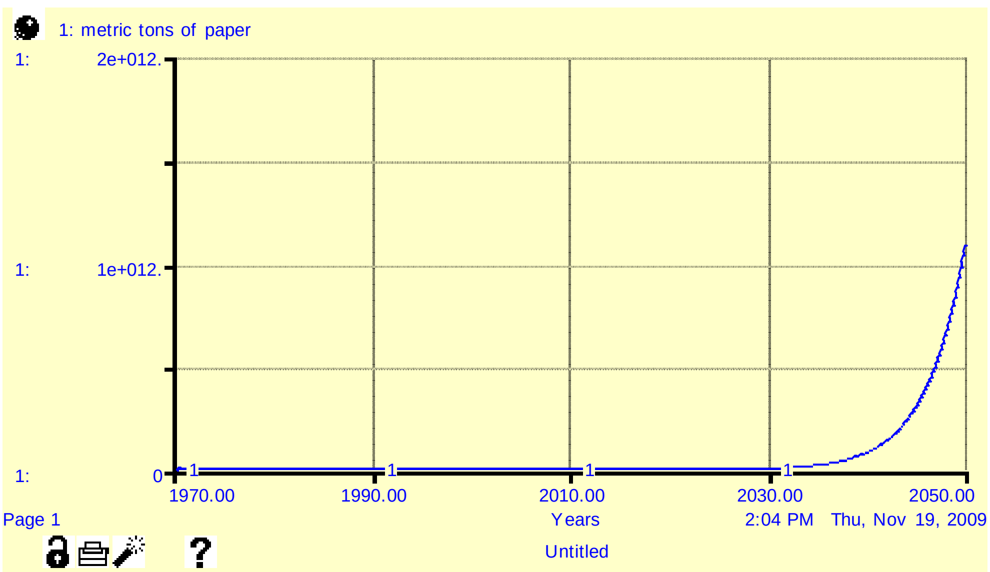

1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
2:02 PM Thu, Nov 19, 2009
Untitled


1: metric tons of paper
1: 3e+012.
1: 1.5e+012
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
2:02 PM Thu, Nov 19, 2009
Untitled

Run 31:

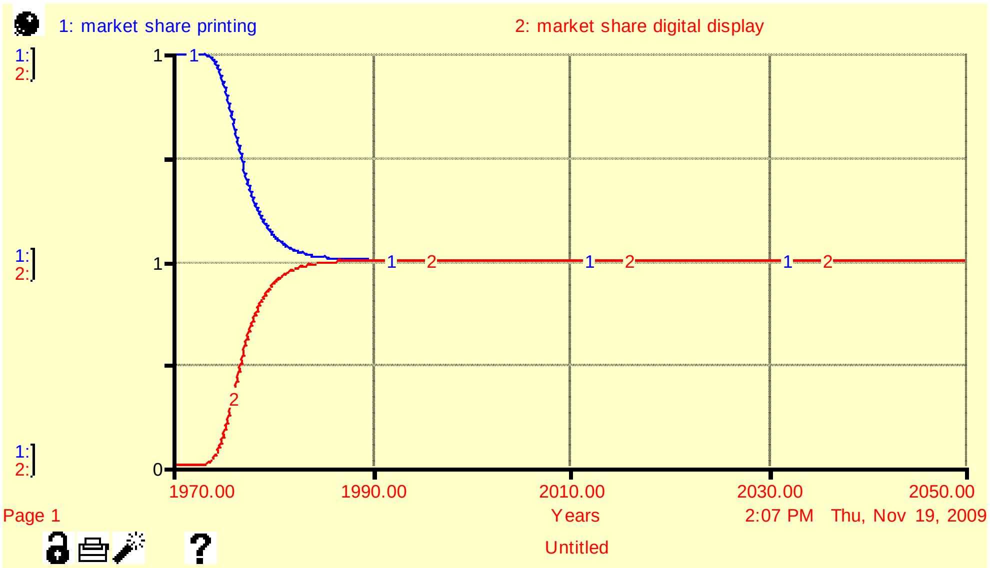


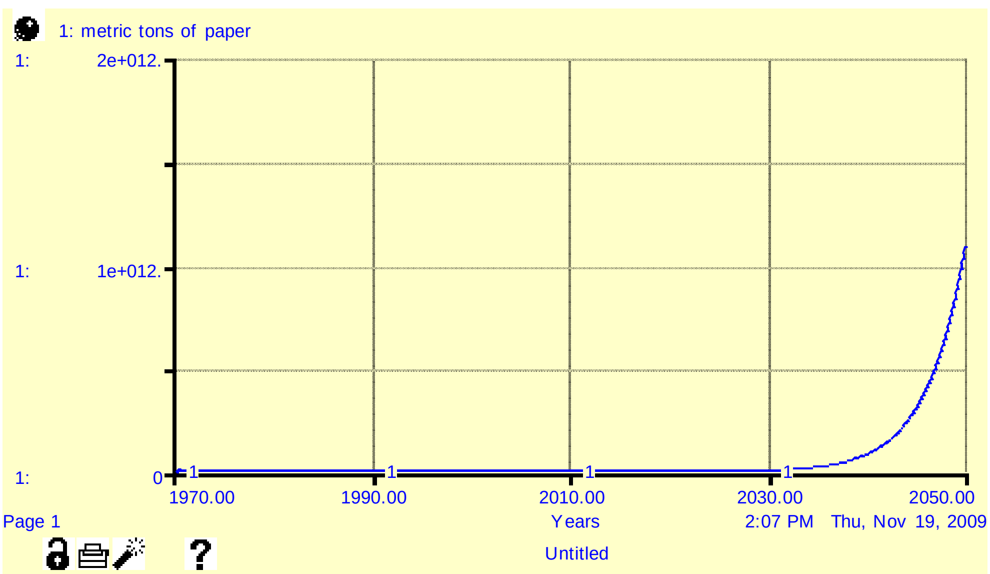
1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
2:04 PM Thu, Nov 19, 2009
Untitled



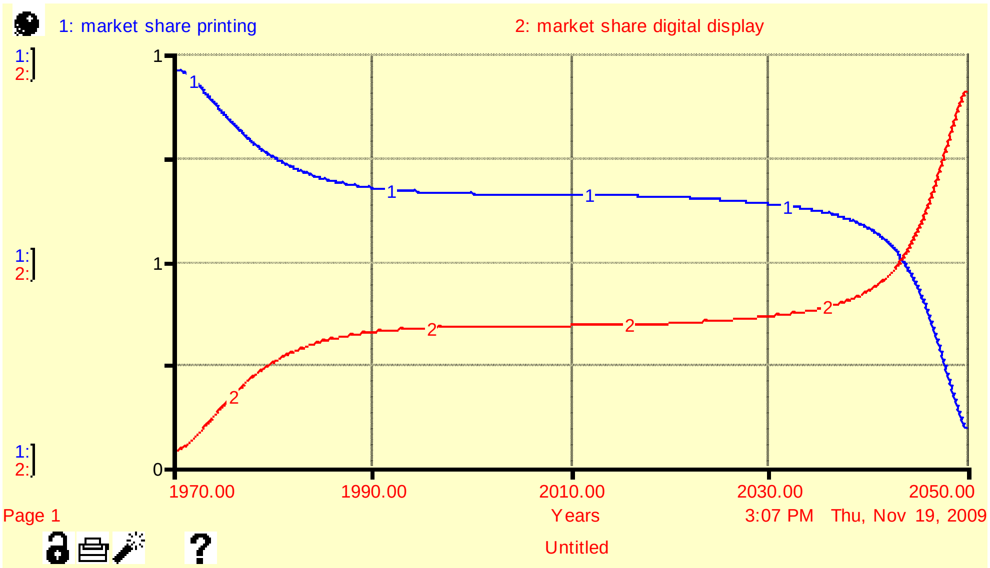
1: metric tons of paper
1: 2e+012.
1: 1e+012.
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
2:04 PM Thu, Nov 19, 2009
Untitled

Run 32:

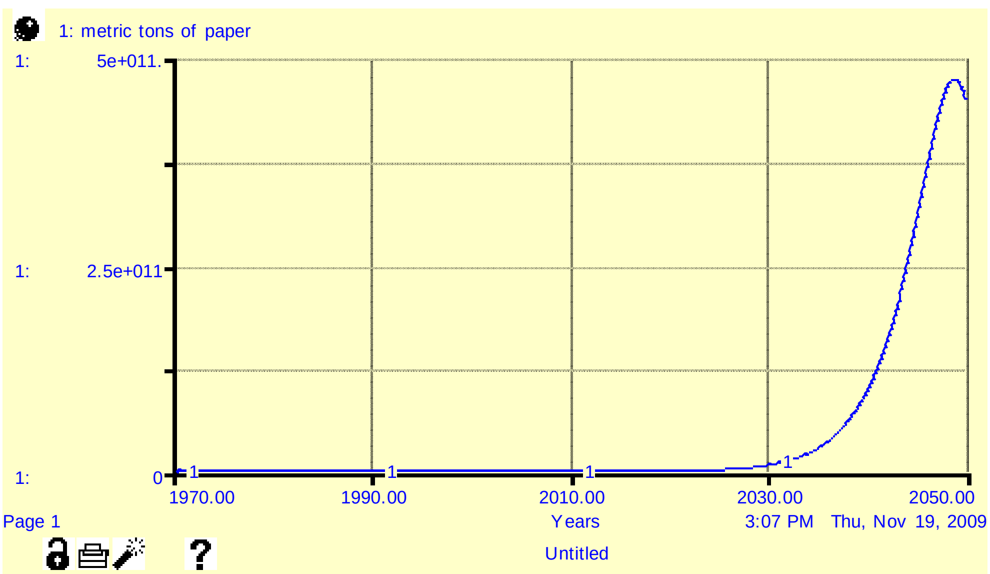

1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
2:07 PM Thu, Nov 19, 2009
Untitled


1: metric tons of paper
1: 2e+012.
1: 1e+012.
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
2:07 PM Thu, Nov 19, 2009
Untitled

Run 33:

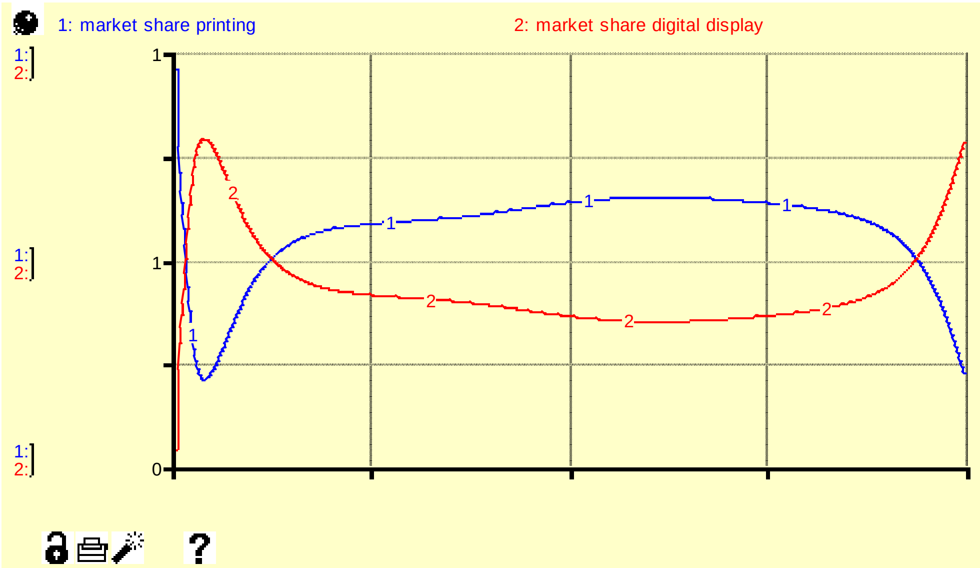


1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Years
Page 1
3:07 PM Thu, Nov 19, 2009
Untitled

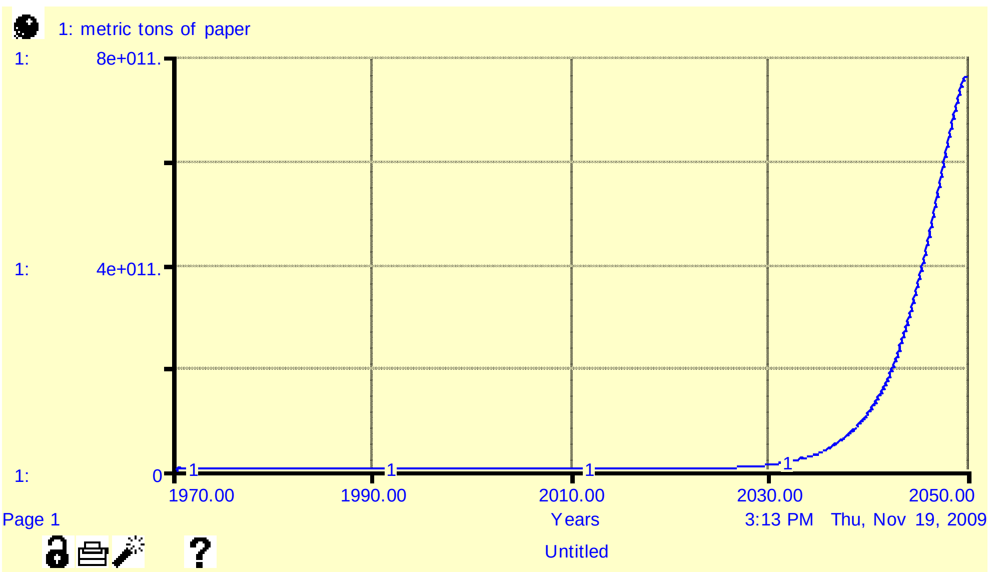


1: metric tons of paper
1: 5e+011.
1: 2.5e+011
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Years
Page 1
3:07 PM Thu, Nov 19, 2009
Untitled

Run 34:

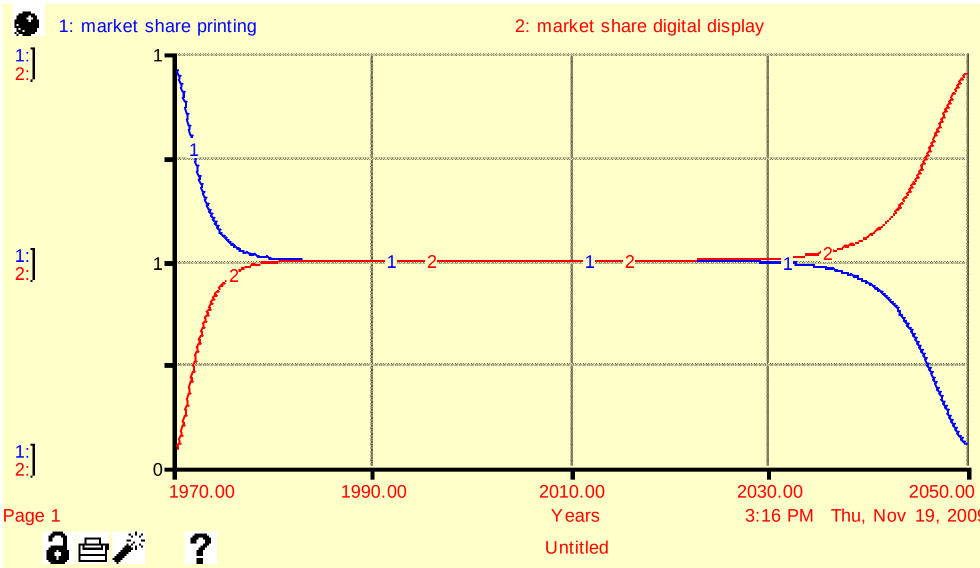


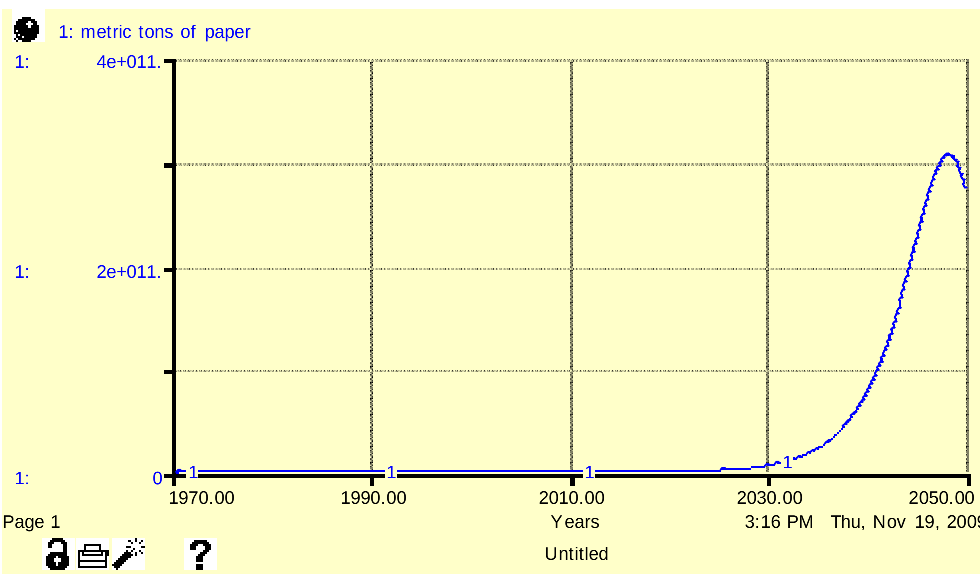
1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0



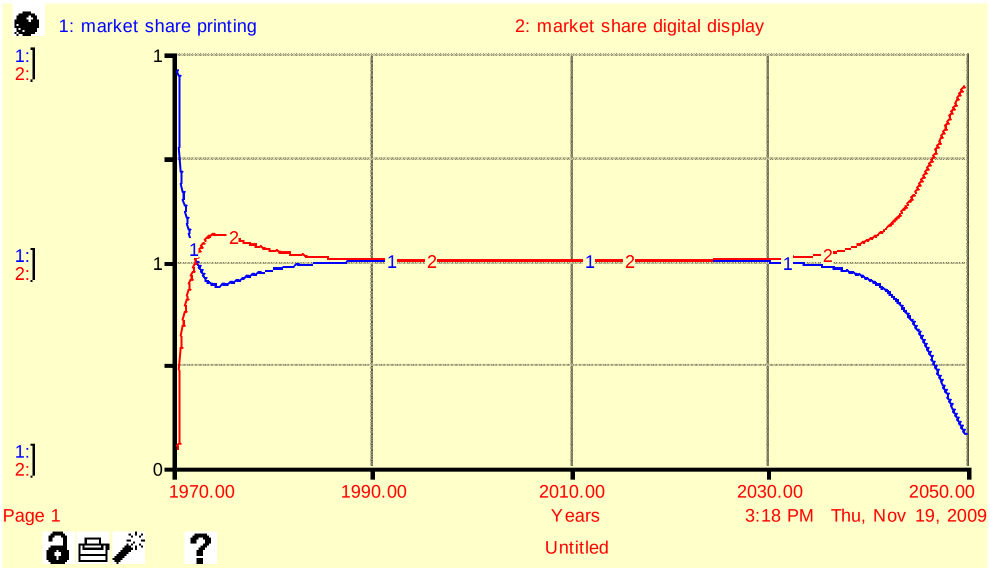
1: metric tons of paper
1:
8e+011.
1:
4e+011.
1:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
3:13 PM Thu, Nov 19, 2009
Untitled

Run 35:

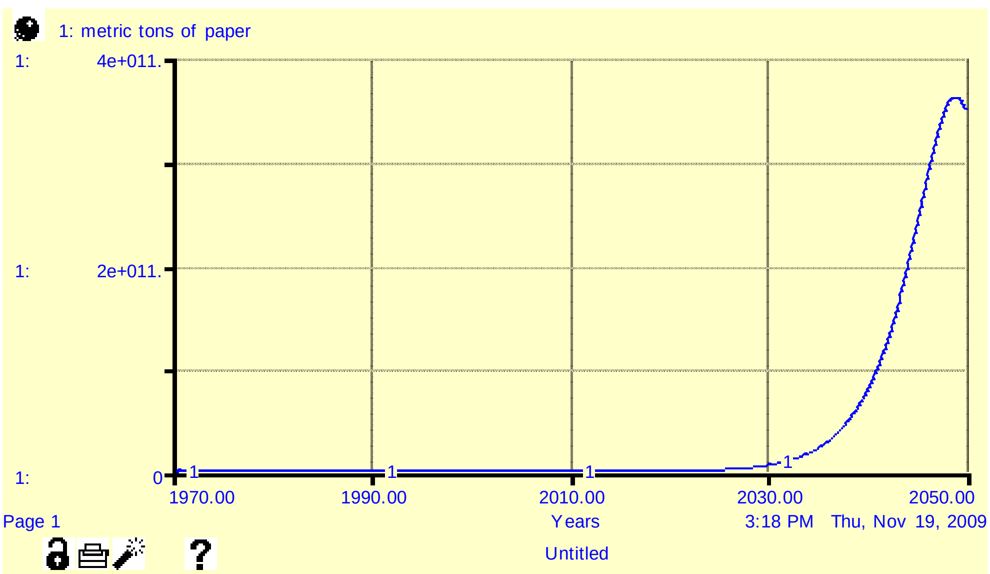

1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
3:16 PM Thu, Nov 19, 2009
Untitled


1: metric tons of paper
1: 4e+011.
1: 2e+011.
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
3:16 PM Thu, Nov 19, 2009
Untitled

Run 36:

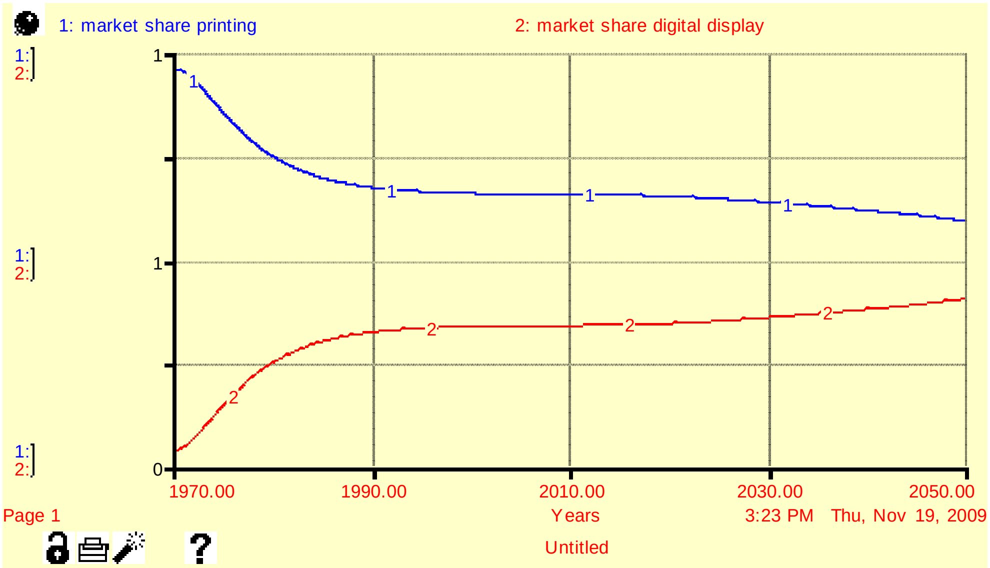


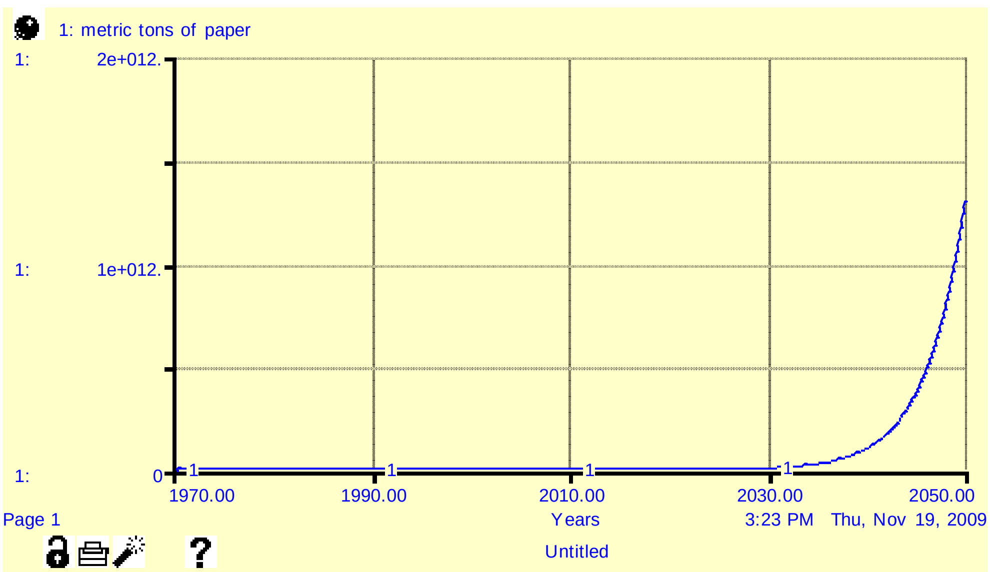
1: market share printing
2: market share digital display
1:
2:
1
1
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
3:18 PM Thu, Nov 19, 2009
Untitled



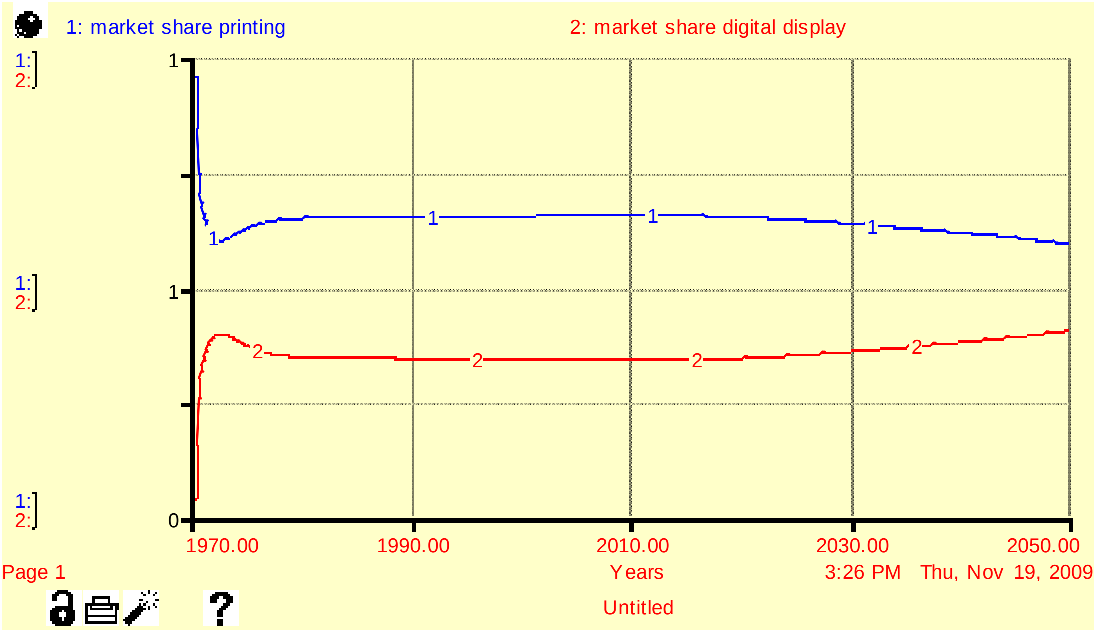
1: metric tons of paper
1: 4e+011.
1: 2e+011.
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
3:18 PM Thu, Nov 19, 2009
Untitled

Run 37:

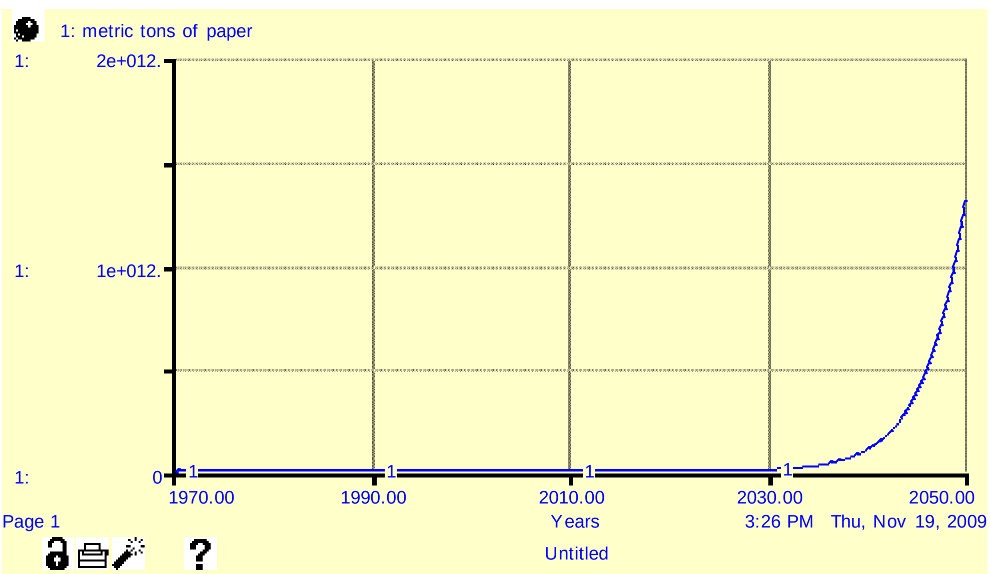

1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
3:23 PM Thu, Nov 19, 2009
Untitled


1: metric tons of paper
1: 2e+012.
1: 1e+012.
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
3:23 PM Thu, Nov 19, 2009
Untitled

Run 38:

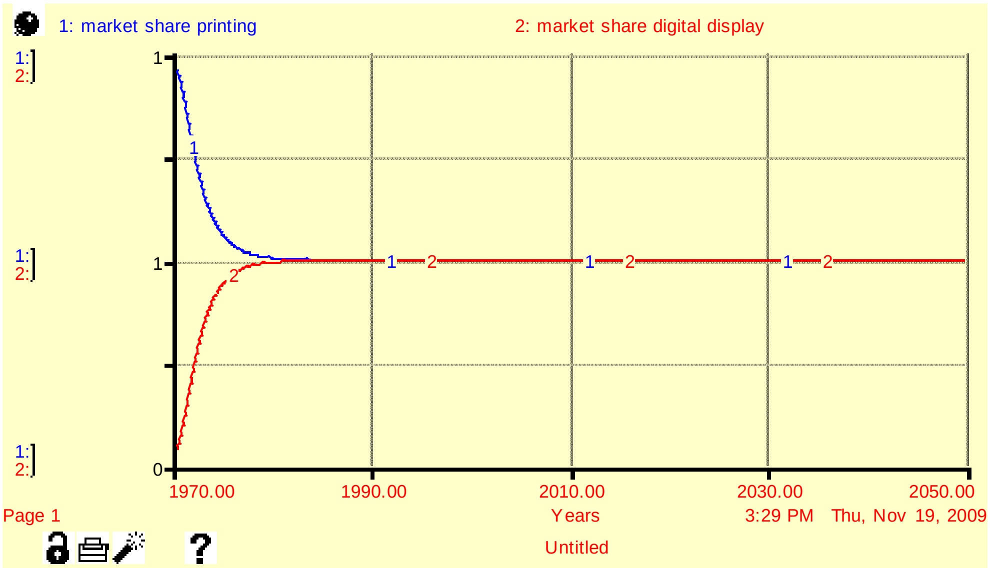


1: market share printing
2: market share digital display
1
1
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
3:26 PM Thu, Nov 19, 2009
Untitled

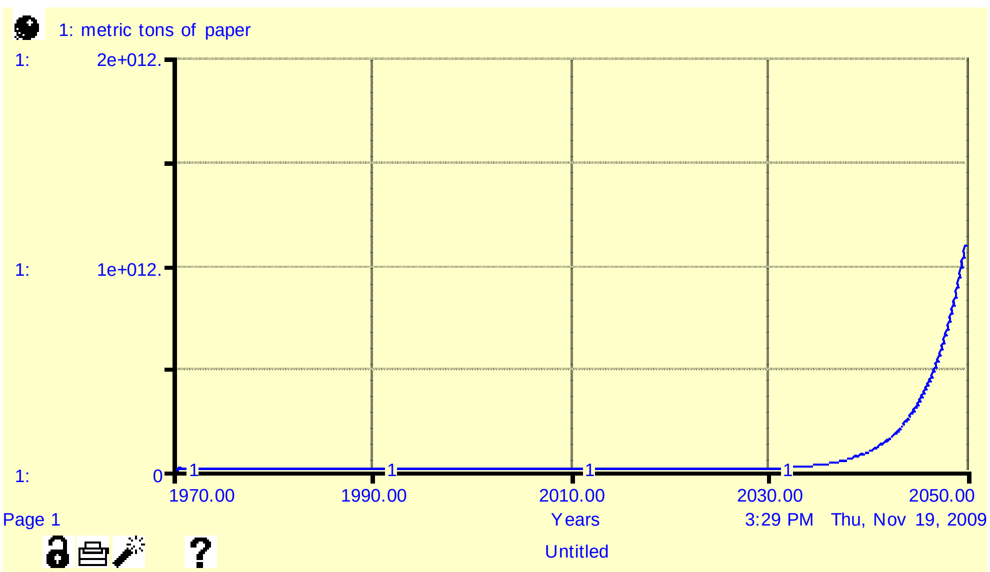


1: metric tons of paper
2e+012.
1e+012.
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
3:26 PM Thu, Nov 19, 2009
Untitled

Run 39:

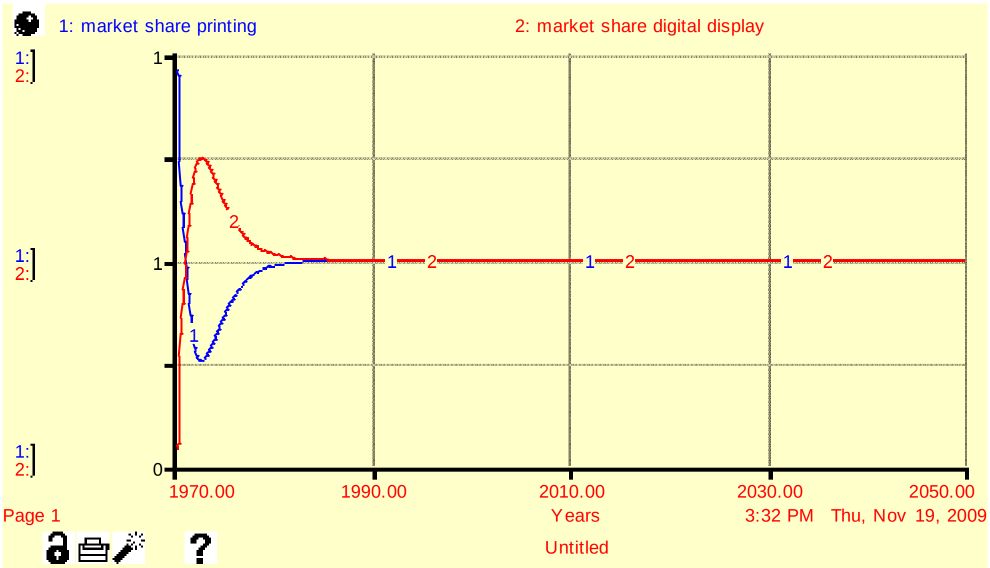


1: market share printing
2: market share digital display
1:
2:
1
1
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
3:29 PM Thu, Nov 19, 2009
Untitled

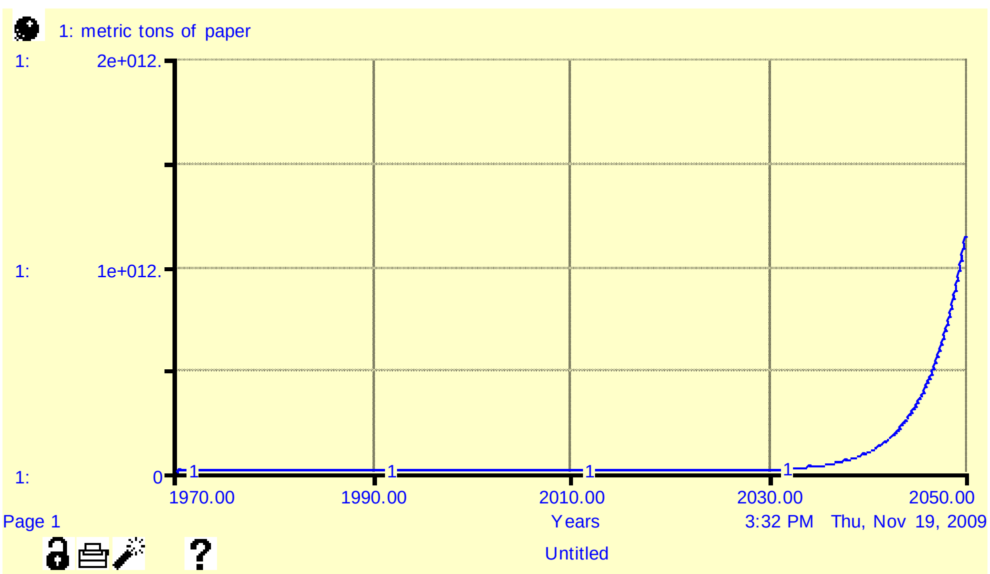


1: metric tons of paper
1: 2e+012.
1: 1e+012.
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
3:29 PM Thu, Nov 19, 2009
Untitled

Run 40:

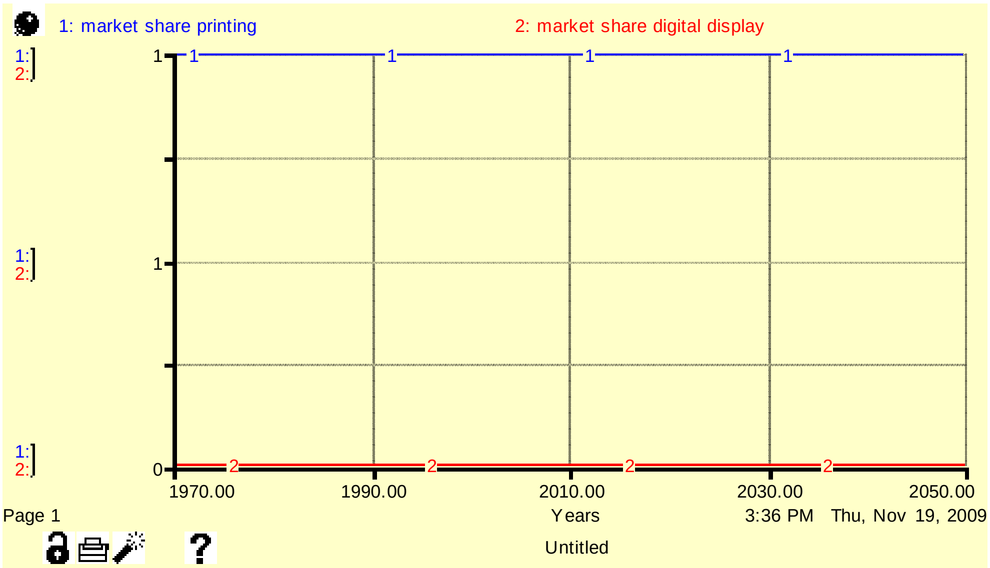


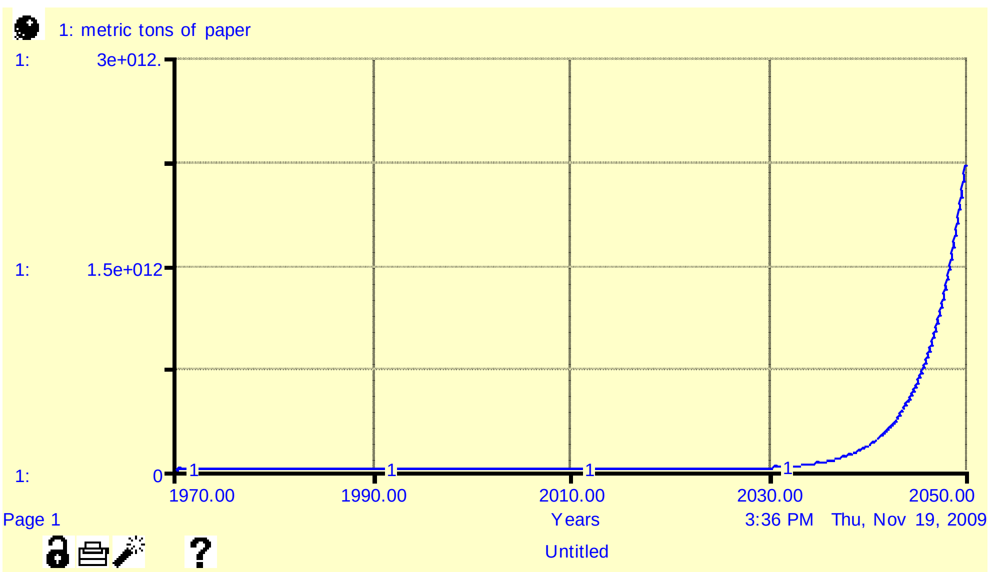
1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
3:32 PM Thu, Nov 19, 2009
Untitled



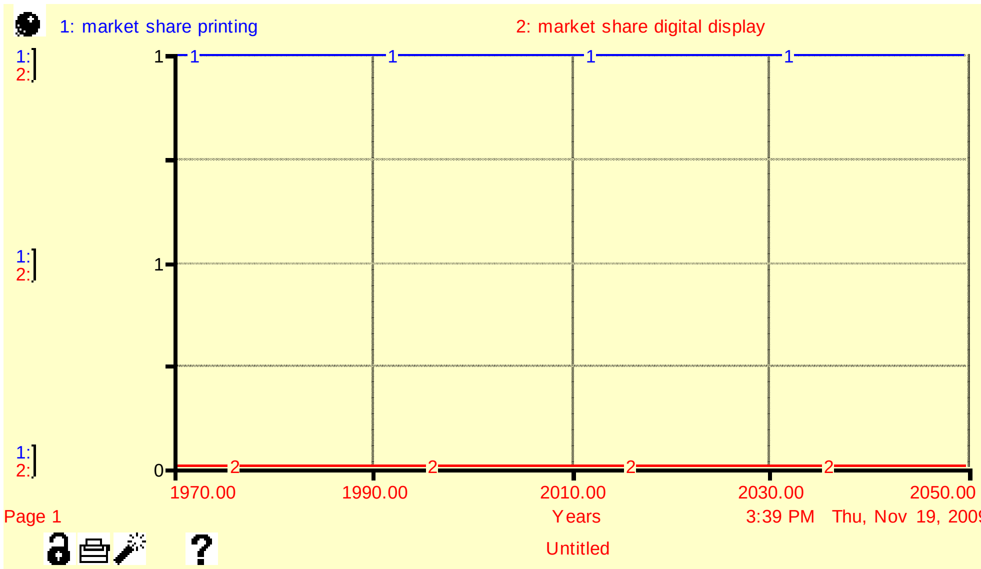
1: metric tons of paper
1: 2e+012.
1: 1e+012.
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
3:32 PM Thu, Nov 19, 2009
Untitled

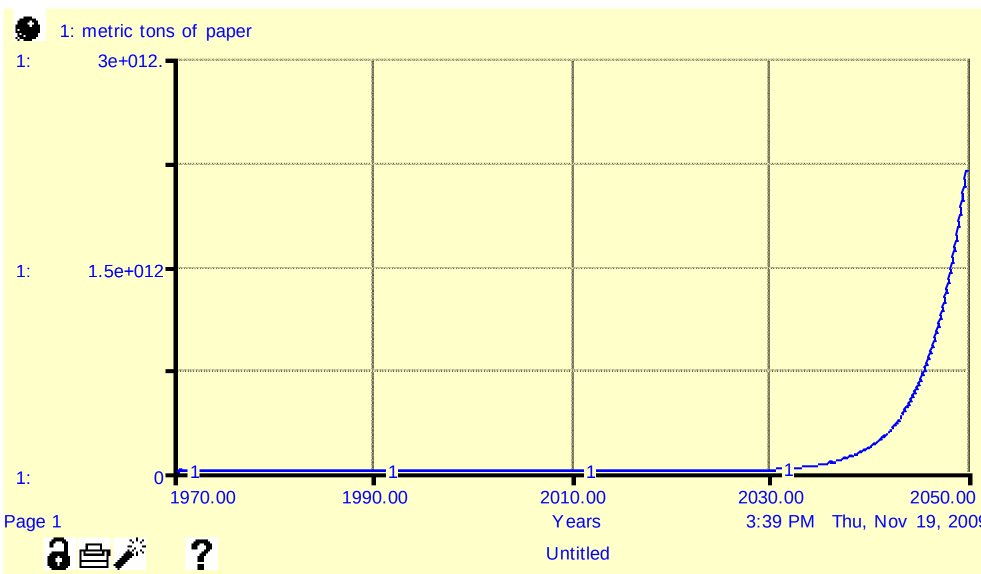
Run 41:


1: market share printing
2: market share digital display
1
1
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
3:36 PM Thu, Nov 19, 2009
Untitled

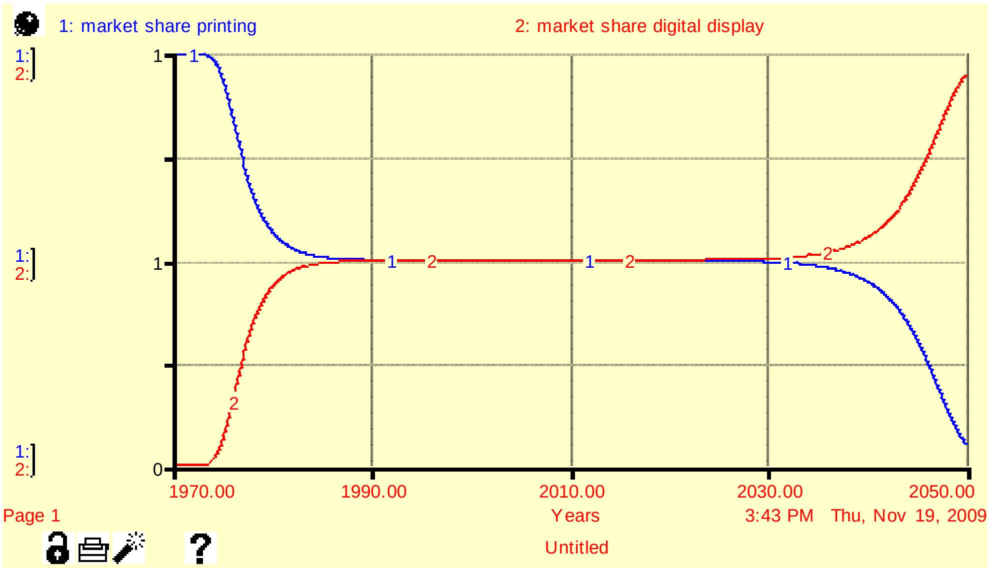

1: metric tons of paper
3e+012.
1.5e+012
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
3:36 PM Thu, Nov 19, 2009
Untitled

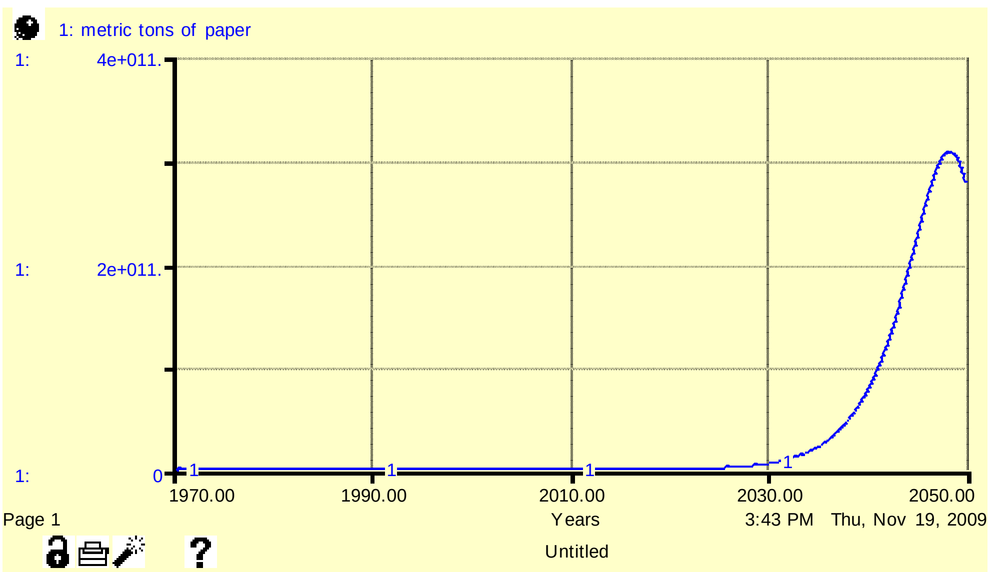
Run 42:


1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
3:39 PM Thu, Nov 19, 2009
Untitled

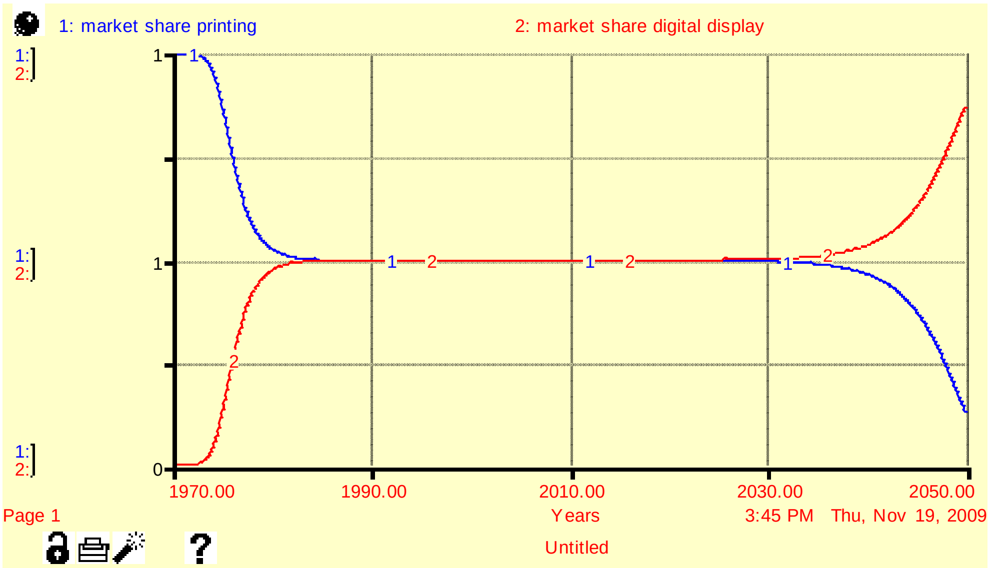

1: metric tons of paper
1: 3e+012.
1: 1.5e+012
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
3:39 PM Thu, Nov 19, 2009
Untitled

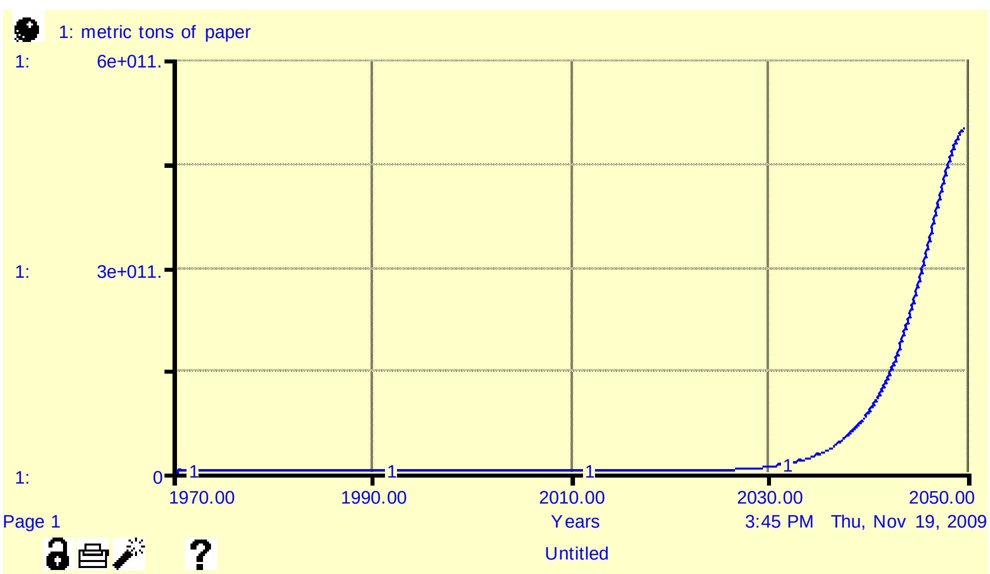
Run 43:


1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
3:43 PM Thu, Nov 19, 2009
Untitled

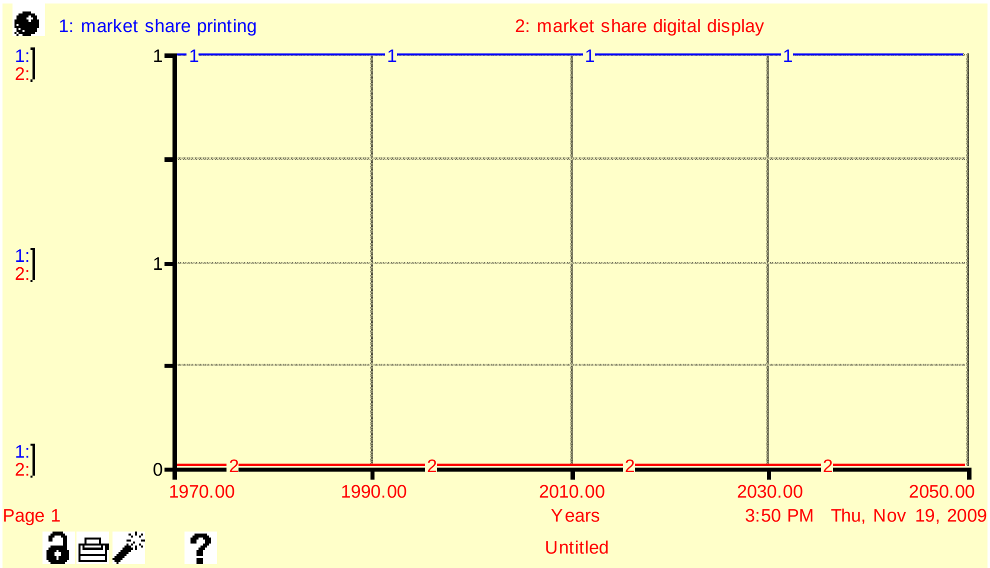

1: metric tons of paper
1: 4e+011.
1: 2e+011.
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
3:43 PM Thu, Nov 19, 2009
Untitled

Run 44:

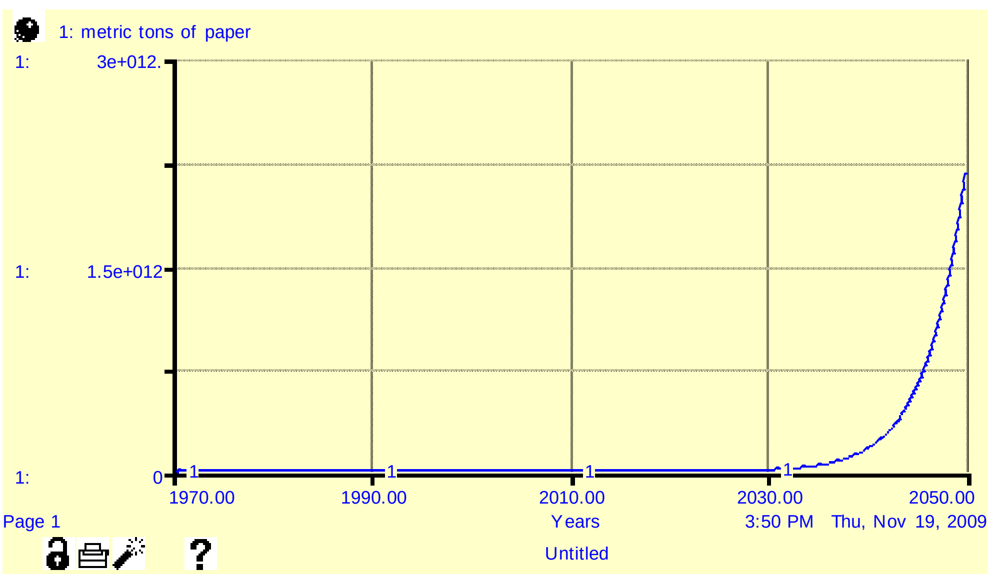

1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
3:45 PM Thu, Nov 19, 2009
Untitled


1: metric tons of paper
1: 6e+011.
1: 3e+011.
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
3:45 PM Thu, Nov 19, 2009
Untitled

Run 45:

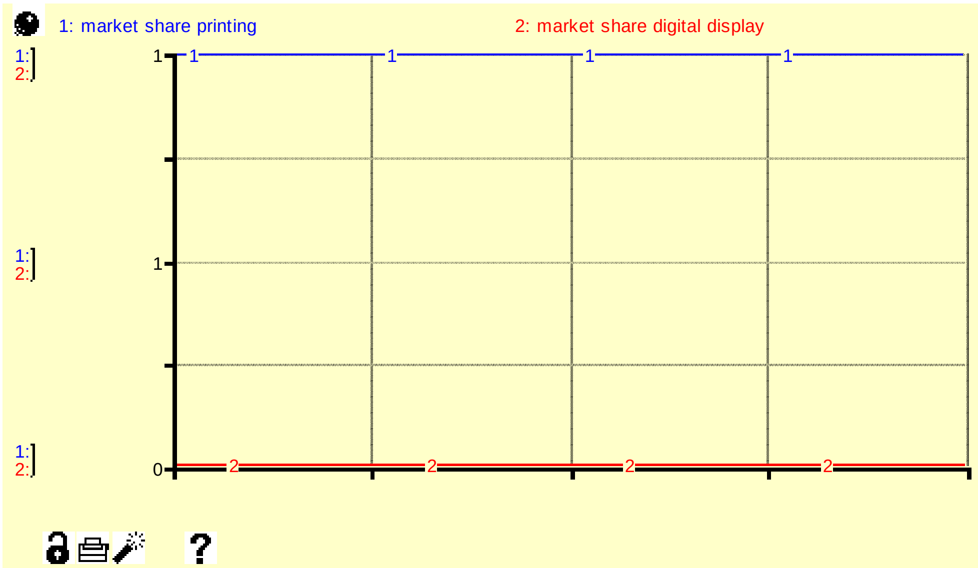


1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
3:50 PM Thu, Nov 19, 2009
Untitled

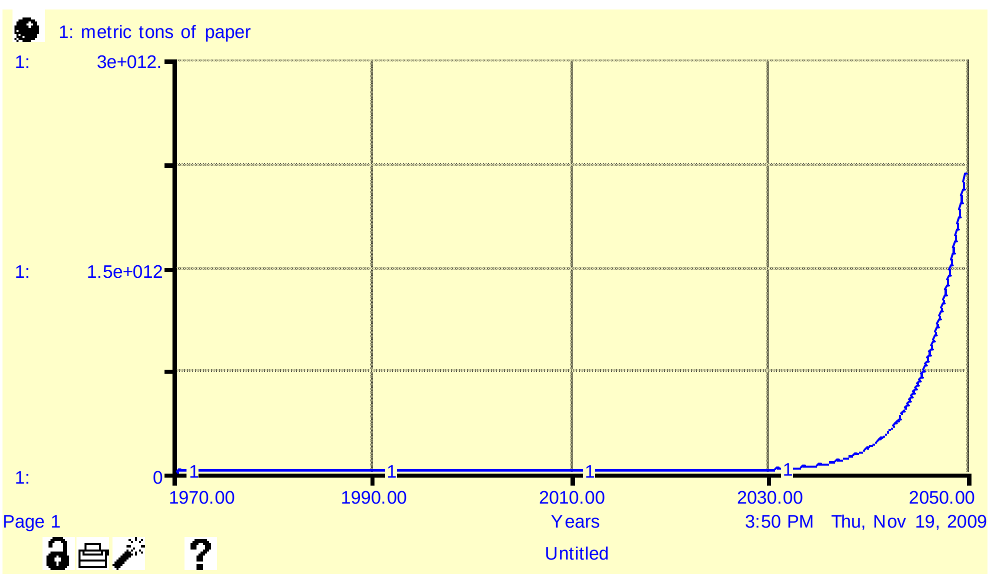


1: metric tons of paper
1: 3e+012.
1: 1.5e+012
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
3:50 PM Thu, Nov 19, 2009
Untitled

Run 46:

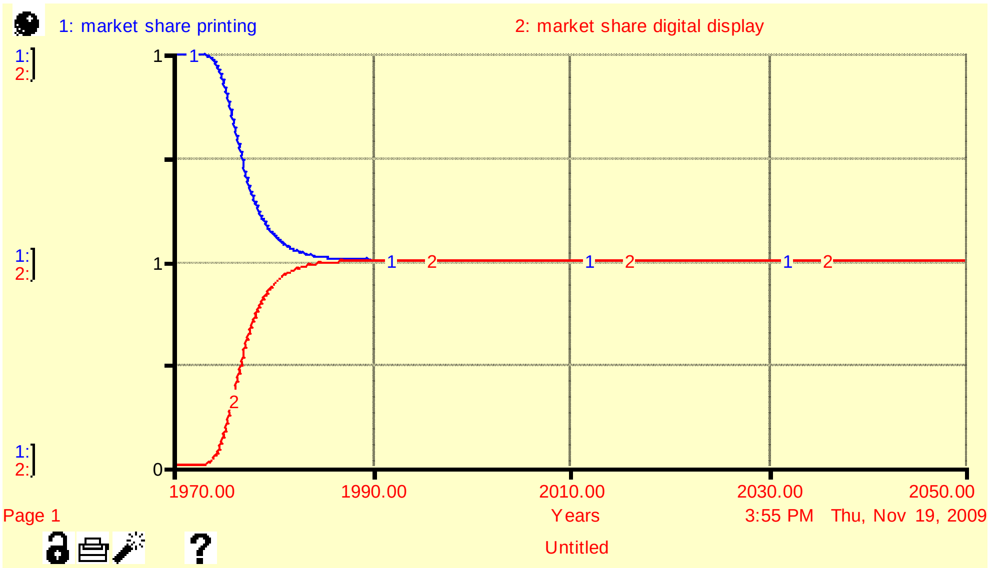


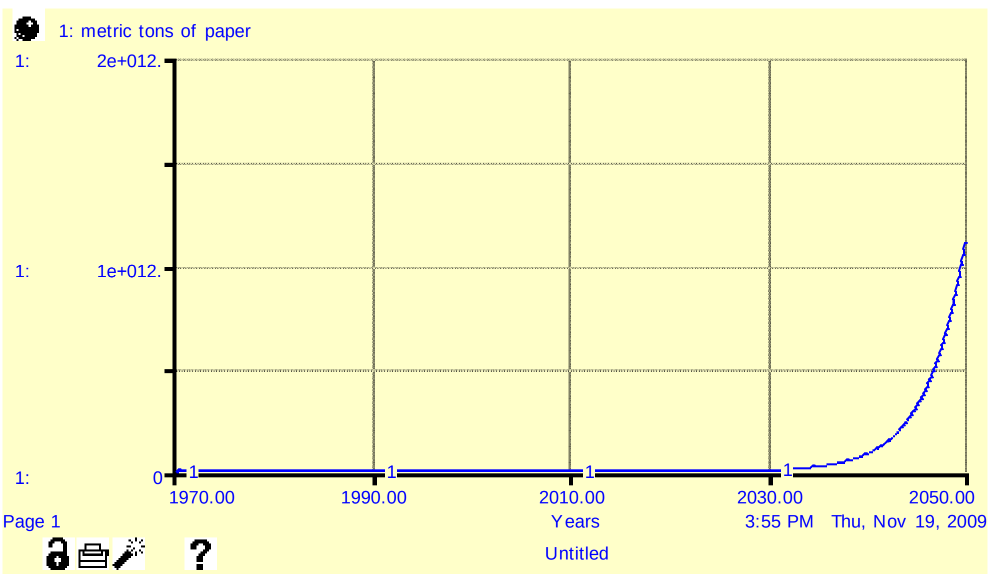
1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0



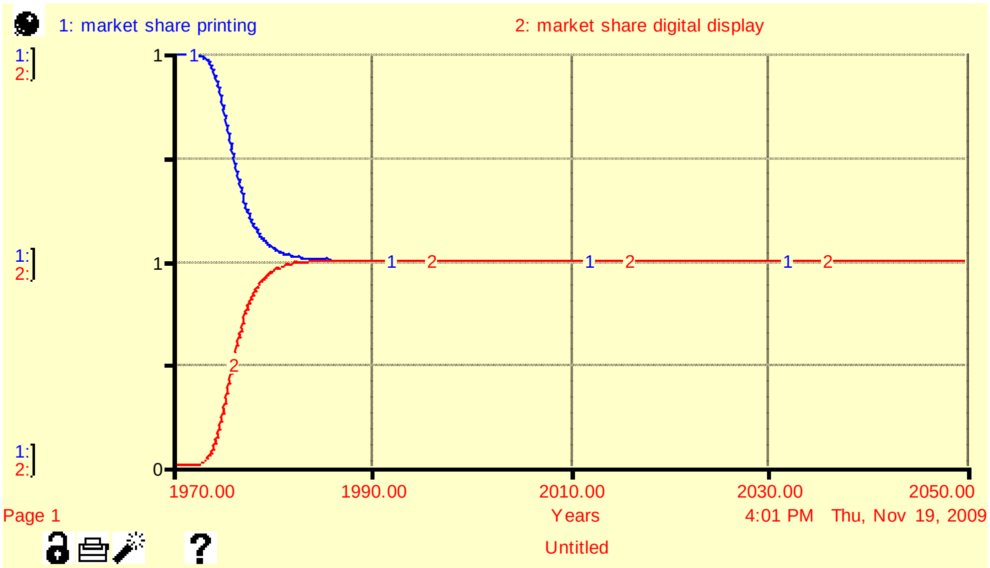
1: metric tons of paper
1: 3e+012.
1: 1.5e+012
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
3:50 PM Thu, Nov 19, 2009
Untitled

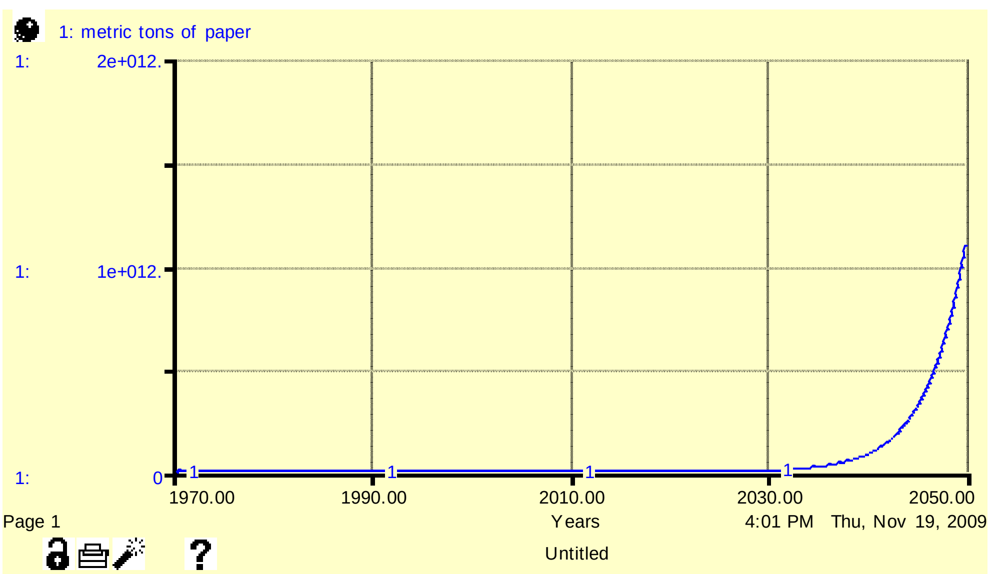
Run 47:


1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
3:55 PM Thu, Nov 19, 2009
Untitled

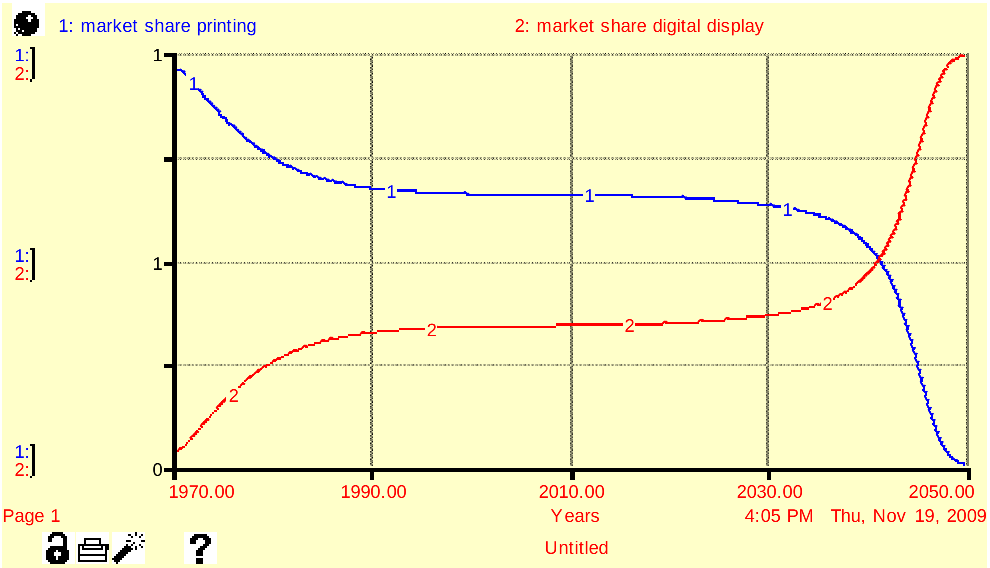

1: metric tons of paper
1: 2e+012.
1: 1e+012.
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
3:55 PM Thu, Nov 19, 2009
Untitled

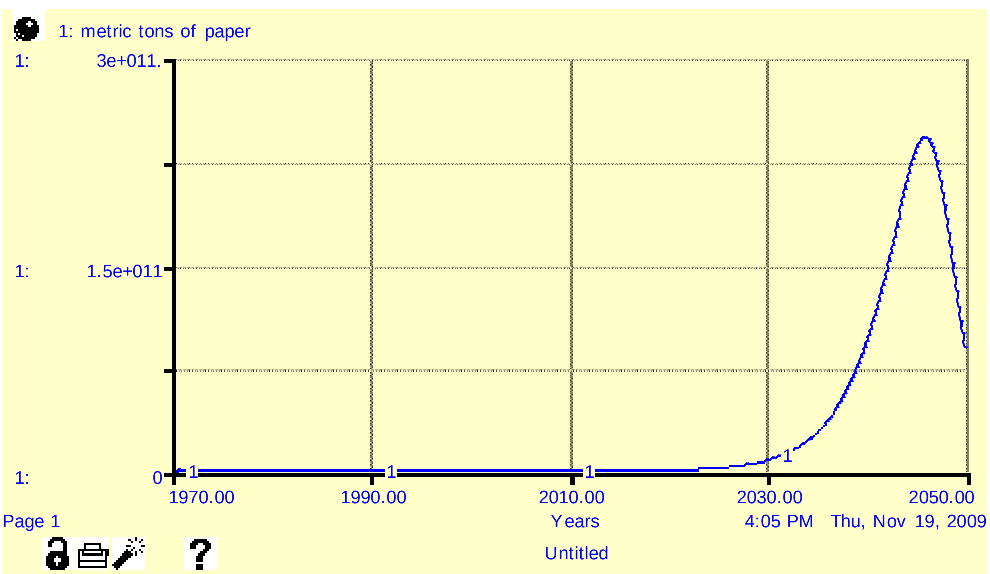
Run 48:


1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:01 PM Thu, Nov 19, 2009
Untitled

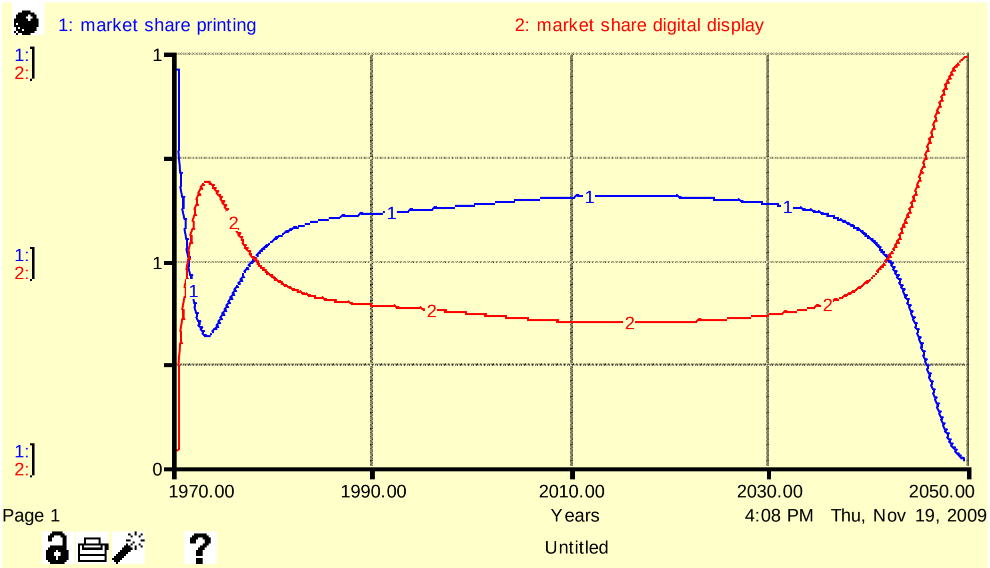

1: metric tons of paper
1: 2e+012.
1: 1e+012.
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:01 PM Thu, Nov 19, 2009
Untitled

Run 49:

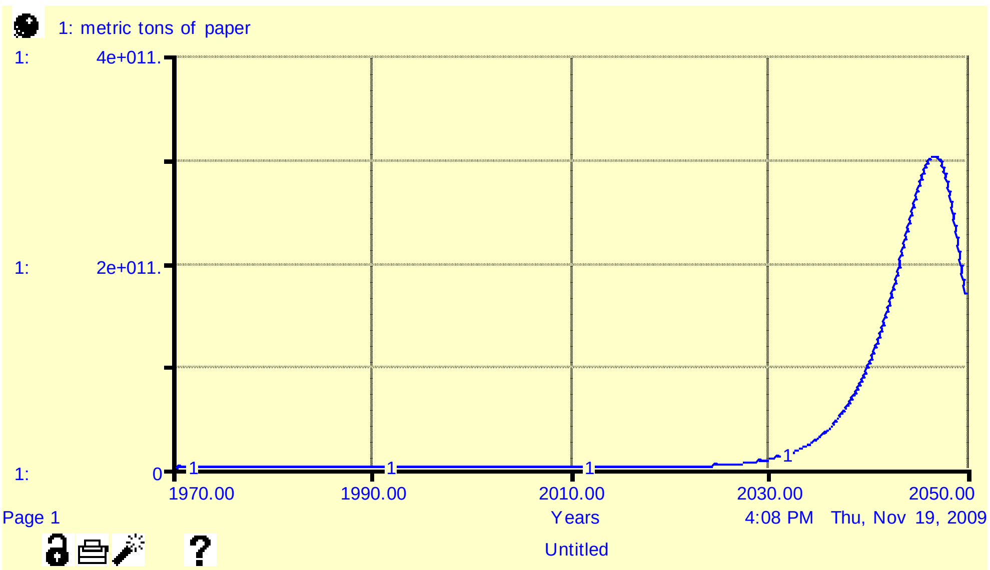

1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:05 PM Thu, Nov 19, 2009
Untitled


1: metric tons of paper
1: 3e+011.
1: 1.5e+011
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:05 PM Thu, Nov 19, 2009
Untitled

Run 50:

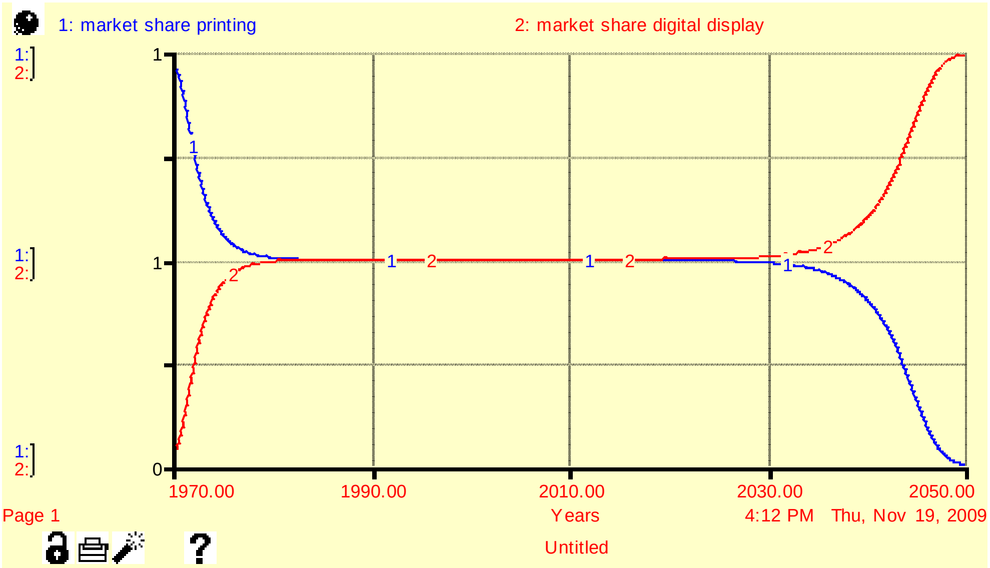


1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:08 PM Thu, Nov 19, 2009
Untitled

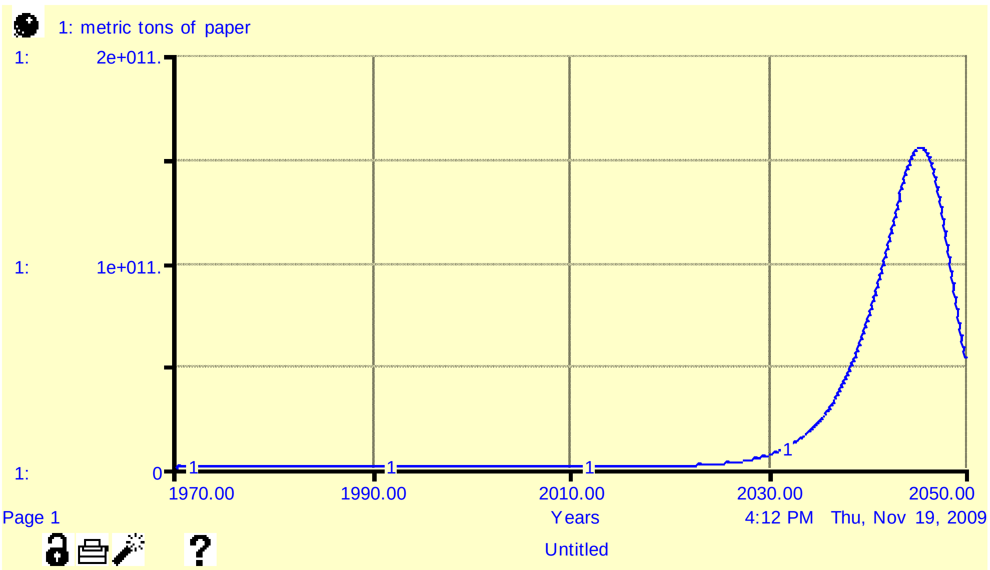


1: metric tons of paper
1: 4e+011.
1: 2e+011.
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:08 PM Thu, Nov 19, 2009
Untitled

Run 51:

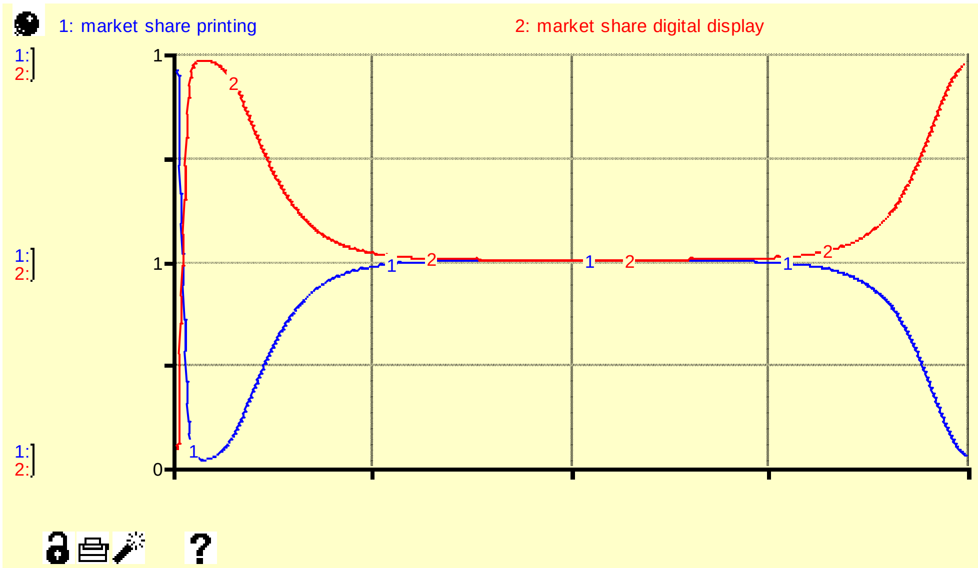


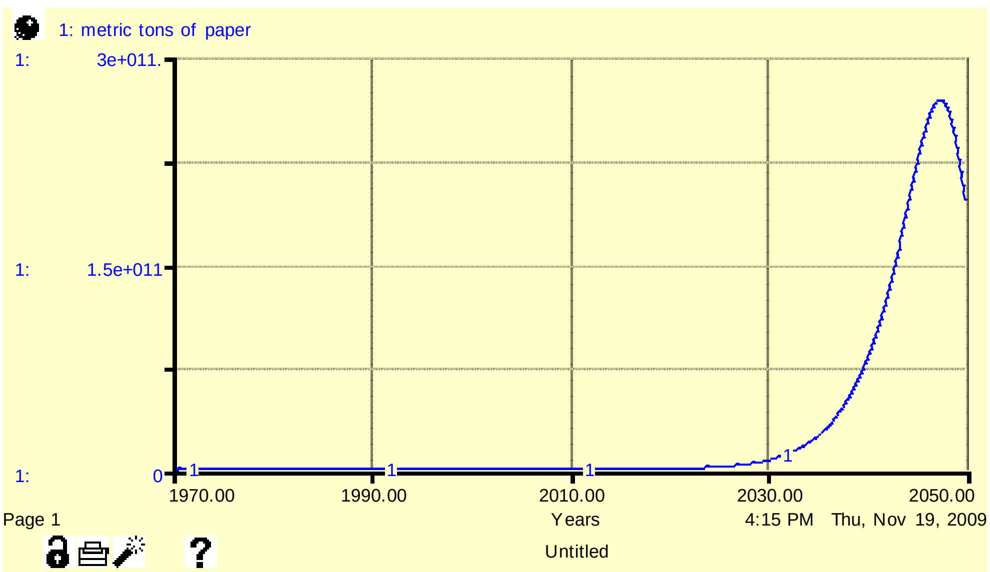
1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:12 PM Thu, Nov 19, 2009
Untitled



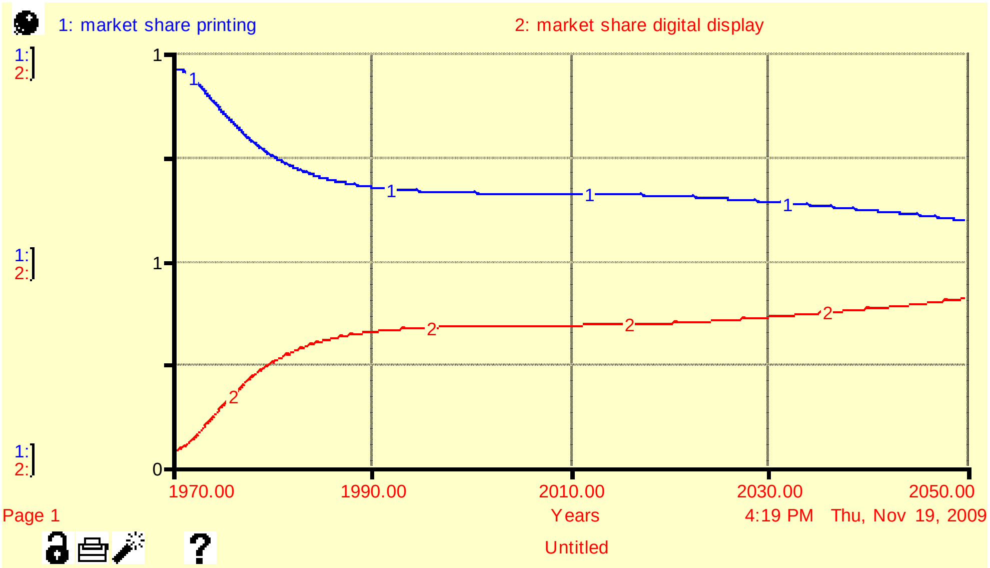
1: metric tons of paper
1: 2e+011.
1: 1e+011.
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:12 PM Thu, Nov 19, 2009
Untitled

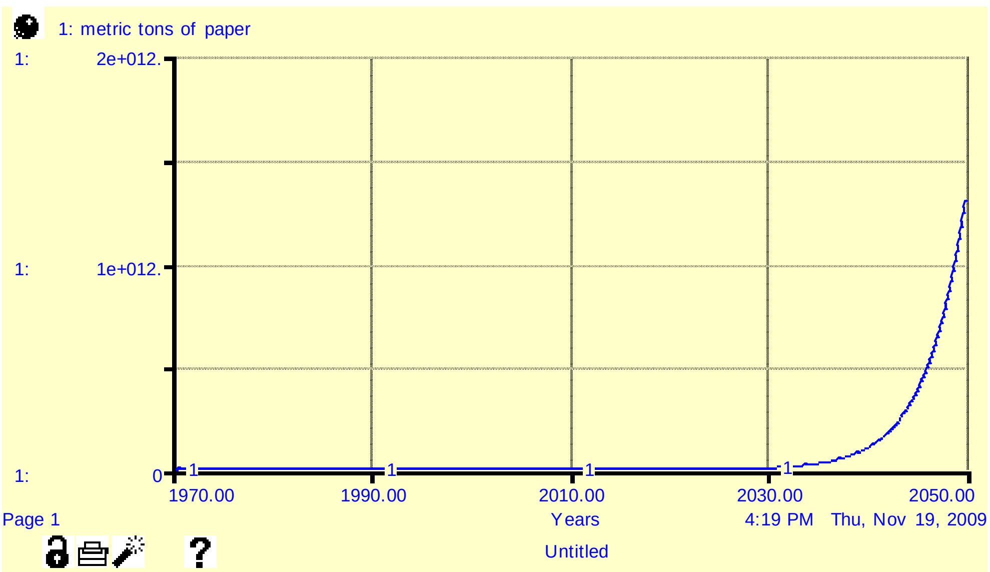
Run 52:


1: market share printing
2: market share digital display
1
1
0

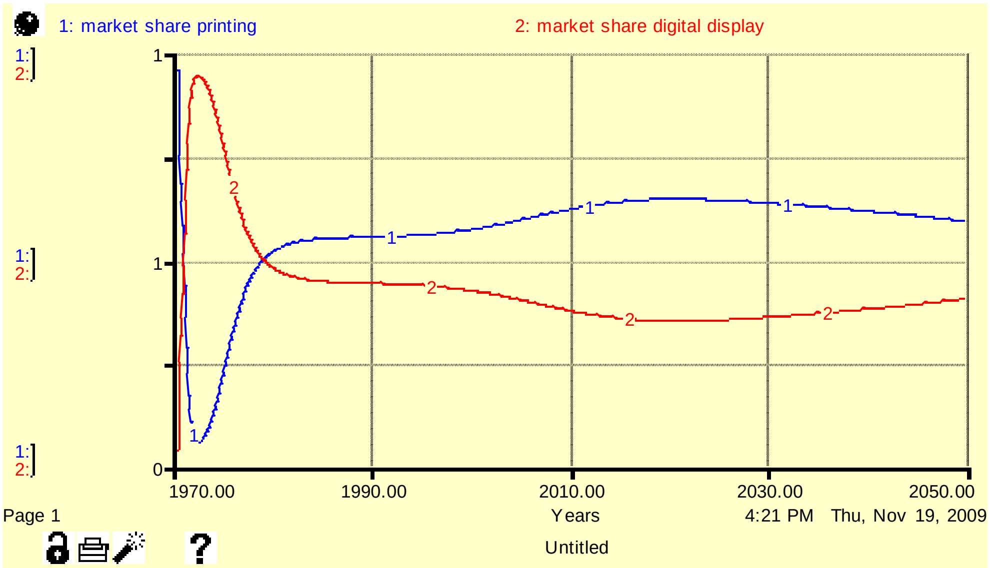

1: metric tons of paper
3e+011
1.5e+011
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:15 PM Thu, Nov 19, 2009
Untitled

Run 53:

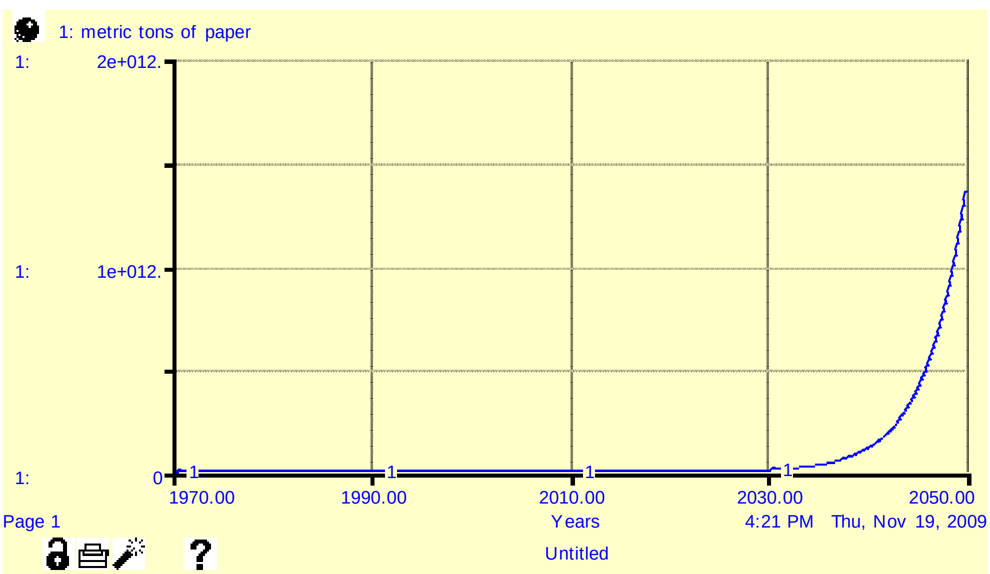

1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:19 PM Thu, Nov 19, 2009
Untitled


1: metric tons of paper
1: 2e+012.
1: 1e+012.
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:19 PM Thu, Nov 19, 2009
Untitled

Run 54:

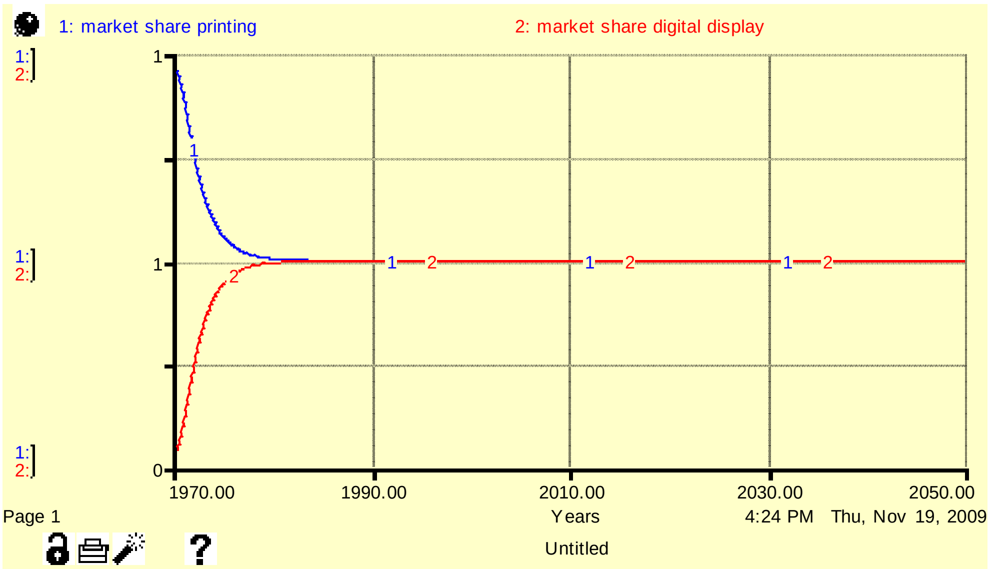


1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:21 PM Thu, Nov 19, 2009
Untitled

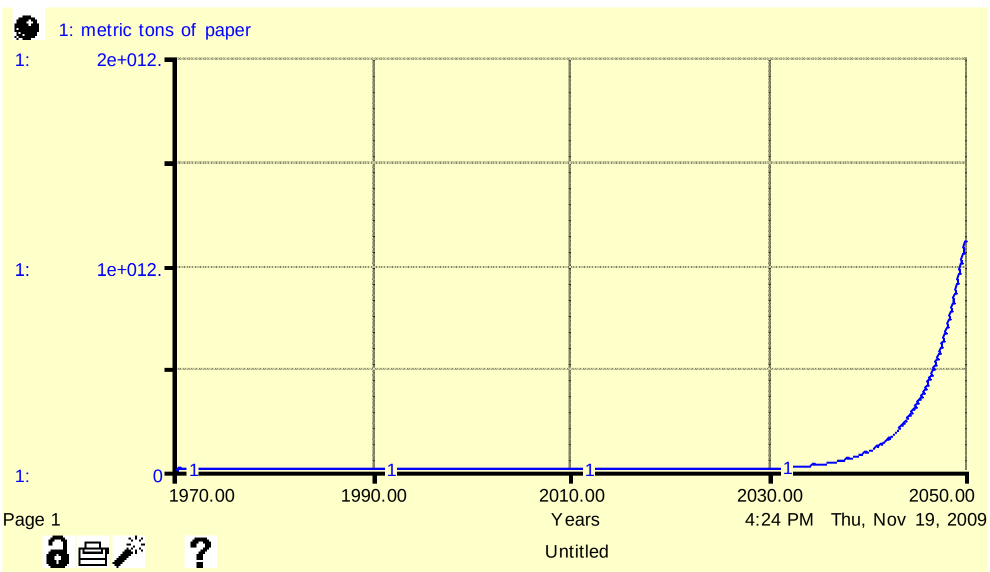


1: metric tons of paper
1: 2e+012.
1: 1e+012.
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:21 PM Thu, Nov 19, 2009
Untitled

Run 55:

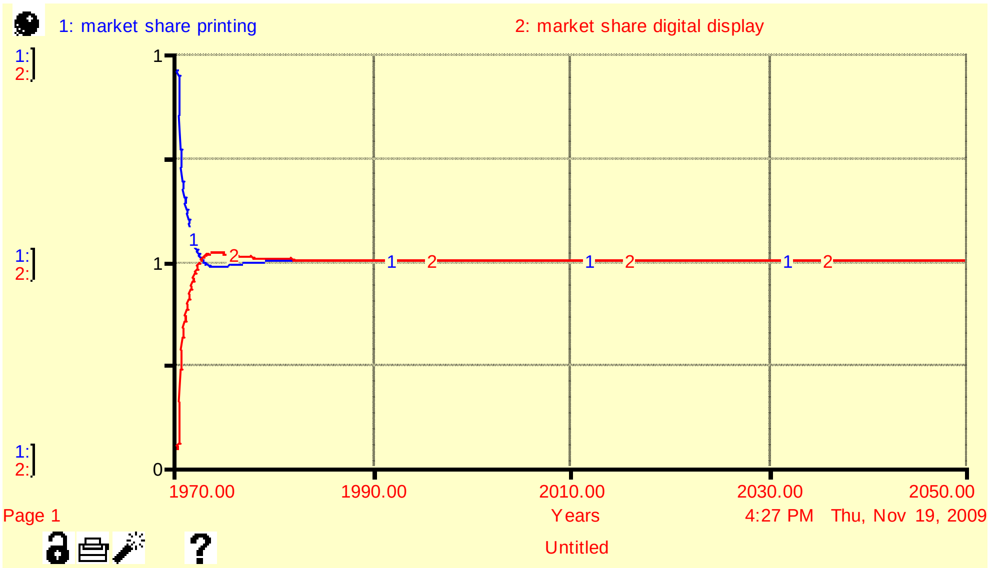


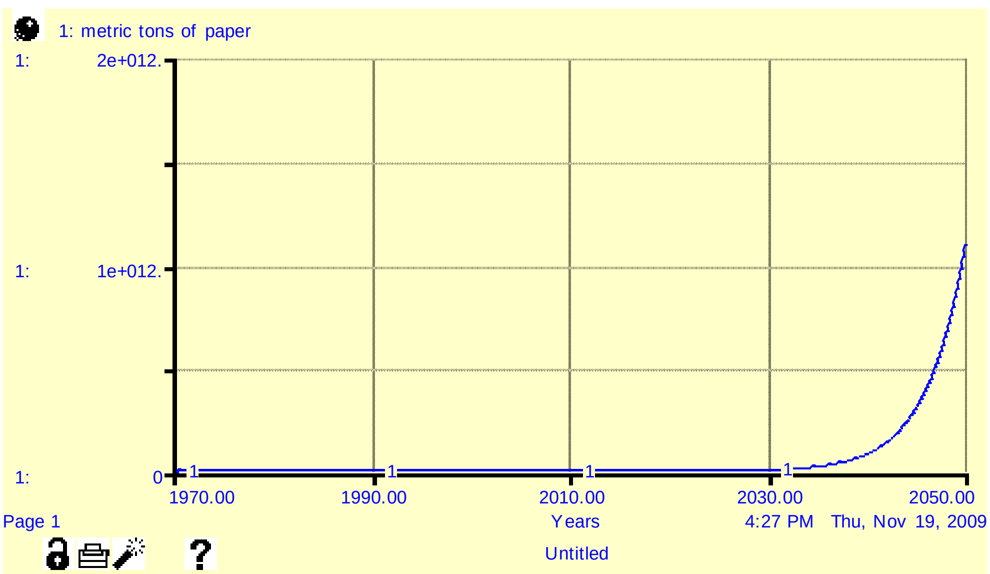
1: market share printing
2: market share digital display
1
1
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:24 PM Thu, Nov 19, 2009
Untitled



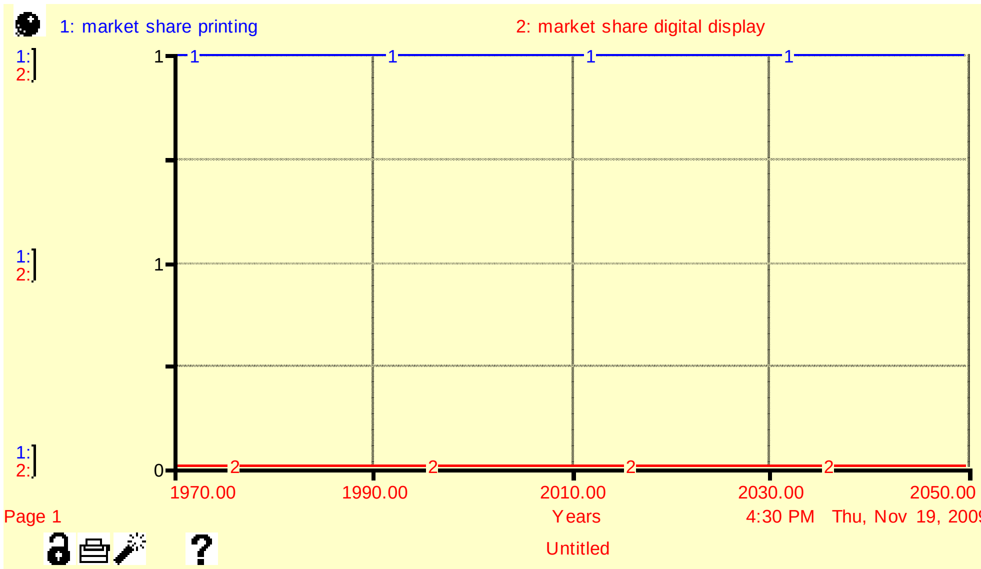
1: metric tons of paper
2e+012.
1e+012.
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:24 PM Thu, Nov 19, 2009
Untitled

Run 56:

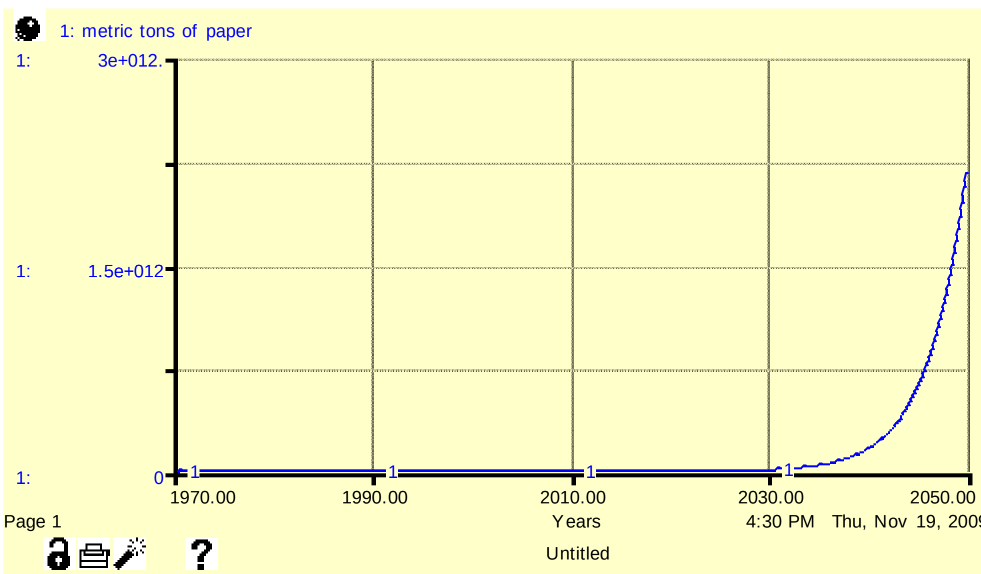

1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:27 PM Thu, Nov 19, 2009
Untitled


1: metric tons of paper
1:
2e+012.
1:
1e+012.
1:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:27 PM Thu, Nov 19, 2009
Untitled

Run 57:

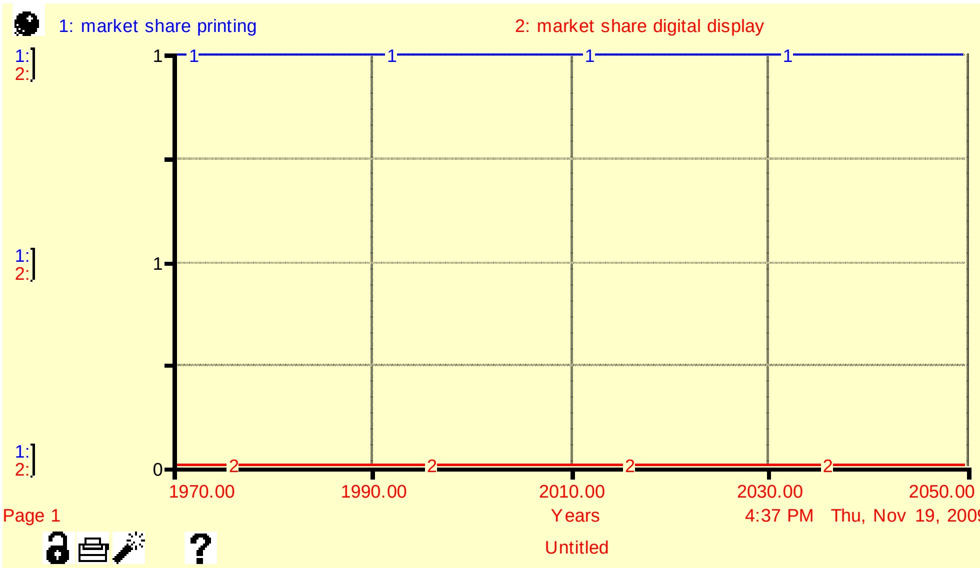


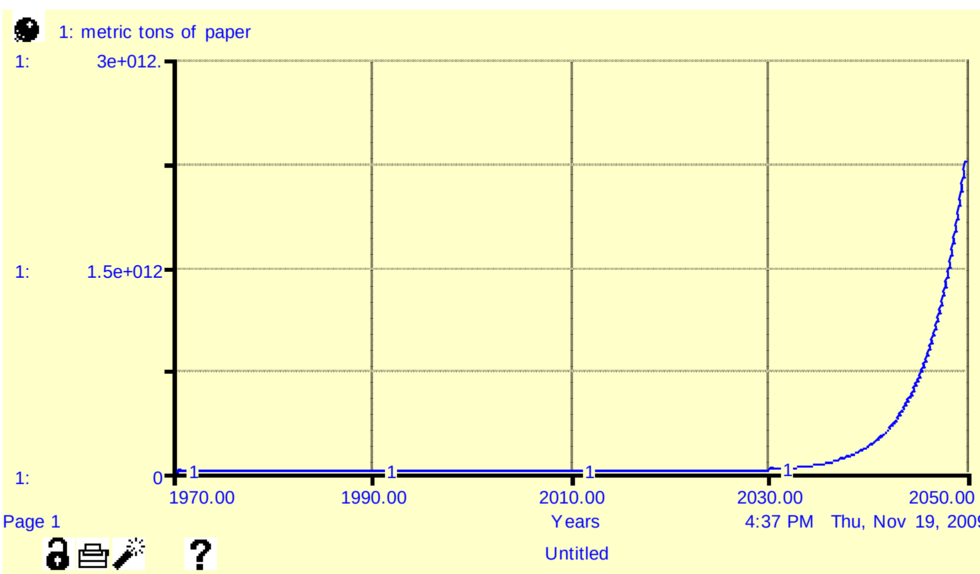
1: market share printing
2: market share digital display
1:
2:
1
1
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:30 PM Thu, Nov 19, 2009
Untitled



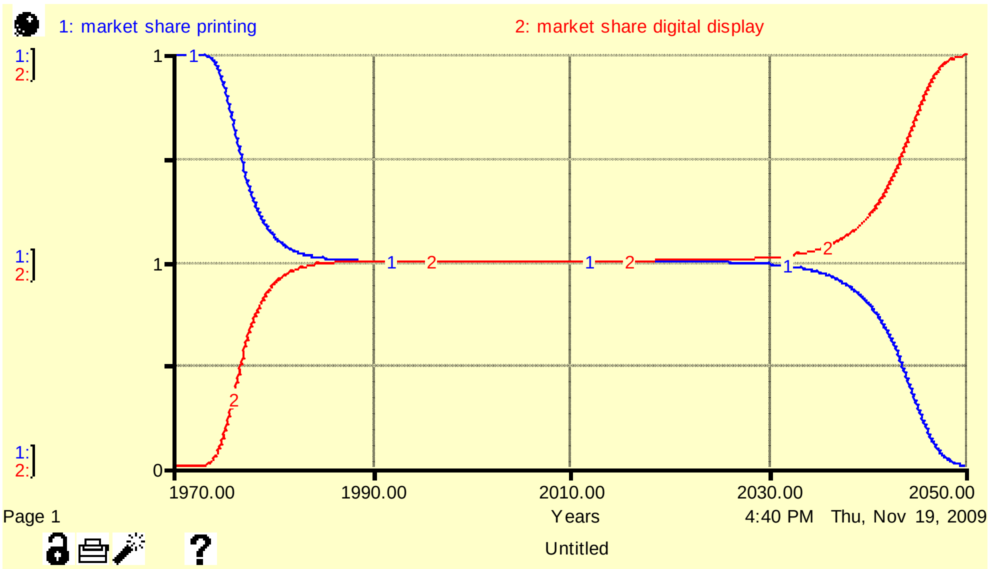
1: metric tons of paper
1: 3e+012.
1: 1.5e+012
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:30 PM Thu, Nov 19, 2009
Untitled

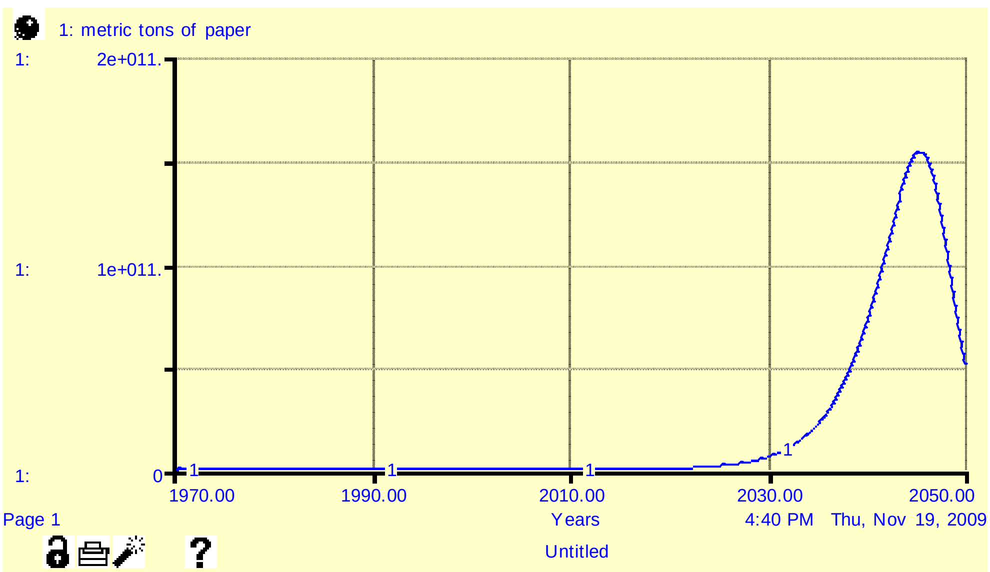
Run 58:


1: market share printing
2: market share digital display
1
1
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:37 PM Thu, Nov 19, 2009
Untitled

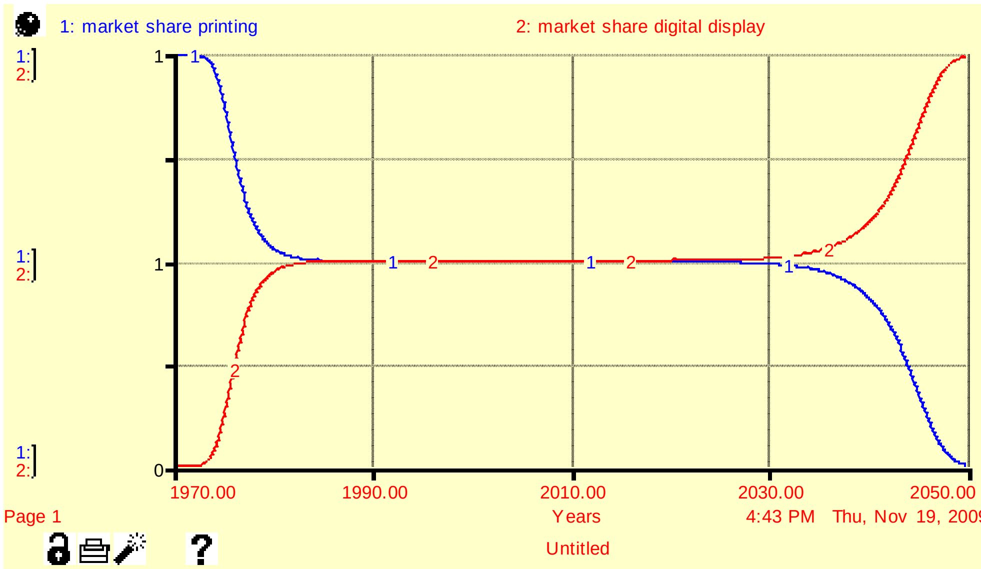

1: metric tons of paper
3e+012.
1.5e+012
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:37 PM Thu, Nov 19, 2009
Untitled

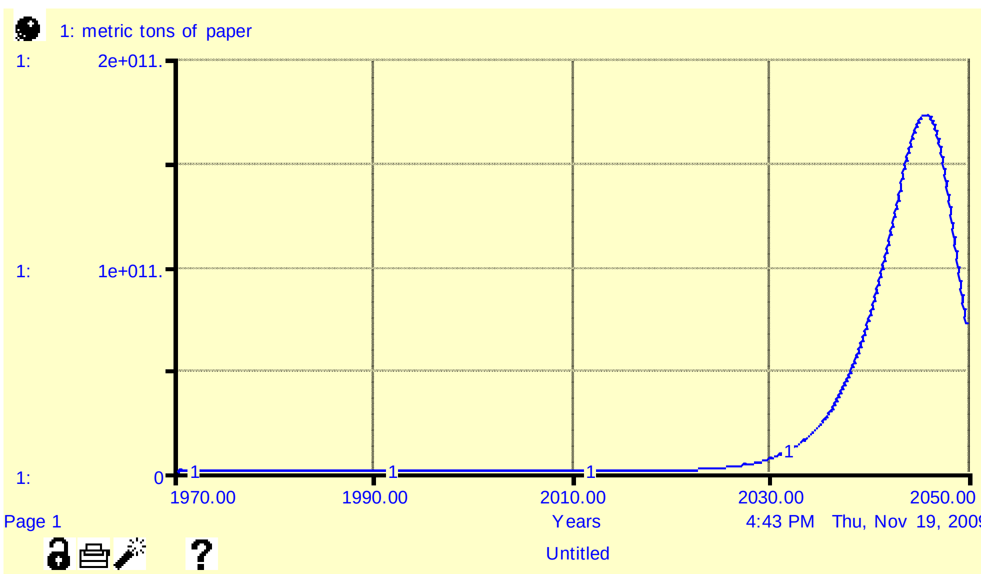
Run 59:


1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:40 PM Thu, Nov 19, 2009
Untitled

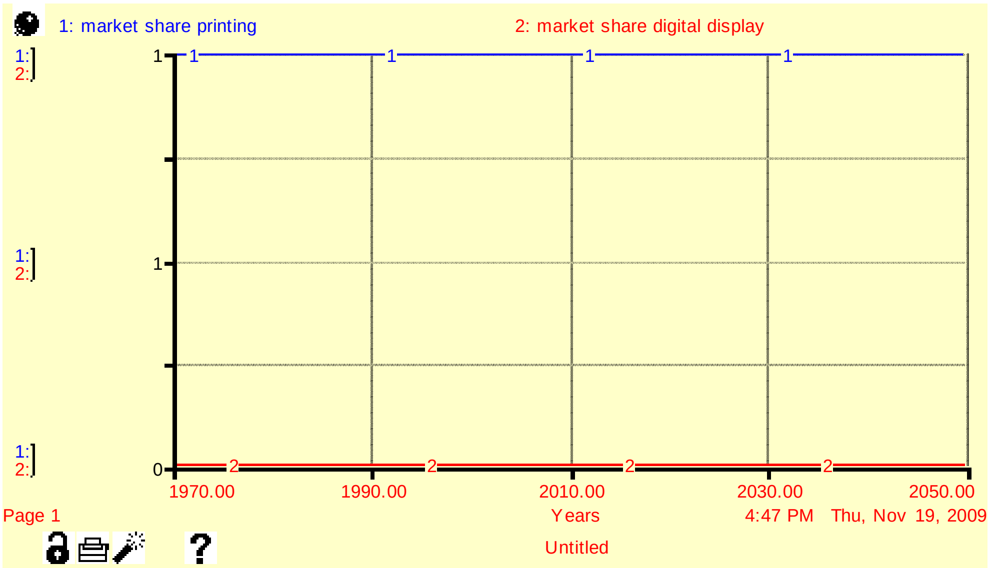

1: metric tons of paper
1: 2e+011.
1: 1e+011.
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:40 PM Thu, Nov 19, 2009
Untitled

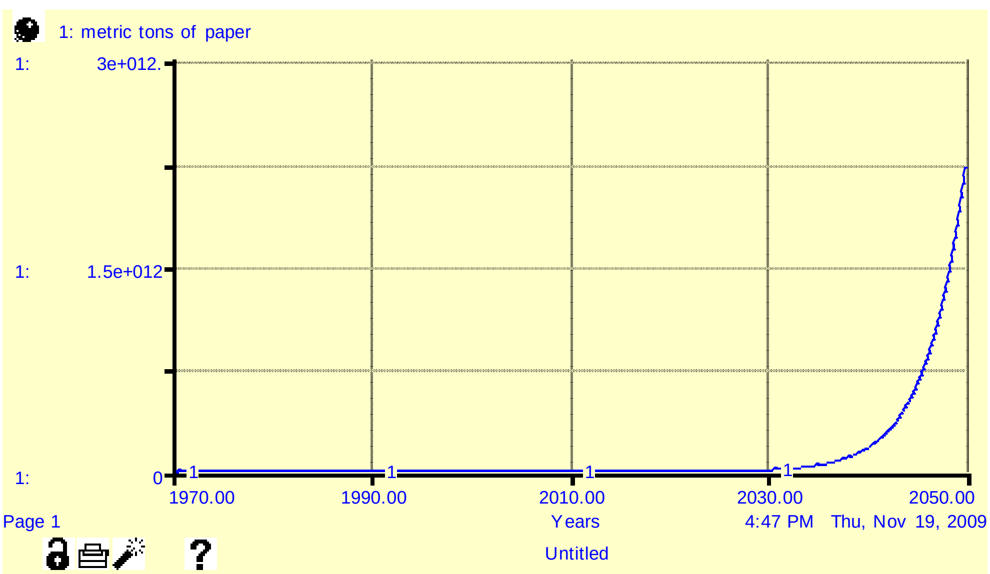
Run 60:


1: market share printing
2: market share digital display
1:
2:
1
1
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:43 PM Thu, Nov 19, 2009
Untitled

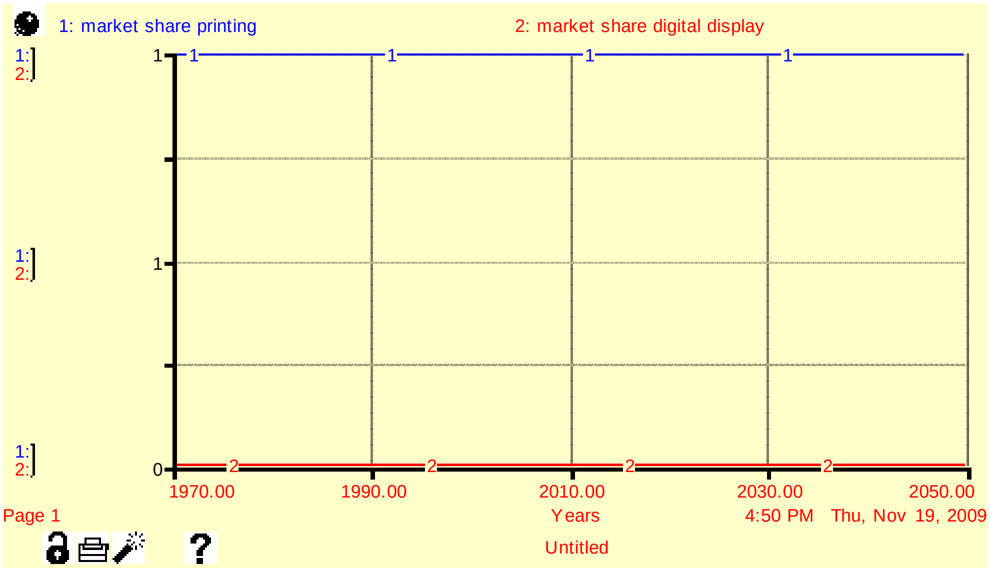

1: metric tons of paper
2e+011.
1e+011.
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:43 PM Thu, Nov 19, 2009
Untitled

Run 61:

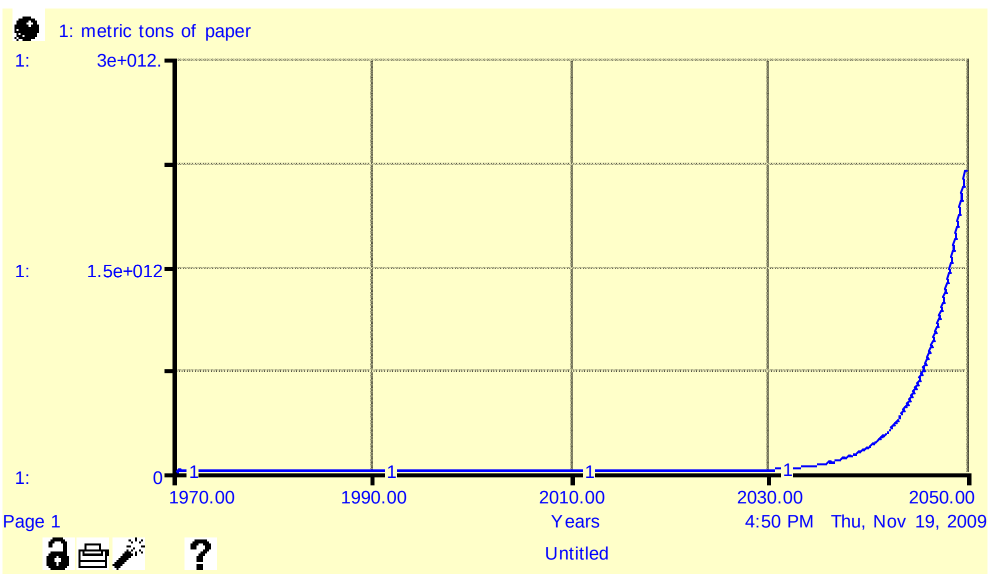

1: market share printing
2: market share digital display
1:
2:
1
1
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:47 PM Thu, Nov 19, 2009
Untitled


1: metric tons of paper
1: 3e+012.
1: 1.5e+012
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:47 PM Thu, Nov 19, 2009
Untitled

Run 62:

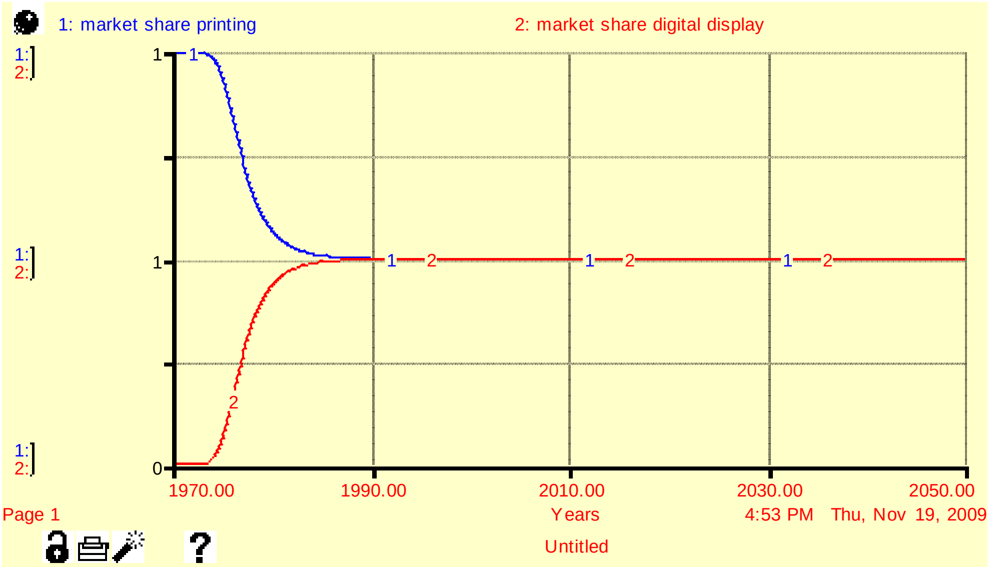


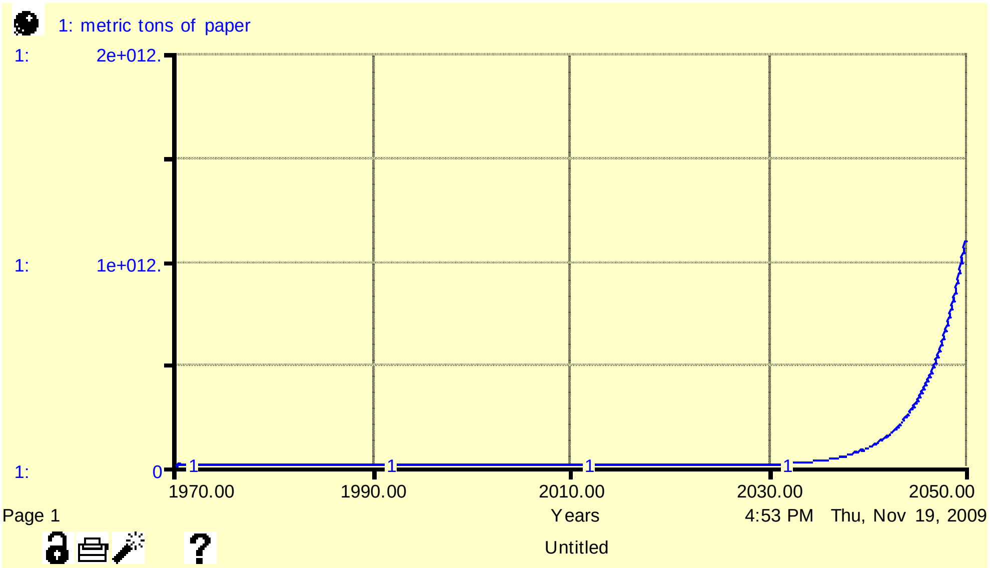
1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:50 PM Thu, Nov 19, 2009
Untitled



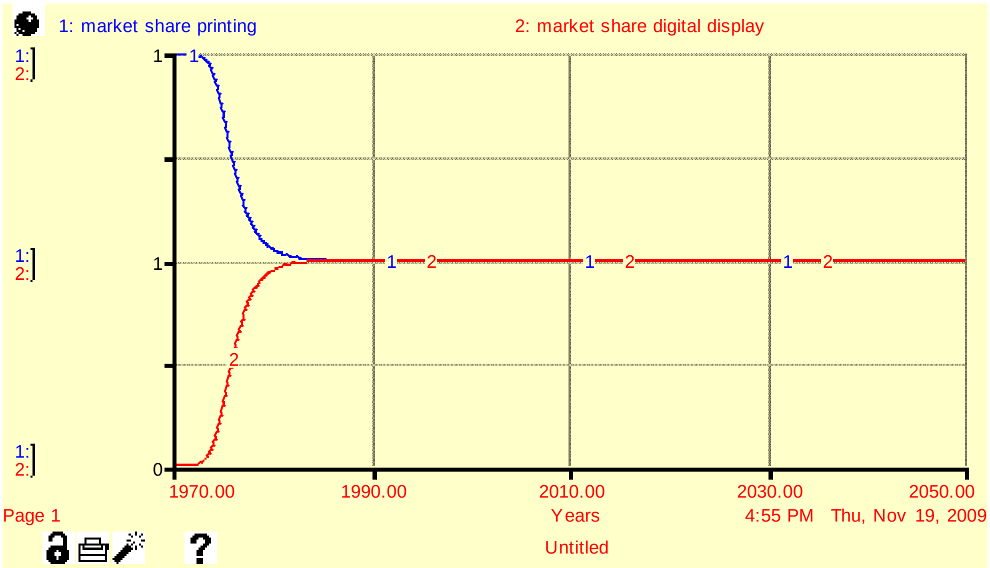
1: metric tons of paper
1: 3e+012.
1: 1.5e+012
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:50 PM Thu, Nov 19, 2009
Untitled

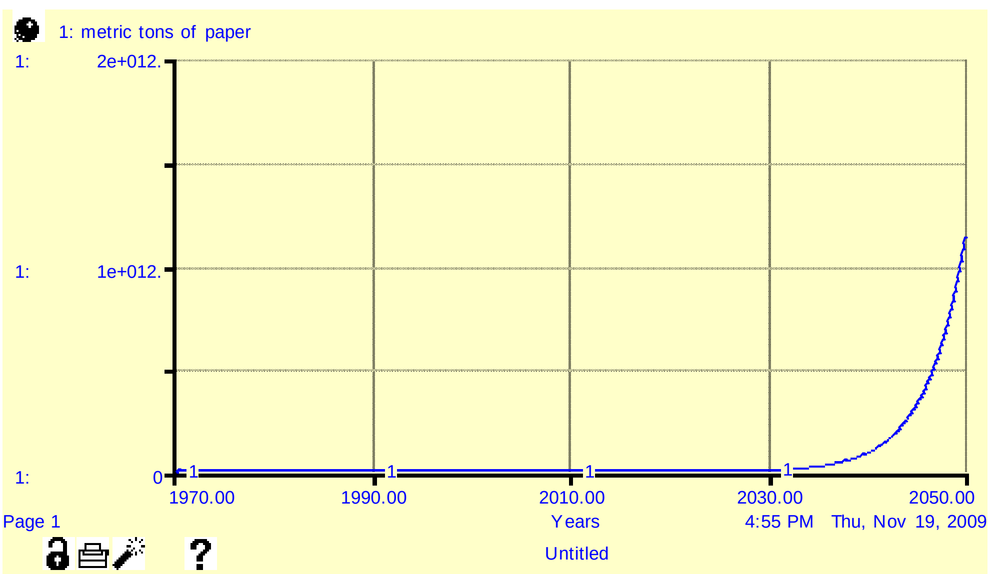
Run 63:


1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:53 PM Thu, Nov 19, 2009
Untitled


1: metric tons of paper
1: 2e+012.
1: 1e+012.
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:53 PM Thu, Nov 19, 2009
Untitled

Run 64:


1: market share printing
2: market share digital display
1:
2:
1
1:
2:
1
2
1:
2:
0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:55 PM Thu, Nov 19, 2009
Untitled


1: metric tons of paper
1: 2e+012.
1: 1e+012.
1: 0
1970.00
1990.00
2010.00
2030.00
2050.00
Page 1
Years
4:55 PM Thu, Nov 19, 2009
Untitled

APPENDIX 3: ANALYSIS OF VARIANCE (ANOVA)

Analysis of Variance for MS crossroads year (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	7	147496	147496	21070.8	*	*
2-Way Interactions	21	29464	29464	1403.0	*	*
3-Way Interactions	35	15605	15605	445.9	*	*
Residual Error	0	*	*	*		
Total	63	192565				

Analysis of Variance for metric tons printed paper peak (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	7	34752038	34752038	4964577	*	*
2-Way Interactions	21	106027457	106027457	5048927	*	*
3-Way Interactions	35	177081979	177081979	5059485	*	*
Residual Error	0	*	*	*		
Total	63	317861475				

Analysis of Variance for peak value metric tons of print (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	7	2.65930E+25	2.65930E+25	3.79901E+24	*	*
2-Way Interactions	21	8.85832E+24	8.85832E+24	4.21825E+23	*	*
3-Way Interactions	35	3.25376E+24	3.25376E+24	9.29646E+22	*	*
Residual Error	0	*	*	*		
Total	63	3.87051E+25				