2008

Print productivity: A System dynamics approach

Jorge Uribe

Recommended Citation

Uribe, Jorge, "Print productivity: A System dynamics approach" (2008). Accessed from https://repository.rit.edu/books/30

Print Productivity: A Systems Dynamics Approach

By
Jorge Uribe
Graduate Student
School of Print Media
Rochester Institute of Technology

A Research Monograph of the
Printing Industry Center at RIT

No. PICRM-2008-05

R·I·T Printing Industry Center
An Alfred P. Sloan Foundation Center

Print Productivity: A Systems Dynamics Approach

By

Jorge Uribe
Graduate Student, School of Print Media
Rochester Institute of Technology

R·I·T Printing Industry Center
An Alfred P. Sloan Foundation Center

A Research Monograph of the
Printing Industry Center at RIT
Rochester, NY
January 2008

PICRM-2008-05

With Thanks

The research agenda of the Printing Industry Center at RIT and the publication of research findings are supported by the following organizations:

Rochester Institute of Technology R·I·T 1829

Alfred P. Sloan Foundation 1934

Adobe

Avery Dennison

GPO U.S. Government Printing Office Keeping America Informed

hp invent

Heidelberg

Kodak

NewPage™

NPES

Scripps Howard Foundation

Standard Register

vertis communications

vigc Vlaams Innovatiecentrum voor Grafische Communicatie vzw Flemish Innovationcenter for Graphic Communication

xerox

Table of Contents

Executive Summary

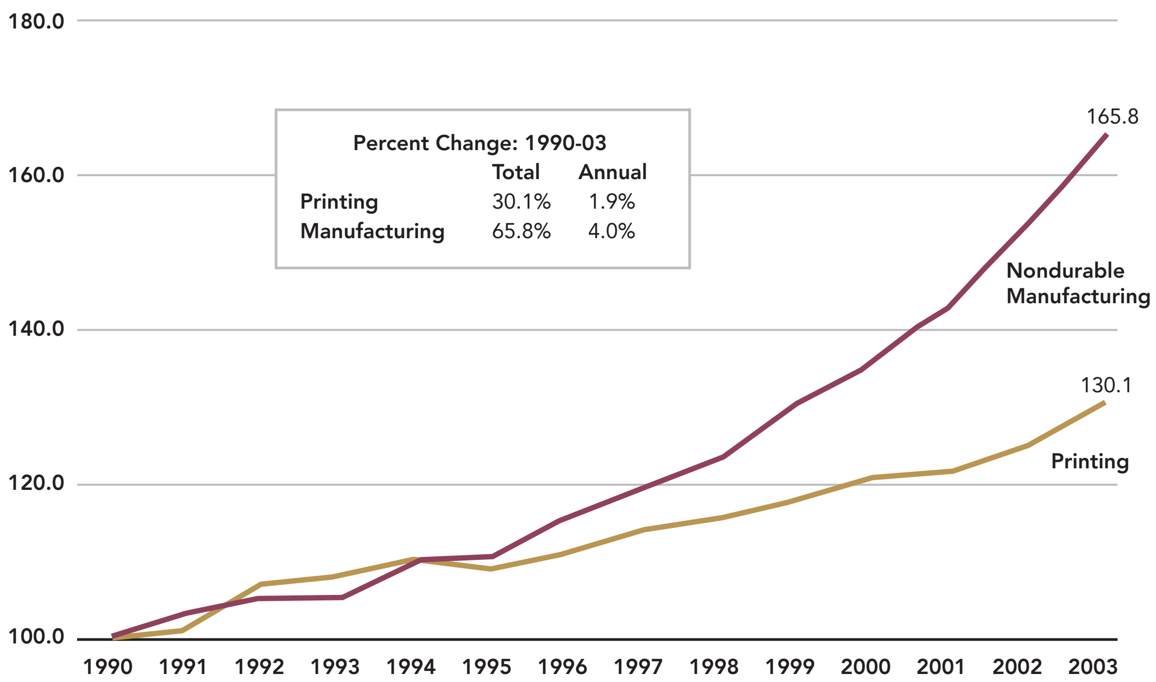
The productivity of the printing industry in terms of real sales per employee has been growing at an annualized rate of 1.9% for more than a decade. The National Association for Printing Leadership (NAPL) reports that the industry is lagging when compared to the average productivity growth of 4% from the non-durable manufacturing industries (2004). Many possible reasons for this lag are presented, but the main causes are the inefficiencies of the print production system when analyzed as a whole. Technology within the printing industry has improved dramatically; however, its implementation usually delivers localized improvements with marginal effects on the whole system. Printers are too focused on the productivity of specific equipment and not enough on the overall throughput of the system.

To address this issue, a computer simulation model of a generic print production workflow using system dynamics was developed. The use of simple tools known as stocks and flows, in conjunction with information feedbacks, resulted in a complete representation of the complexity of the system. Through multiple iterations and interaction with the model, opportunities for productivity improvement of individual print companies can be identified.

Additionally, the model acts as a learning tool for testing mental models and for improving the understanding of the print production system. The model was used to simulate five scenarios: status quo, aggressive sales, press productivity improvement, shrinking order size, and synergy. The synergy scenario achieved the best overall results when compared to the status quo scenario. Under this scenario, the throughput of the whole system increased by 47% during the simulation, considering both fixed capital and labor resources. Therefore, through correct policy design and implementation, real productivity gains for the whole system can be achieved.

Chapter One – Introduction

At the present time, any major manufacturing industry faces the constant challenge of producing faster, cheaper, and better. As the world's economy moves towards globalization and manufacturing facilities are created worldwide, there is a strong need for high productivity in order to stay competitive. The printing industry is facing all these challenges, but is not showing the improvements necessary. Any company that is able to produce high-quality goods at lower costs will eventually lead the market. This is evidenced when the productivity of the printing industry is evaluated. Improvements on an annualized basis are considerably lower, and the printing industry falls well behind when compared with other industries.



Real (inflation-adjusted) sales per employee by year, commercial printing and nondurable manufacturing. Index values with 1990 = 100.0. Print figures are NAPL estimates. Manufacturing figures are compiled by NAPL from Bureau of Labor Statistics and Bureau of Economic Analysis data.

Figure 1. Productivity growth of the printing industry (NAPL, 2004, p. 44)

Figure 1 shows the productivity of the printing industry compared to the average productivity of non-durable manufacturing industries. While the overall annual productivity increase is 4%, the printing industry lags behind with an increase of only 1.9% (NAPL, 2004). Obtaining the underlying reasons for this situation requires complex questioning, but these are questions that should be asked. If the industry as a whole is not productive enough, it is not a problem for the individual print shop.

Instead, it is a huge opportunity for any shop that is able to break away from the group and capture a substantial share of the market.

Instead of starting with reasons behind the productivity issue, a more significant approach is to describe the specific differences that make the printing industry such a diverse, complex, and dynamic industry.

The first difference is the wide diversity of printed products. Print is ubiquitous; printed products are found in many locations and modes of use around the world. This wide availability is one of the reasons why many small printing shops exist. Small firms usually do not exist in other traditional manufacturing industries, where the rule is consolidation and market control by oligopolies.

However, the printing industry is also a mass production industry. This presents the first complexity: mass production and product diversity do not mix well. The printing industry is essentially a make-to-order production system with custom products. This makes most productivity improvements more difficult to implement.

Manufacturing industries are classified as either labor-intensive or capital-intensive. The printing industry can be classified as both, presenting the second complexity. Printing by itself is very capital-intensive; while downstream finishing and postpress activities are typically labor-intensive, creating this anomalous situation. The printing industry is also known as a secondary industry, since the printed product is not always the main product being sold. For example, in packaging, the main product is the product the printed product encases. In other instances, the main product is information.

Lastly, there are almost as many workflows and business models as there are printing companies, presenting the third and final complexity. Thousands of different combinations of equipment and resources can be found, but no single one provides the only solution. A print shop's configuration and business model depend on many factors. Among them are product specialization, target market, labor costs, and experience. In summary, the printing industry is one of the most complex and diverse industries. This complexity creates many opportunities for improvement and better decision-making.

The high complexity of a print shop production system leads to difficulties that may be the fundamental cause of the low productivity rates. First, the higher the complexity of the system, the more likely managers' decisions are to be errant. Most decisions and policies in a printing company are based on mental models and non-interrelated data. These decisions are usually not optimal and take a long time to improve through trial-and-error and experience. As technology evolves, experience is no longer as useful, and errors in the decision-making process may happen again. If an open discussion is held among printing managers on the "ideal print shop," many different and conflicting concepts arise. For example, some managers blame the problems on labor costs and overcapacity, while others blame the production volumes or the economy in general. Some focus on press speeds and latest technologies, while others mention specialization on specific market niches. The reality is that the dynamics of print are highly complex and poorly understood; therefore, mental models by themselves usually fail.

The specific problem addressed in this monograph is the low productivity of the printing industry in general. When searching for the root cause of the problem, one finds a common scenario after visiting several print shops. The processes needed for producing a printed product are usually disconnected or not aligned. The main focus is on the efficiencies of specific equipment as opposed to the efficiency of the system as a whole. Additionally, the production system is very rigid, and does not allow for fluctuations in customer demand. A close observation of the production process reveals that some machines are producing at levels close to their top speed, while others are idle for large portions of the day. Materials do not flow well, and data on how fast a process needs to work according to customer demand is a rare finding. Lastly, too much waste, or *muda* (Womack & Jones, 2003), is observed in the system when it is analyzed.

The challenge is therefore to improve the print production system. Influencing policies and mental models is a key factor of success, as is increasing the productivity of the system, lowering lead times, and creating standardized 'best practices' for use throughout the system.

Chapter Two – Theoretical Basis

This monograph relies extensively on the field of system dynamics. The following section provides a brief overview of this field and a description of its main tools.

System Dynamics and Systems Thinking Definitions

System dynamics is a very young field, introduced in the early 1960s by Jay Forrester in his book *Industrial Dynamics* (1961). Prior to the advent of computers, solving analytically even the simplest of models was an immense challenge. This limited the use of system dynamics to conceptual diagrams of systems. Today, with the use of computers, any model—no matter how complex—can be successfully run, generating results and immediate feedback. The field of system dynamics is still growing, but it is becoming well-known for its powerful approach to complex systems.

John D. Sterman defines system dynamics as follows: "System dynamics is a perspective and set of conceptual tools that enable us to understand the structure and dynamics of complex systems. System dynamics is also 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" (2000, p. vii). This definition clearly indicates the main strengths of this field, namely, enabling the understanding of complex systems and allowing the creation of computer simulations (micro-worlds) where individuals and organizations can experiment and learn at a lower cost than in real life.

In *Managing from Clarity*, Ritchie-Dunhan and Rabbino provide another perspective: "Systems thinking is about seeing, understanding, and working with 'the whole.' It focuses more on the relationships that link the parts of the whole than on the parts themselves" (2001, p. 5). The importance of this concept for improving productivity is the need to understand the productivity of the whole production system as opposed to the productivity of isolated processes or equipment.

Tools for System Dynamics and Systems Thinking

System dynamics is based on the feedback loop structure of systems and also on the behavior of variables known as stocks and flows. Therefore, the modeling process uses two main tools—causal loop diagrams and stock and flow diagrams—accompanied by time delays.

Causal Loop Diagrams

Complex systems are characterized by having feedback loop structures, meaning that the system contains variables that affect other variables in recurrent motions as part of a sequence of events. One example is the hen-and-egg relationship. As the number of hens increase, the number of eggs increase; and, as the number of eggs increase, the number of hens also increases. These two variables, when modeled, have a reinforcing loop structure between them. The relation is exponential (Sterman, 2000). These types of variables have causal relationships and are very common in systems. However, causation is different from correlation. Hens and eggs probably have very good correlation, but their real relationship is causal: hens hatch eggs, and eggs represent the initial stage of a hen.

Causal loop diagrams are excellent tools at the start of the modeling process. They quickly capture different hypotheses about the dynamics of a system and show interrelation among variables. They are also very important when capturing the mental models of different individuals or teams (Sterman, 2000). Their main job is to aggregate local ideas through feedback loops that create the initial diagram of the system. However, causal loop diagrams lack the mathematical foundation needed to create computer-simulated systems.

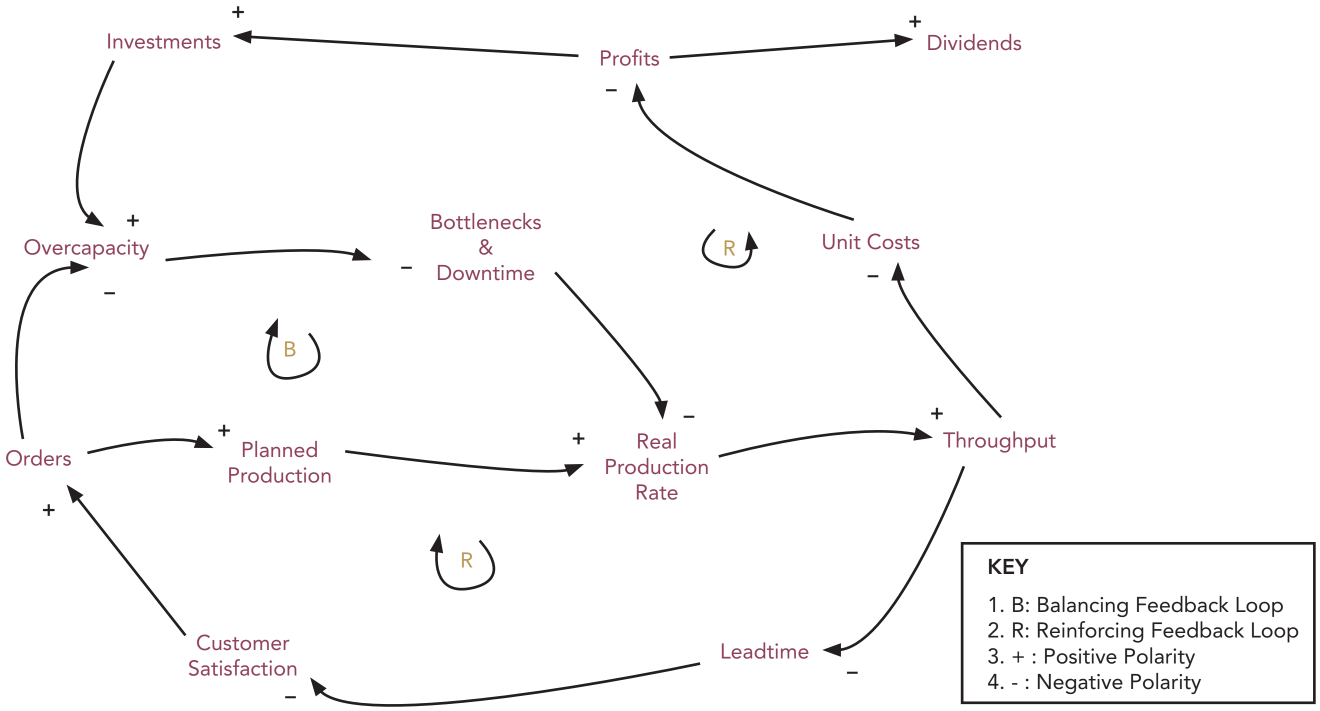


Figure 2. Causal loop diagram of a production system

Figure 2 shows an example of a causal loop diagram of a production system. The different variables are connected through causal links with positive or negative polarity. The polarity indicates the way the effect variable changes as the cause variable changes. Hens and eggs have a positive polarity: as one increases, the other also increases. When causal links are closed in a circular fashion, a feedback loop is created. Feedback loops can be reinforcing (represented by the R with a circular arrow), meaning they expand the behavior each revolution. Feedback loops can also be balancing (represented by the B with a circular arrow), meaning they decrease the behavior each revolution toward a goal or equilibrium. Lastly, feedback loops usually contain time delays that are responsible for the common non-linear behavior of complex systems (Sterman, 2000).

Stocks and Flows

The biggest limitation of the causal loop diagrams is their inability to capture the flow and stock structure of systems (Sterman, 2000). Stock and flow structures are key elements of dynamic systems. Stocks are variables that accumulate. Therefore, stocks characterize the state of the system at any given time and provide the information needed for decisions. Stocks also contain the history of previous events (Sterman, 2000). Flows represent rates or amount per unit of time. Inflows and outflows affect the levels of stocks. Stocks may only change due to the net difference between inflows and outflows at a given time.

The best way to understand stocks and flows is with the bathtub-and-pipe analogy.

A bathtub is a stock; it accumulates water. Meanwhile, the bathtub has an inflow of water through a pipe controlled with a valve and an outflow of water, which usually is a constant. If the inflow is greater than the outflow, then the level of the bathtub increases, and vice versa. The stock and flow structure, in conjunction with some information feedbacks, are everything needed to create and simulate even the most complex systems of the world. Lastly, the stock and flow structure has a mathematical representation through integral and differential equations. This is essential, since the state of a system represented mathematically can be estimated at any given time by a computer.

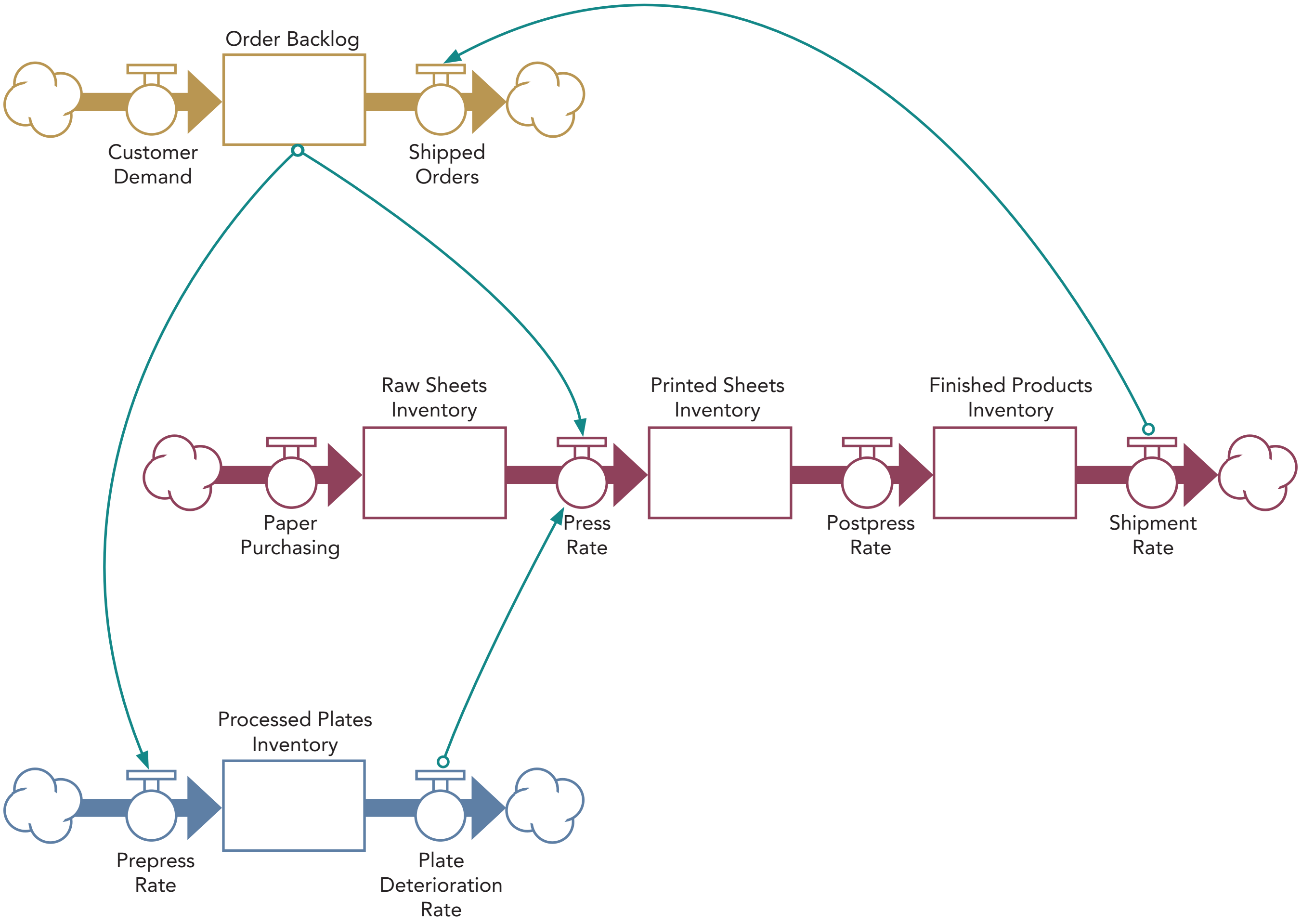


Figure 3. Stock and flow representation of the print production system

Figure 3 shows an example of a stock and flow diagram of the print production system. The top structure represents the inflow of orders, their accumulation through a backlog, and their final exit once the product is shipped. The order backlog activates two other flows: the paper flow and the plates flow. Plates are processed according to the specific needs of each order. They accumulate in the processed plates inventory, are used for printing, and are disposed of. With the plates and the order information, the press activates itself. It takes paper from the inventory, applies ink, and sends it to postpress. Postpress then converts the paper into the final printed product. Orders are shipped from the finished product inventory, and the whole cycle starts again.

Delays

Dynamic systems are affected by information and material delays. Delays are critical components of any model, and their effect needs to be captured when creating and running the simulation. A delay is a process whose output lags behind its input in some fashion (Sterman, 2000). In real life, we see the effects of delays in the decision-making process. It takes time to collect the information needed to make a decision. It takes time to make the decision. It takes time to fully implement the decision. It takes time to finally see the effects of a decision.

Delays are responsible for the oscillation and non-linear behavior presented by many systems. An example related to the printing industry can better describe the impact of a delay. When a company is fully booked, the lead time starts to expand, and customer satisfaction decreases. Usually, at this moment the need for additional equipment is quickly evaluated, and the decision is made. However, there are significant delays from the date of the purchase to the final receipt and installation of the new equipment. There is an additional delay related to learning how to use the new equipment. Finally, when the added capacity is prepared, the problem that originated the decision is likely gone. At this stage, the added capacity is ready, but the demand is not present. The pressure then goes back to the sales team. These types of dynamics generate significant oscillations in complex systems.

For the purpose of the model, the delay function is defined as:

DELAY(<input>, <delay duration>, <initial>)

Where: The <input> is the value or variable that is going to be delayed.
The <delay duration> is a fixed or variable lag time that the input variable will be delayed.
The <initial> value (optional) is the value of the input before the first delay duration.

The software available for system dynamics are bundled with tools to create models using stocks, flows, and information feedbacks. Therefore, once the conceptual model is defined, structuring the computer simulation is straightforward. Additionally, the software includes graphical aids to better interact with the model. A popular approach is to build control panels. These are used by the person(s) experienced with the model to try different strategies and get immediate graphical feedback on the results.

Chapter Three – Literature Review

The intense competition within the printing industry makes productivity a topic of high interest. There are many ways to look at productivity, both in general terms and in specific terms related to the printing industry. The following sections provide different opinions, points of view, successful and unsuccessful tools, common languages, and new initiatives that have direct or indirect impacts on productivity. Print production systems, workflows, and current modeling efforts related to the printing industry are also presented.

Productivity in General Terms

The productivity and reliability of a printing system are key factors of success; however, evaluating and understanding productivity is a complex process (Kipphan, 2001). The first question is how to measure productivity. From the economic point of view, the productivity of non-durable manufacturing industries is measured as annualized real sales per employee (NAPL, 2004). This metric is very useful at the industry level. It enables comparisons between printing firms, and it also enables comparisons among industries. For a single company, it is rather challenging to see productivity as merely sales per employee. Using that view, managers will tend to fire many people or create lofty promotions to boost their sales. Obviously, none of these approaches is sustainable in the long run.

From a more basic perspective, Millet and Rosenberg (1992) characterize productivity as the relation of throughput (saleable output per unit of time) given a set of resources (labor and capital). If a printing company is able to produce higher output with a fixed set of resources (although in reality they change very slowly), then that company is more productive. In a short time frame, a higher throughput can be directly related to a higher level of productivity. Throughput can grow infinitely, but once it exceeds customer demand, the additional throughput becomes inventory.

Not many printers realize that they only need to meet the rate of demand. This is the underlying reason why, many times, they exceed in capital investments precisely in the wrong areas of the system. Lean manufacturing uses the term *takt time* to refer to demand frequency (Dennis, 2002). The goal of any lean production system is to bring the cycle time (real production frequency) as close to the *takt time* as possible (Imai, 1997). Consequently, the purpose of a productivity improvement program should be to increase the throughput of the system until it is very close to the rate of demand and sustain it at this level. This sounds easier than it is in reality, especially when considering the fact that customer demand is far from constant.

As discussed previously, productivity growth in the printing industry is very low. Multiple factors, explanations, and opinions for this problem have been collected from several sources. One of the first comments found is that we need good equipment, good operators, and good management. This sounds true; however, it is not as exciting or easy to implement as are other schemes (O'Brien, 2000). Maintenance is also part of the equation; it is believed to be "the first and foremost contributor to productivity" (O'Brien, 2000, p. 8).

Another popular view of the productivity issue is in relation to training and automation. In terms of training, two concepts arise: a) having technology without knowing how to use it is useless, and b) using technology without leveraging it in the most productive way is ineffective (Kelly, 2002). There seem to be large time delays between the development of new technology and its proper implementation and use. Most agree that the problem is not the lack of new technology. The problem is assuming that technology by itself is enough (NAPL, 2004).

Automation is also part of the same vicious cycle. Automation should be implemented where it makes sense to the business and where workers will be properly trained to fully exploit the advantages (Hoover, 2000). Many times it is not. Another explanation is overcapacity and its imminent effect: price wars (Millet & Rosenberg 1992). It seems that these two related situations have eroded the sales part of the equation, and that firings have kept pace to maintain productivity. This is a dangerous perspective. Instead, what might be happening is the consolidation of the industry among the bigger, more productive players (Roth, 2004).

Also, there are many explanations related to internal situations of print production. Productivity is believed to depend on the printing speed, make-ready, and utilization rate of the equipment (Kipphan, 2001). The idea that everything will be fixed if presses run faster and have shorter make-readies is widespread. Most improvements from the vendor side are in the areas of faster presses and automated make-ready, including material handling and closed-loop controls (Bauer, 2005). Many times, the full capacities of the equipment are not used, and the automated make-ready becomes a missed opportunity (Peacock, 2004). Additionally, with faster make-readies come the problems of extremely short runs and shorter lead-times (Bellander, 1998). Today's poor efficiencies are commonly blamed for these two situations, which represent the new demands of print buyers.

Another reason for the productivity issue is the presence of waste in all its forms within the production floor. Examples are piles of paper in different production stages, poor flow, downtime, disorganization, poor planning and constant urgencies, excessive employee movement and talking, defective product, and et cetera. Some state that it is not an issue of overcapacity; it is really under-utilized capacity (Dickenson, 2003). In some plants, the press operator has to collect many of the elements that make a job. This is clearly time wasted, as it could be better spent on printing (Hoover, 2000). Others run their new and extremely fast presses too slowly—as slow as 50% of the vendor-rated speed (Hoover, 2000). Non-value-added activities comprise most of the day-to-day activities in any print plant, and these can easily account for as much as 90% of production time. The opportunity for improvement is hidden in these non-value-added activities, while companies usually focus on streamlining the 10% of value-added activities with marginal success (Womack & Jones, 2003). There are probably many more conditions and situations that could be discussed. However, all of the concepts presented represent an overview of the various mental models dealing with productivity. It is important to note that some of these models contradict or reinforce each other, and that there is a need for a common starting point as well.

Tools for Productivity Improvement

Multiple tools and techniques exist to assist printers with the improvement of their plants and production. Most of these tools promise a productivity boost as part of their advertising and sales strategies. However, many times the productivity gains are not achieved. One reason might be the tool itself, but, many times, the problem is that the tool was not designed with the system in mind, or that the system was not adjusted to the tool. Most of the tools, if used properly, can provide great results. The most popular tools are presented here briefly.

The tools may be divided in two major groups: high-tech and organizational. Among the high-tech tools are those related to innovations and new technologies, as well as those based on robust hardware and software. PDF and JDF (with all their relatives: MIS, CIM, CIP4, XML and XSL) are the tools with the greatest advances today. When considering PDF in terms of productivity, it provides a standardized file format for interchanging image, graphic, and text content between design and production (Cost & Daly, 2003). It has become the industry standard, and will probably continue to gain ground as time goes on. By streamlining the exchange of graphical information and standardizing a file format for doing so, PDF has achieved great success and will continue to bring productivity improvements in the creative and prepress processes.

JDF is much newer and is intended to be the electronic job ticket (Cost & Daly, 2003). As the job ticket, it is related to all the production equipment and processes—a tough task indeed. JDF seems to have all the characteristics for success: it is complete enough, well designed, and flexible; is supported by major vendors; and has reached the critical mass of interest ("JDF: An ambitious", 2005). However, its real implementation has been slower and less successful than expected. JDF is not recommended for a production system that is unproductive and disorganized, as, even with the implementation of JDF, it is very likely that such as system will continue to be unproductive and disorganized. JDF will only streamline some key areas of productivity among the system, namely, information exchange and automatic setup of equipment.

RR Donnelley is building a pilot JDF program in its Ohio site. They state that it is not an investment in technology and automation by itself; they are trying to achieve higher productivity and a lower unit cost of production (Ward, 2004). Their main objectives include:

- Error reduction,
- Turnaround reduction,

- Increased throughput with reduced headcount,
- Better use of equipment, and
- The development of an integrated and predictable workflow (Ward, 2004).

RR Donnelley must be thinking more broadly than just JDF to accomplish all of these objectives—they must think of their Ohio plant as an entire system to be successful.

One other perspective indicates that the only way to make the digital puzzle truly efficient and productive (without wasting money, time, and effort) is through collaboration across the production workflow. JDF and XML provide a common language that can literally connect all points of the workflow (Kasdorf, 2003).

Among the organizational tools, the most commonly used are ISO9000, Six Sigma, Theory of Constraints (TOC), and Lean Manufacturing. Individually, these tools are bundles of specific tools that target different areas of the organization in an attempt to achieve overall improvement and synergy. These organizational tools are interconnected and share similar objectives; therefore, most people have trouble distinguishing the differences among them. Additionally, many companies implement several of them at the same time in a search for synergy, hoping to find that lucky element that fixes all of their problems, and thereby causing even more confusion.

In terms of productivity, the goal of ISO9000 is to comply with customer requirements. It focuses on the reduction and elimination of non-conforming products and processes.

Six Sigma is focused on defects and variation. Its approach is to reduce variation in order to reduce defects, which will therefore increase productivity.

TOC focuses on bottlenecks. The concept is to set the bottleneck as the heartbeat of production. All other processes must then work at that rhythm. This guarantees that the production system will produce at its maximum capacity as dictated by the bottleneck.

The last tool is Lean Manufacturing. Its goal is to eliminate waste throughout the whole system. In lean terms, waste is very broad and includes all types of activities and materials that do not add value to the product in relation to the final customer.

All these tools have a common scheme: they nurture and promote continuous improvement. However, Lean Manufacturing is probably the most systemic and productivity-centered approach of them all, and is worth further analysis.

Lean Manufacturing has its own lexicon of Japanese words. The first is *muda*, which means waste or any human activity that absorbs resources, but creates no value to the customer (Womack & Jones, 2003). The founder of Toyota Production Systems, Taiichi Ohno, defined these seven main types of *muda* in manufacturing (Dennis, 2002):

1. Motion: unnecessary movement of people.
2. Waiting: by an upstream activity or by people for equipment to finish their work.
3. Conveyance: unnecessary transport of goods.
4. Correction: making and having to fix defective products.
5. Overprocessing: a subtle form of *muda* related to doing more than what the customer requires.
6. Inventory: keeping of unnecessary raw materials, parts and work in progress.
7. Overproduction: making products that do not sell. Overproduction is known as the root cause of all manufacturing evil.

To better understand *muda* in terms of printing, let us use some examples. A press operator looking for the production manager because the instructions are not clear is an example of "motion." The prepress operator asking for a font or a file from the ad agency is an example of "waiting." Transporting finished goods back to the warehouse for accounting purposes is an example of "conveyance." Remaking a plate because it has a misspelling is an example of "correction." Overadjusting the color of a print, or processing images in RAW format without the customer asking for it (or noticing it), are examples of "overprocessing." Piles of paper, ink, work in progress, and finished goods are all clear examples of "inventory." Lastly, printing books according to projected sales and forecasts is an example of "overproduction." As can be seen from these examples, the printing industry and its day-to-day activities are plagued with *muda*. It sounds dramatic, but it is a real problem. The good news is that there is an antidote to *muda*: "lean thinking" (Womack & Jones, 2003).

Lean thinking (and, therefore, lean manufacturing) is based on five straightforward and easy-to-understand principles. These principles rule all the decisions in the production system. Used together, they strive to create a production process as free of *muda* as possible.

"Value" is the first principle. It is the key starting point, and can only be specified by the final customer or in terms of the final customer. Value is defined as a product (good or service) that meets the customer's needs at a specified price and specific time (Womack & Jones, 2003). One additional requirement is that the customer must be capable of paying for the product. Once value is defined, *muda* is consequently defined as anything that does not contribute to that value. In a printed product, value can be described as the permanent structures (ink, shape, etc.) applied to the substrate with the purpose of visualizing information (Kipphan, 2001). Value is mostly contained in the printed product; consequently, all activities that do not participate in any part of the physical transformation from raw material into finished product are *muda*.

The second principle is identifying the "value stream." The value stream is the set of all actions required from order entry through manufacturing and delivery (Womack & Jones, 2003). The value stream is divided into three segments: actions that create value, actions that create no value but are unavoidable under current technology (*muda* type I), and extra actions that create no value and can be eliminated (*muda* type II) (Womack & Jones, 2003). Lean eliminates all *muda* type II actions and focuses on reducing all *muda* type I actions.

The third principle is "flow." Its purpose is to align closely together all the remaining value-adding steps in order to make the product flow as simply and quickly as possible.

The fourth principle is "pull." In its simplest form, it means that downstream steps will pull the product as needed from upstream steps, guaranteeing no overproduction.

The fifth and last principle is "perfection," which suggests that the first four principles interact with each other in a continuous improvement circle, always thriving for perfection (Womack & Jones, 2003).

There are two more words in the lean lexicon that are related to the current printing reality: *mura* and *muri*. *Mura* refers to the unevenness or fluctuation in work, usually caused by fluctuating production plans (Dennis, 2002). A consequence of *mura* is unreliable delivery, which is known as one of the top reasons why print buyers drop printers (Merit, 1992). Dealing with this problem is rather difficult, considering that customer behavior tends to be unpredictable, and subsequent planning difficulties occur when printers deal with urgent and non-urgent orders in parallel (Olson, 1998).

Muri means that something is hard to do, due to factors like poor design, specifications, parts, tools, etc. (Dennis, 2002). Historically, printing has been considered a tough and difficult job. One cautionary view of the future is that, since new technologies are making printing easier than ever, no *muri* will be left for the craftsmen.

Print Production System and Workflow

"Workflow" has become a popular term in the graphic arts. However, its definition is rather vague and includes all kinds of functions (Poyssick & Hannaford, 1996). It has evolved into the concept of a system built of the activities related to prepress and how prepress is setup and organized. "Flow" is part of the word workflow, indicating that one of the objectives of a workflow is to actually make the work flow. This is clearly aligned with the third lean principle. Additionally, prepress is the process in the printing industry that has likely advanced the most in the last decade, becoming completely digital and, for the most part, automated.

For the purpose of modeling the whole print production system, it is wise to broaden the definition of workflow to include all the steps necessary to get a job in the door, produce it, and ship it (Gehman, 2003). In this way, workflow is closely related to throughput capacity, and success will depend on how we design, analyze, and manage it (Poyssick & Hannaford, 1996).

A workflow is made of materials and information flow (Bellander, 1998). System dynamic models are made of the stock and flow of materials and information feedbacks. It is not a coincidence that, when people talk about their workflow, they are talking of how their production system is designed to perform certain activities in the most efficient ways. In the real world, workflows can fail for a myriad of reasons. A common problem is that workflows are designed in very rigid formats, without considering rework or product mix (Poyssick & Hannaford, 1996). Other problems include workflows of a high complexity or large size that are designed to account for all possible variations, but no one really understands them (Poyssick & Hannaford, 1996). The flaws common to workflows may also affect the modeling process. Caution during the creation of the model is needed, since the model will actually simulate a print workflow.

One last concept related to flow is known as Little's Law. It states that the inventory of units within the boundaries of a process is equal to the throughput rate multiplied by the flow time, which is the time spent within the process boundaries (Anupindi, Chopra, Deshmukh, Van Mieghem & Zemel, 1999). This law is useful when determining the best way to model a process, either by defining the process as a stock or as a flow. Workflows can be improved in many ways. The most common ways are improving logistics, increasing flexibility, decreasing variability, and eliminating processing cost (Anupindi et al., 1999).

Workflow under this context can also be understood as the print production system. Workflows come in multiple shapes, 'flavors,' and levels of detail. This presents a huge problem when trying to model the print production system. There are no clear agreements on the way a print product should be manufactured; this condition is illustrated by the size and diversity of the industry. In any event, modeling is an abstract activity and, as such, requires a common approach to printing.

A group of researchers in Sweden investigated eight large print companies with different product mixes and production prerequisites, covering the entire process from prepress to finishing and distribution (Bellander, Handberg & Stenberg, 1998). They analyzed each company using a method called "Systematic Description of Activities" (SDA) which generates results in a graphical way called activity graphs, or "A-graphs." Even though each A-graph was different for each company, they were able to divide print production into six common phases: product planning, creation and preparation of components (image and text), pagemaking and imposition, duplication in a printing press, postpress, and distribution (Bellander et al., 1998).

Similar abstractions have been developed by many different authors. Some of the clearest process maps of the printing industry are presented by Kipphan in the *Handbook of Print Media* (2001). He divides the scenario into two groups: the larger picture referred to as media production, and a narrower picture related to the printing industry called print media production. As shown in Figure 4, it is interesting to see how print media fits into the media structure.

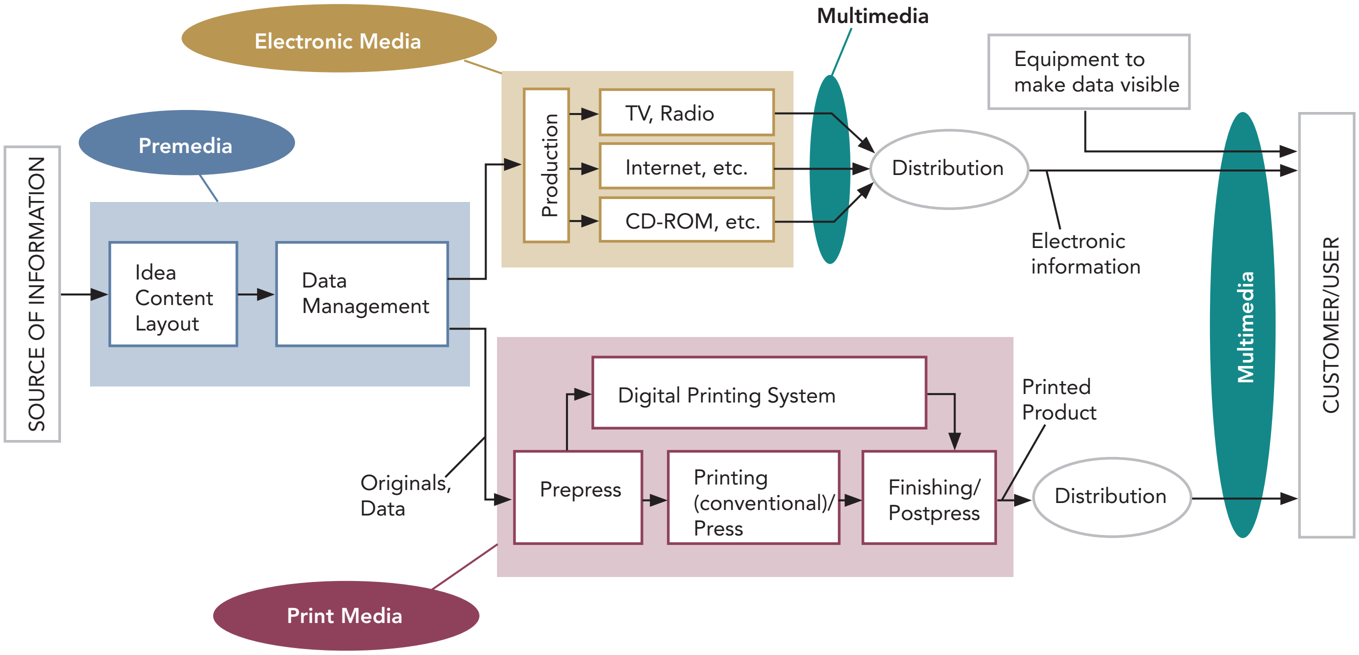


Figure 4. Structure for producing electronic media, print media, and multimedia documents (Kipphan, 2001)

According to this structure, premedia plays a huge role in media production. It controls the creative content from ad agencies or designers, manages it, and populates the databases. This content is further spread to electronic/multimedia production or to print media production, then finally is distributed to the customer. Print media is part of the whole chain, and the other media players may be more or less important to the print shop, depending on its market niche. Lean thinking will suggest streamlining this whole value-added chain (Womack & Jones, 2003), but anyone in the industry will agree that it is just "too big of an elephant to handle." Therefore, focus will be shifted towards the print production system.

Print production is made of material and data flows among the three main processes known as prepress, press, and postpress (Kipphan, 2001). Plates flow between prepress and press, and printed sheets flow between press and postpress. All processes are interconnected through data flows and are interlinked with storage or buffer areas (Kipphan, 2001). Figure 5 better shows this interaction of processes, materials, and information.

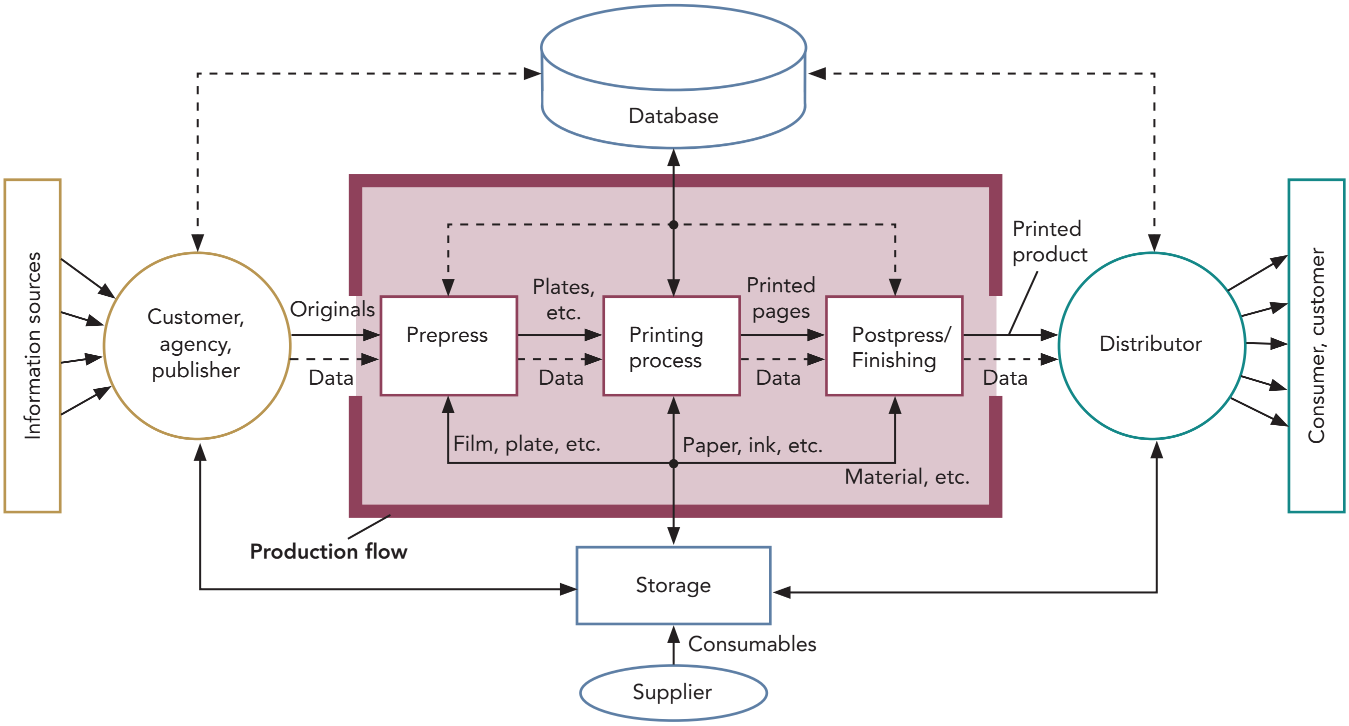


Figure 5. Production flow, material, and data flow for print media production (Kipphan, 2001)

The six phases described by the Swedish researchers can be reclassified under the structure presented in Figure 5. Many people have arrived at the same conclusion and have agreed with this process map view of the print production system. Each of the value creation processes (prepress, press, and postpress) are aligned in chronological order, and their interaction results in the transformation of an order from raw material into a finished print product ready to ship. No matter how digital or analog a workflow is, or even how rare the product is, printers always need these three processes. This widely accepted process map is the starting point of the modeling process.

Computer Simulation and Modeling in the Printing Industry

Computer simulation and modeling have not been widely used in the printing industry. Nevertheless, some very interesting simulation products and models do exist. SHOTS (or Sheetfed Offset Training Simulator) is a great example. SHOTS is an interactive computer training system that offers press personnel a simulation of real pressroom conditions (Sinapse Graphic International, n.d.). It works like a flight simulator, bringing a complete offset press with all its elements and controls onto a computer screen. Operators can learn the latest technologies without costly press time and production mistakes. The program provides screen shots of the resulting printed sheets, allowing the operators to evaluate quality and then make adjustments to their work. Some users consider that computer simulation training has taken over where vendor and in-house training has left off (Hoover, 2000).

Another approach was taken by a group of researchers from Finland. They used a discrete network simulation technique and a software product called Extend to create a detailed model of the production system of a newspaper company. The goal of the model was to try different ways to operate the equipment in order to find good balance between the production costs, the service level, and the risks and costs of running late (Bäck, Lehtonen, Karttunen, Kuusisto & Launonen, 1998). The simulation model was flexible enough to allow different alternatives, such as varying the number of presses, mailing lines, number of loads, and scheduling. Other modifiable variables were the structure of the newspaper, the number of copies, and the printing speed. To approximate the network flow to real production conditions, disturbances during production and random changes in the start-up time were included. One of their conclusions worth mentioning is their belief that it is very difficult or impossible to design and construct a generic simulation model that adjusts to different kinds of printing production chains. Instead, it is reasonable to simulate the phases to produce a certain product or product type (Bäck et al., 1998). This statement is a challenging one for the goals of this particular monograph, as it indicates that under proper abstraction and using the correct tools a generic simulation model should be achievable.

One last approach was developed in the University of Zagreb, Croatia. The method selected was the use of stochastic simulation that could be optimized mathematically. The model was applied for both a simple prepress workflow and a digital print house. Stochastic modeling relies on the definition of processes, each accompanied by a level of probability and stochastic (Njezic, Ziljak, Pap & Svilicic, 2003). The stochastic model is a rigid mathematical representation of print production and has limited interaction with the user. However, by being mathematical, it can be optimized by running different scenarios and graphing their results. This will provide an approximation to the optimal solution, but the fact that the model actually has a mathematical optimum raises questions regarding its correlation to the real world. The researchers went a step further and were able to link the model to a CIP4 system with the use of XML. This means that production planning could be directed automatically by the model, according to the results of different simulated scenarios based on the current order backlog. Modeling and simulation are considered essential methods for designing the printing systems and reproduction processes of the future (Njezic et al., 2003).

During the review of existing literature, no publications were found on the use and application of system dynamics within the printing industry. As a result, this current research has a certain degree of novelty. Nevertheless, exploring new fields is always a challenge with a risk of failure.

Chapter Four – Hypotheses and Objectives

The nature of this research calls for a different approach when referring to hypotheses. Instead of accepting or rejecting a hypothesis through statistics, the purpose of the model is to incorporate hypotheses of different knowledgeable people from the industry. The endogenous opinions on the causes of the low productivity rate are incorporated into the model. The linkage of different local hypotheses results in a well-structured model, representing different areas of the workflow and similar explanations of effects, usually separated by time delays.

Therefore, this research project has objectives instead of hypotheses. The primary objective is to create a computer simulation model that conceptualizes the dynamics of a print production system. The purpose of the model is to provide an understanding of the current state of the print company being modeled and to indicate a path for higher productivity. In addition, the model exhibits each of the following characteristics:

- The model is simple enough to be easily explained and understood at the managerial level of any printing company.
- The model is ample and flexible enough to permit the analysis of any printing company, no matter their workflow, product family, technology, or print process.
- The model is comprehensive enough to include different dynamic structures and print production processes affecting the overall productivity of the system.

The secondary objective of this project is to validate the model using estimated data representative of a printing company. The data is loaded into the model, run once to obtain the current state, and then run several times with different strategies and policies in order to identify opportunities for improvement.

Chapter Five – Methodology

The methodology of this monograph follows the guidelines indicated by John Sterman in his book, *Business Dynamics: Systems Thinking and Modeling for a Complex World* (2000). The experience of the author in the modeling process and the reputation of this book as "the" handbook of system dynamics provide support for the use of this methodology.

Modeling Process

The modeling process is divided into five phases: problem articulation, formulating a dynamic hypothesis, formulating a simulation model, testing, and policy design and evaluation.

Phase 1. Problem Articulation (Boundary Selection)

The model needs to address a specific problem, and should not try to model the whole complexity of a system. The analogy of a map better explains this need. A map is a model designed to solve the problem of location in a particular area and provides the information needed in order to move from Point A to Point B. If the map does not have a specific purpose and tries to include all the complexity of the area, the map may end up being more complex than the problem and will clearly be useless. Therefore, the model must have a specific goal, solve a specific need, and simplify rather than attempt to emulate an entire system in detail (Sterman, 2000). The clear definition of the problem also identifies the model boundaries and scope of this monograph.

Phase 2. Formulating a Dynamic Hypothesis

Using the current knowledge and experience of people related to the industry, a working theory of the origin of the problem is formulated. Many different opinions arise, and the theory should capture as many of them as possible. However, the model focuses almost entirely on endogenous variables (i.e. process efficiency, bottlenecks). Exogenous variables (i.e. fluctuations in raw material costs, economic growth) are either included with minor participation or excluded completely. The idea is to fix the problem from within the printing workflow and not to blame the problem on the economy, customers, or other external forces. Variables not related to the problem are excluded, as are variables that add too much complexity to the model without offering extra benefits. In this phase, different system dynamics tools are used, such as causal loop diagrams and stock and flow maps.

Phase 3. Formulating a Simulation Model

Once the dynamic hypothesis has been formulated (including different aspects and points of view), a simulation model is designed that tries to capture all the interrelations in a dynamic system. The idea is to link the different explanations of the same problem into one single model that simulates the different behaviors defined in Phase 2. This phase usually creates new insights and feedback to the previous ideas. This process is a constant iteration of modeling data against real world data (Sterman, 2000). The model is modified and tested until a functional and complete version is available.

Phase 4. Testing

Even though testing occurs constantly from the start of the modeling process, a severe test must take place once there is a fully functional version. The test consists of extreme conditions that do not normally occur in real life, but that have predictable outcomes of exactly what the model should do in these situations. Extreme conditions in a print shop may include the complete breakdown of all the equipment, an increase in orders of 1,000%, or a dramatic shortage of raw materials. Testing also includes the verification of equations and dimensional consistency of variables. The variables must also represent meaningful concepts in the real world (Sterman, 2000).

Phase 5. Policy Design and Evaluation

Estimated data representing a printing company is used during Phases 3 and 4 to ensure a solid model, with good foundations and a correlation to real life. However, actual company data is used as the input data for simulation under the final version. This allows the model to then be used for learning. Current data is inputted, accompanied by existing policies and practices. The model indicates the present status or baseline of the company. Then, new policies and decisions can be made, and the model is run again. Better results imply improvement, and worse results indicate a need for another attempt. At this stage, the model becomes a great learning tool and a powerful simulator for developing entirely new strategies, structures, and decision rules.

Human beings learn better through direct experiences. Basic activities like walking and riding a bike are learned by trial-and-error, with immediate feedback and adaptation. However, in complex systems, the feedback is far away in time and space, generating a learning dilemma (Senge, 1990). Simulators shorten this gap and enable the user to learn from direct experimentation, even within complex systems where the effects of the actions are visible only years later.

Complex systems are highly non-linear, and usually a combination of new policies provides the best results by driving synergy (Sterman, 2000). This phase enables the analysis of five different scenarios under the same company data. Each specific result constitutes a case study of how the model can be used to better design and implement policies that improve the workflow. Lean manufacturing policies may also be tested, and the results should indicate how these will affect the overall productivity of the print shop.

Data Collection

Numerical data and statistical estimation are key components of the model's building, testing, and final use phases. Therefore, estimated data representative of a printing company is collected. Once the variables in the model are defined, a spreadsheet is designed to help any print shop collect its own data for proper use of the model. In the case of variables currently measured by the companies, historical data from previous months of operation can be used. For completely new variables (i.e., those never previously measured), a random sample of at least 30 data points is considered sufficient.

Chapter Six – Results

The results are related to the development of the methodology in the process of creating the model, then running different scenarios in order to learn which sets of policies produce the best overall productivity gains.

Phase 1. Problem Articulation (Boundary Selection)

The purpose of the model is to indicate ways to increase productivity of a print production system by increasing its throughput (saleable output per unit of time) given a set of resources. The resources are fixed under the time frame of the model, but mechanisms for additional capacity can be added if needed. The problem articulation was presented in the Introduction.

Phase 2. Formulating a Dynamic Hypothesis

Using the current knowledge and experience of people related to the industry, a working theory of the origin of the problem represented by a causal loop diagram has been developed. As shown in Figure 6, the causal loop diagram illustrates different areas of the system, its interrelation with other areas, the feedback structures, and model boundaries.

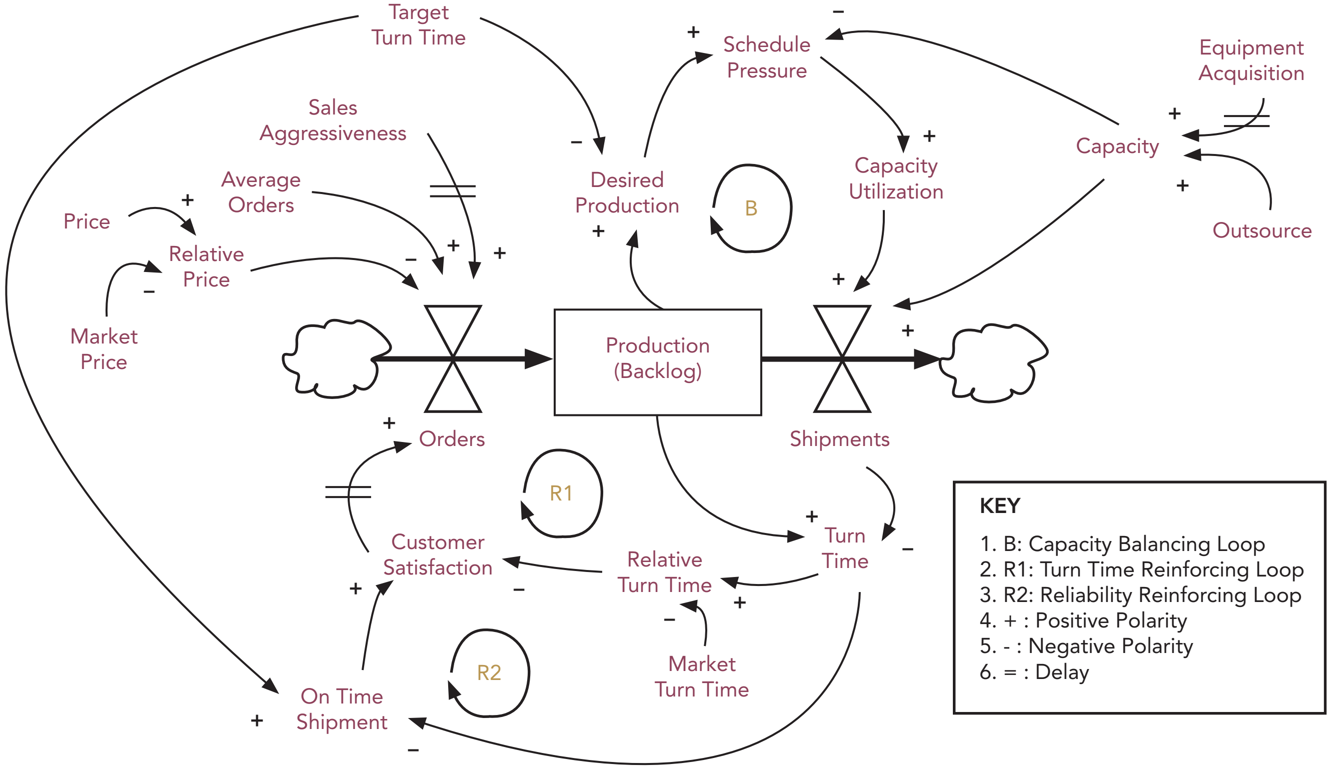


Figure 6. Causal loop diagram of the print production system

Model Description

The model represents the interaction between some limited sales variables, the production stock, two reinforcing feedback loops related to customer satisfaction, and one balancing feedback loop related to production capacity. The production stock is developed in Phase 3 and includes the main print processes: prepress, press, and postpress.

Production Stock and Flow. The impact of productivity happens within the production stock. This model represents a print production system that operates under the assumption of a make-to-order policy. The backbone of the model is a stock and flow structure where the orders come into the production system, are processed for a given time (production delay), then shipped. The production backlog represents the orders waiting in line to be processed. The production backlog increases when the order input exceeds the output capability of the system and vice versa. The make-to-order assumption is valid for most of the printing companies.

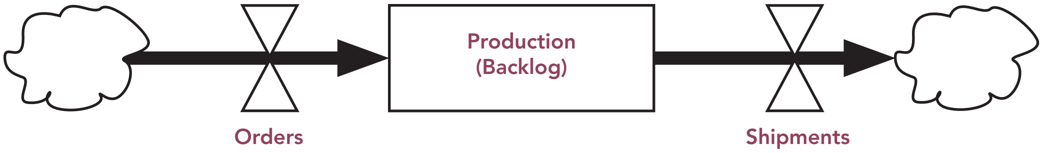


Figure 7. Production stock and flow

Every order comes into production (the backlog), then is processed and shipped. The processing time is the production delay and is described as turn time. Turn time is defined as the time that elapses from the order reception to the order shipment. This concept is different from lead time, which includes the logistics of delivering the order to the customer. Logistics are out of the model boundary; therefore, the concept of turn time is used. The production stock is determined and later simulated by the main print processes: prepress, press, and postpress. For now, the main concept is that orders come into a production backlog, get processed for some time, and are finally shipped. The rest of the model concentrates on the feedback structures that control the system.

Order Inflow. The production stock is affected by the rate of the order inflow; therefore, it is very important to understand what affects this inflow and how the rate of the inflow can be changed.

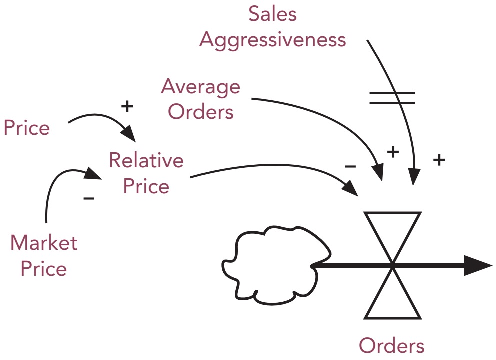


Figure 8. Order inflow

The order inflow can be affected by multiple variables; however, the model must focus on the variables relevant to the problem and relevant to the policies that will be part of the simulation process. The first variable that has a direct impact on the order rate is "relative price." Relative price is defined as the ratio of the price of the company to the market price. Based on basic demand theory, if relative price is less than one then the order rate increases, and vice versa. The impact of price depends on the print market that is being analyzed. However, as shown in Table 1, price has been decreasing in importance in some markets. For example, advertising agencies that purchase print classified price as the fifth factor of importance when selecting a print provider (Pellow, Sorce, Frey, Olson, Moore & Kirpichenko, 2003).

Table 1. Importance of factors when selecting a print service provider
(Pellow et. al., 2003)

Factors to consider when selecting a print service provider*	Importance
Dependability	9.45
Print Quality	9.15
Turnaround time	8.41
Ease of doing business	8.19
Price	7.93
The specific technology used by the provider	6.85
Other factors	6.16
Unique capabilities	6.04
Geographic proximity	5.79

* Ranked on a scale of 1 to 10, where 1 meant "not at all important" and 10 meant "very important."

The second variable, described as "average orders," is a variable used to replace the complexity of the market. This variable indicates that a printing company that has been established in a market will have an average inflow of orders, based on historical order patterns. The average orders variable can also be used to describe cyclical order patterns, if those patterns are considered important.

The third variable is described as "sales aggressiveness." For simplicity, the sales team can have, at a certain time, two different strategies: aggressive or sustainable. When aggressive, the sales force is pushed to get as many orders as it can. When sustainable, the sales force is directed to maintain its current sales volume. Most companies operate under the first strategy, no matter what. However, the idea is to offer an alternative strategy to the sales force if it decides that the aggressive strategy is not the most suitable under cases such as maximum capacity utilization. This decision involves a delay when changing from the sustainable strategy to the aggressive strategy and vice versa. The delay is related to the time that it will take the sales force to spread the new strategy and to obtain an effect on the order volume from the customers. Many more variables could be included in the model, but the current variables are considered enough for the model purpose and boundaries.

Reinforcing Feedback Loops. The model incorporates two reinforcing feedback loops that represent the key metrics of the current printing industry. These also affect the order inflow. Today's customers demand fast and reliable service from printing companies. Fast service is expressed by the "turn time reinforcing loop" (R1). On-time shipments are used as the reliability metric and are expressed by the "reliability reinforcing loop" (R2).

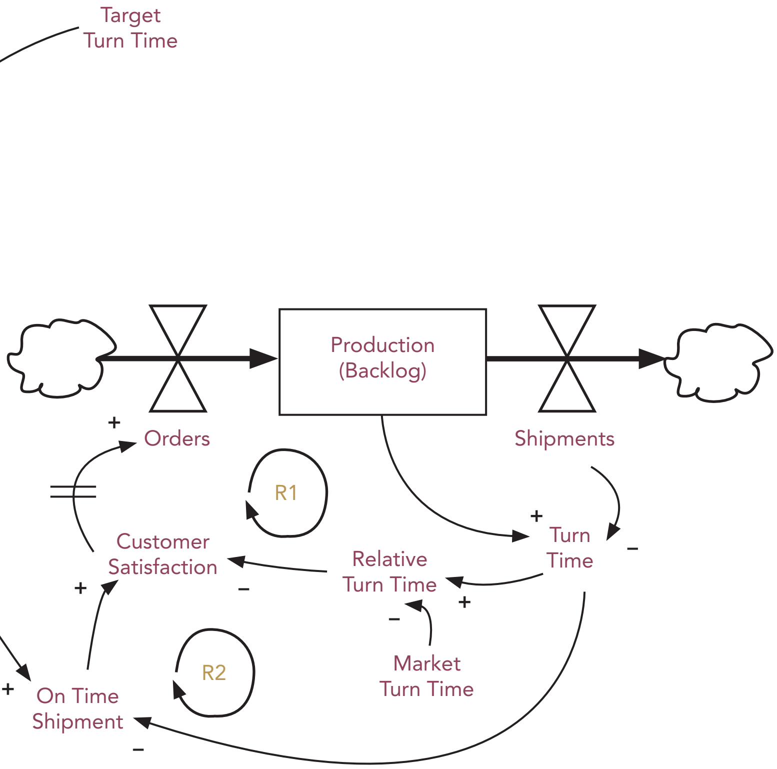


Figure 9. Reinforcing feedback loops

The turn time feedback loop (R1) is the representation of how lower turn times can grow a printing business. The loop starts with the "turn time" variable. Turn time depends on the shipments outflow and the current production backlog. The first effect of productivity is expressed here in both the backlog size and the shipment rate. The turn time is affected by the shipment rate—at a higher rate, the turn time is lower. The backlog size also affects the turn time. A large backlog increases the turn time, since the order waits in line longer.

The company turn time is also compared to the market turn time, using the ratio known as "relative turn time." A relative turn time larger than one has a negative impact on customer satisfaction and vice versa. After a time delay (=), the customer satisfaction level has an impact on the order inflow. If a printing company is able to ship with a lower turn time than the market for a significant period of time, then orders grow exponentially. Turn time (equivalent to turnaround time) is a very important factor when selecting a print provider; it was classified as the third factor of importance by advertising agencies that buy print services. (This rating of factors is shown in Table 1.)

The reliability reinforcing loop (R2) expresses the effect of shipping the orders on time. The main reason why print buyers leave one printer and seek out another is the issue of late deliveries (Merit, 1992). This statement clearly indicates the importance and impact of this loop and the relevance of the loop for the model purposes. It is also reinforced by the survey results shown in Table 1: advertising agencies classified "dependability" (the same concept as reliability) as the main factor considered when selecting a print service provider. The reliability loop also starts from the "turn time." In this case, the turn time is compared to the "target turn time," which is the turn time promised to the customer and indicated to production. For the model, the target turn time is fixed for a certain time and may be modified at certain intervals of the simulation.

"On-time shipment" is determined as a percentage of orders shipped early or on time when the turn time is compared to the target turn time. A higher target turn time has a positive effect on the on-time shipment, but has a negative impact on other areas of the model. (Further explanation of this effect is in the following section.) A higher turn time will negatively affect the on-time shipments if the shipments are late compared to the target turn time. The target turn time and turn time concepts are key elements for any printing company. These concepts control the dynamics of the production behavior and provide the promise dates given to customers for each order. The on-time shipment percentage directly affects customer satisfaction and, after a delay, affects the order inflow, closing the loop.

A key factor for any printing company is quality. Quality was classified as the second most important factor by advertising agencies when selecting a print provider (shown in Table 1). Since the purpose of the model is to focus on productivity, quality is not part of the model and is considered as a given. If needed in the future, the quality factor may be included in the model as an additional reinforcing loop.

Balancing Feedback Loop and Order Outflow. The counterpart of the reinforcing feedback loop is the balancing feedback loop. This loop controls growth. Its dynamics are related to a given capacity of a printing company and its capacity utilization; therefore, this loop is called the "capacity balancing loop" (B).

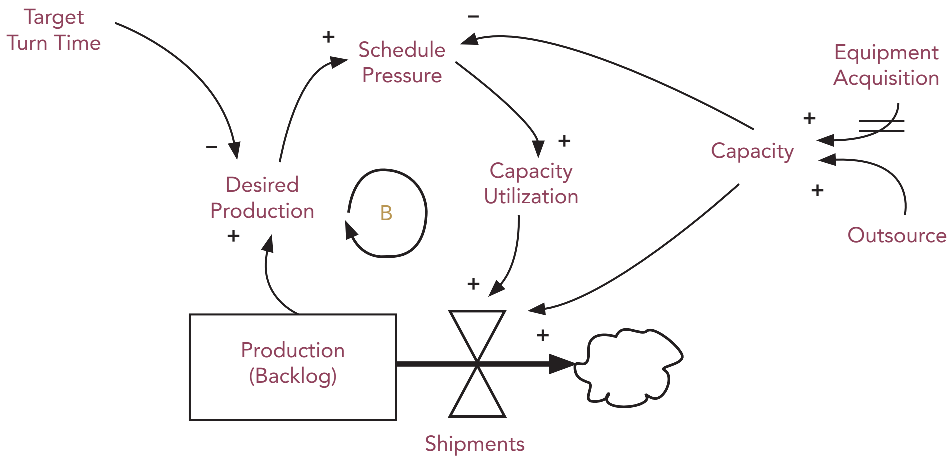


Figure 10. Balancing feedback loop

“Desired production” represents the ratio between the production backlog and the target turn time. This ratio represents the number of orders that need to be processed per unit of time in order to ship the orders on time. This is also related to the concept known as *takt time* under lean manufacturing terminology. Ideally, production should adjust its speed to comply with desired production at all times. “Schedule pressure” is defined as the ratio between desired production and capacity (Sterman, 2000). If the ratio is lower than one, then there is plenty of capacity to produce the orders on time. If it is higher than one, then a capacity constraint situation exists, and orders might suffer a shipment delay.

“Capacity” is defined as the historical rate of production under normal conditions and current knowledge; it is assumed to be fixed for a certain amount of time during the simulation. “Capacity utilization” is a function of the schedule pressure. This function indicates the quantity of orders processed. For overcapacity situations, the capacity utilization matches desired production. In capacity constraint situations, the capacity utilization is somewhat higher than the capacity, in order to represent short-term decisions that affect the processing of orders such as the use of overtime. However, the system will not stay at a level higher than the capacity indefinitely, and there is also a true maximum that can be reached. Finally, the loop closes by affecting the shipment rate. This rate has a maximum determined by the capacity.

The outflow rate of shipments is affected directly by capacity and capacity utilization. Capacity may be increased without a delay by using outsourcing. Capacity may also be increased by equipment acquisition. However, equipment acquisition always comes with a time delay representing the time needed to investigate different options of machinery, to approve the acquisition, and, finally, to receive and install the equipment. Delays greater than six months are normal in the printing industry when purchasing presses. In the short term, considering a fixed capacity, the shipment rate grows together with desired production until the shipments max out. This is due to capacity constraints that limit growth.

The dynamics captured under this causal loop diagram (CLD) are very representative of any printing company. The CLD indicates how orders grow as customers are satisfied and that there are limits to growth due to capacity constraints. Balancing this system is quite a challenge, since many things vary simultaneously and the different delays that affect the system make the dynamics difficult to anticipate without running the simulation. The next step is to consider the internal dynamics of the production stock. These dynamics are well represented by a stock and flow structure of the main printing processes: prepress, press and postpress. Phase 3 develops this structure and makes the whole model suitable for the iThink™ software.

Phase 3. Formulating a Simulation Model

The next phase is the development of the stock and flow structure of the model in order to simulate it. The first step is breaking down the production backlog into a sub-model that describes the nature of a printing company. This structure is the one that makes the model a true print production model, instead of a general production model. The sub-model represents the stock and flow structures of the main printing processes: prepress, press, and postpress.

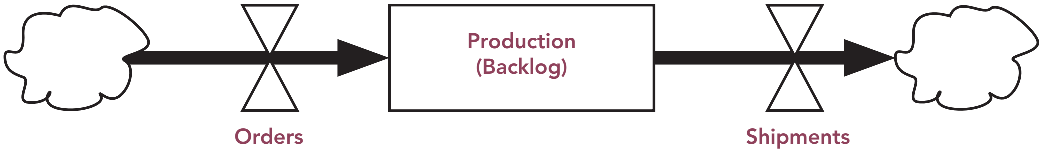


Figure 11. Production stock and flow

Every time an order comes into the system, it carries the following attributes that affect how the order is processed: number of colors, number of sheets, and a finishing complexity level. These attributes are kept as simple as possible in order to maintain the model at an aggregate level. The number of colors (usually equivalent to the number of plates) is the sum of colors printed in the front and in the back. The number of sheets is calculated by dividing quantity of units of the order by the number of units that can fit in a sheet. If there are multiple presses with different sheet sizes, a standard sheet size needs to be defined. The finishing complexity level is defined as "high" if the order requires three or more separate postpress activities, "medium" if it requires one or two separate postpress activities, and "low" if postpress is done inline. A separate activity is one that is easily identified as a separate process because it is either located in a different place within the print shop or if it needs different equipment that is not linked, requiring the movement of work-in-process inventory. For example, a newspaper operation with inline finishing is classified as having a low finishing complexity level. An offset order for a label that requires separate diecutting is classified as having a medium finishing complexity level. A high-end package requiring separate finishing activities like hot stamp, diecutting, spot UV varnish, and final assembly, is classified as having a high finishing complexity level.

Orders coming into the system also trigger two flows: plate flow and paper flow. For ease of use, the paper flow is measured in number of sheets, which applies both for sheetfed and web presses. These flows are known as coflows since they are linked together as part of the printing process. Figure 12 illustrates the stock and flow structure of the sub-model. It indicates how plates and paper flow through the prepress, press, and postpress processes during the fulfillment of an order.

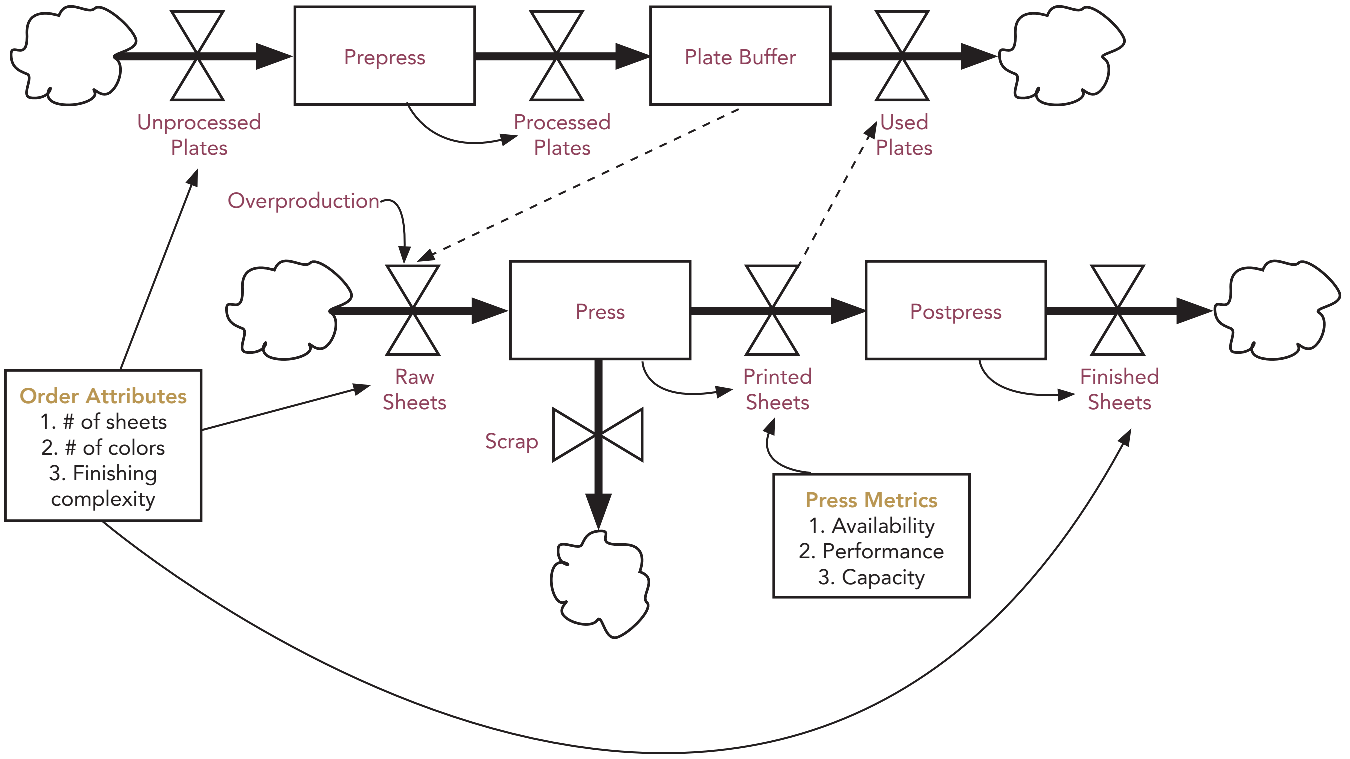


Figure 12. Print production sub-model

Prepress – Plate Flow

As shown in Figure 12, the prepress process involves the plate flow. Once an order enters the system, it carries as an attribute the number of colors. An assumption is made that every color requires a plate; however, the model user can avoid this assumption and provide data on the number of plates directly. Unprocessed plates enter the prepress process by batches equal to the number of colors required by the order. The batch is processed for some time—mostly for design and layout—then the processed plates enter the plate buffer. The prepress processing time includes all of the time elapsed from the order entry until the plates are ready to be used in the plate buffer.

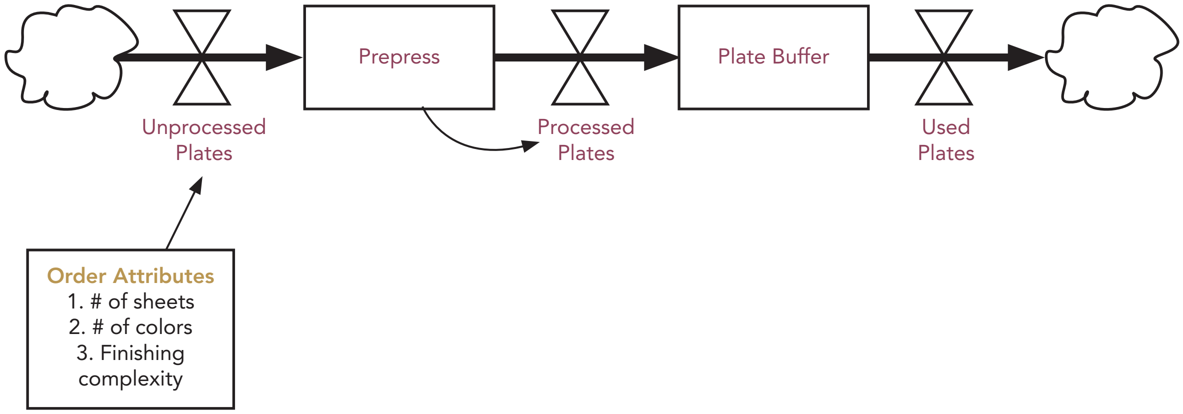


Figure 13. Prepress - plate flow

When the plate buffer has enough plates to process an order, the paper flow may start. These flows are linked by the dotted lines as indicated in Figure 12. The paper flow prints the sheets of an order and uses the plates from the plate buffer. For simplicity, plates are not reused; new plates need to be made for every order.

Press and Postpress – Paper Flow

The most important flow is the paper flow. If plates are available, the press process can start to print an order, according to the amount of sheets that the order requires. Each order is printed in a batch equal to the amount of sheets, plus a percentage of overproduction used for scrap. The press process is constrained by the press metrics of availability, performance, and capacity. These metrics determine how the equipment runs.

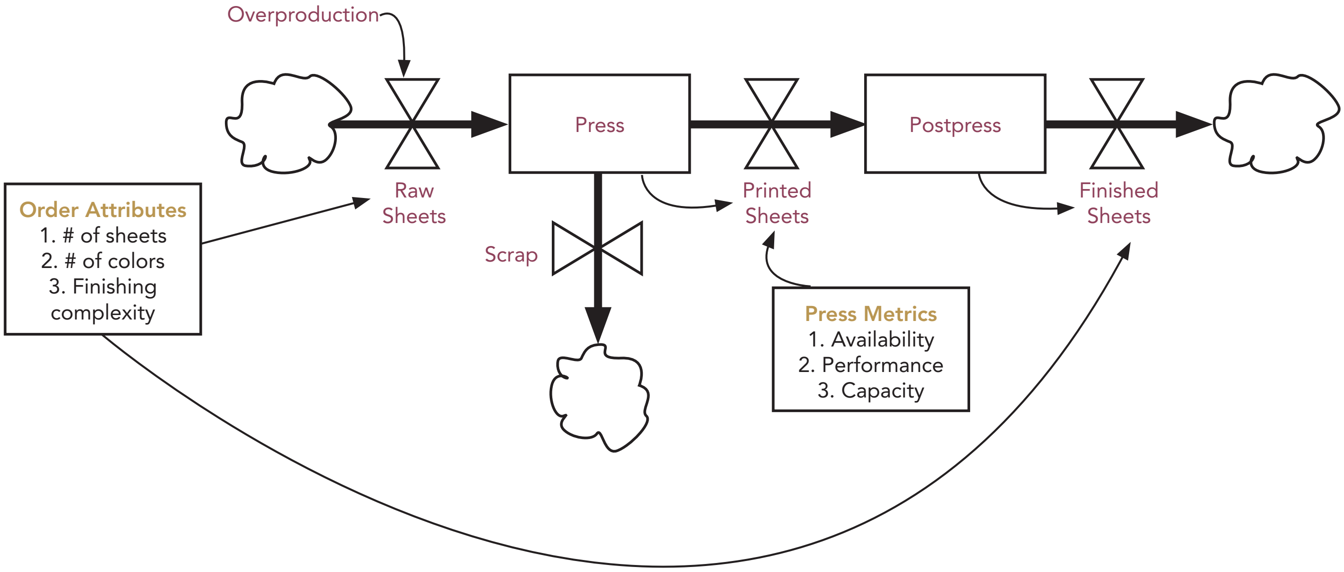


Figure 14. Press and postpress - paper flow

The press metrics are determined for each press in the shop, and are then aggregated for the model.

Availability is defined as the percentage of run time (good production time) of the planned time (run time / planned time). The run time can also be calculated by subtracting the setup time and the downtime from the total planned time. Following these principles, the full planned time is divided into setup time, run time, and the remaining time, which is downtime.

Performance is defined as the percentage of the average run speed of the maximum press speed indicated by the press manufacturer (average run speed / maximum press speed) (Lean Enterprise Institute, 2004).

Capacity is defined as the maximum number of sheets (according to the standard sheet size) per unit of time rated by the press manufacturer. Capacity is determined using the assumption that each job is completely printed with a single pass on a press. This assumption avoids the difficulty of aggregating capacity of multiple presses that have different number of color stations.

The real printing rate of production results from the multiplication of the availability, performance, and capacity. For example, if a press is designed to produce 10,000 sheets per hour and has 5 color stations, its capacity is 10,000 sheets per hour, regardless of the number of color stations. If the percentage of setup time is 35% and downtime is 15%, then the availability is 50%. If, on average, the press runs at 7,000 sheets per hour, then the performance is 70%. For this example, the real rate of production is 10,000 sheets per hour x 0.5 x 0.7 = 3,500 sheets per hour. This is the real output of the press process. Since the press process is a stock that creates a material delay, it must be defined as the time that the material spends in the process. To calculate this time, the number of sheets inside the press process (stock level) is divided by the real rate of production.

The scrap rate is another part of the press process. In order to exclude quality from the model, scrap is only included as part of the material flow. The overproduction percentage needs to be higher than the scrap rate to ensure that all orders are processed completely. This maintains the assumption that there are no orders reprinted due to quality issues. If needed, a "reprint" variable could be added to the model.

The postpress activities are also completed in batches per order. The postpress processing time will vary according to the complexity level of the finishing required. The average time of the postpress process is calculated for each complexity level, then provided to the model. After postpress, the sheets are classified as finished sheets and the unit of measure is kept as sheets for standardization purposes. The finished sheets are immediately shipped to customers. Order fulfillment happens after the sheets are shipped. The postpress process does not have a capacity constraint, a specific setup time, downtime, or a scrap rate due to the following reasons: the many types of postpress equipment that a print shop can have, the difficulties in aggregating them, and the variety of finishing requirements.

As shown in Figure 12, the print production sub-model provides the key productivity-related information for the model: turn time and throughput. The turn time determines the on-time shipments and the competitiveness of the print shop. The throughput provides the effective capacity of the print shop. These outputs are where the model becomes useful for productivity purposes. The model can simulate different scenarios and provide the results on turn time and throughput of the whole system. It provides a holistic approach to productivity, which is usually uncommon among printers. Most printers focus on the press metrics; however, in many cases, improving the press metrics will have no or a very minimal impact on the turn time or the throughput. In other situations, a minor improvement on one of the press metrics can have a large impact on the turn time and throughput. This is dependent upon the specific information and workflow of each print shop simulated.

Lastly, the print production sub-model has the capacity loop integrated within the stock and flow structure. This is a measure of the output of the production backlog stock as finished sheets throughput, which enables a simulation of the model without providing exact capacity data for the whole system if that information is unknown or poorly estimated. When a printer is asked about capacity, the usual answer is that it depends on the type of product, volume, or other production variables. However, the crux of the question is commonly avoided. Another reality is that printing companies rarely refuse any order that a customer wants to place, which means that they assume infinite capacity. As part of the press metrics, capacity is fixed according to the number of presses a print shop has. However, any productivity gains of the whole system (measured as higher throughput and lower turn time) have an effect on the capacity balancing loop presented in Phase 2.

Phase 4. Testing

Even though testing occurs constantly from the start of the modeling process, a severe test must take place once there is a fully functional version. The test consists of extreme conditions that do not normally occur in real life, but that have predictable outcomes of exactly what the model should do in these situations. In order to complete this phase, it is critical to understand fully the functional version of the model within the iThink™ software.

Causal Loop Diagram and Variable Description

As shown in Figure 15, the causal loop diagram developed in Phase 2 is replicated in the final model, including the turn time reinforcing loop and the reliability reinforcing loop.

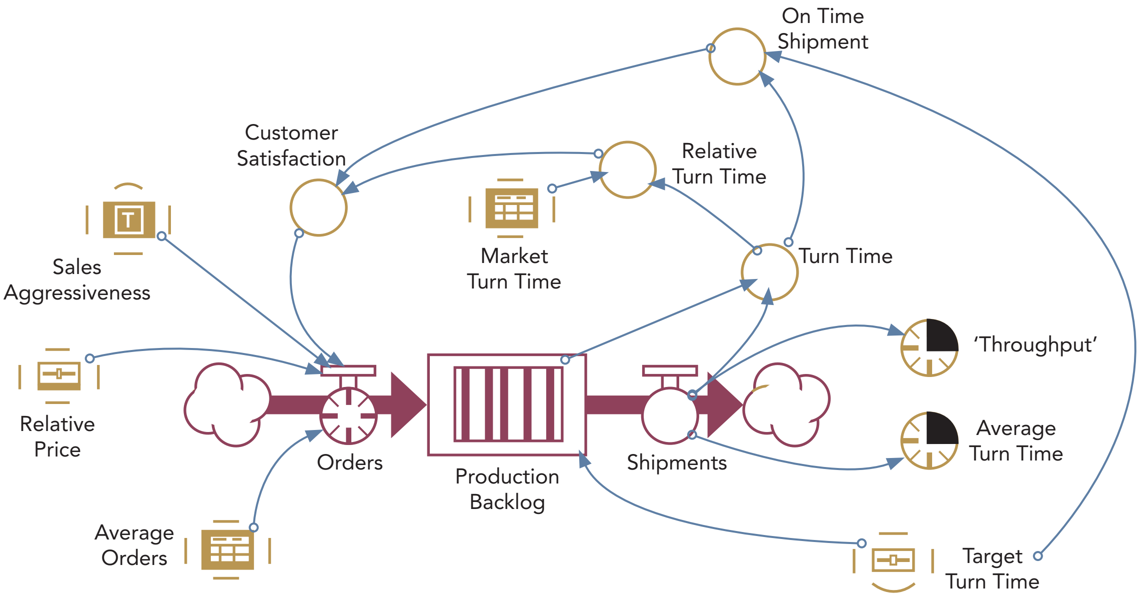


Figure 15. Causal loop diagram in iThink™

The two extra variables (throughput and average turn time) were added for measuring and graphing the results of every simulation run. The balancing feedback loop has been eliminated since the capacity constraints are defined within the production stock sub-model.

Sales Aggressiveness. Sales aggressiveness is a binary decision variable consisting of an on/off switch. When "on," the sales force achieves 10% more orders than their average after a two-month delay. When "off," there is no impact on the order inflow. The delay indicates that this decision does not have immediate impact. The values of 10% and two months are estimates for this particular simulation; they may be changed to suit specific estimates of other companies.

Relative Price. Relative price is also a decision variable, indicating the ratio of the company's price and the market price. The impact on orders is linear and inverse. For example, a 10% decrease in the relative price ratio results in a 10% increase of incoming orders. To maintain the validity of the linear assumption, a limited range from 0.75 to 1.25 has been defined.

Average Orders. The average orders variable is used to input the statistical history of incoming orders of the print shop. For simplicity, only the average is incorporated. If desired, more detailed historical data including cycles and seasonal demand may be included. Also, organic growth common to most industrial businesses has been excluded as it is considered outside of the boundaries and purpose of this model. However, when it is considered necessary, an organic growth rate related to market growth can easily be added.

Customer Satisfaction. Customer satisfaction is one of the key variables of the model. The performance of the company affects the customer satisfaction level, and this in turn has an impact on future order volumes. Customer satisfaction is dependent on relative turn time and on-time shipments. A three-month delay will affect this variable. In other words, the level of customer satisfaction has an impact on the order entry flow only after three months. The following equation defines this variable:

(A*On-time Shipment + B)*Relative Turn Time

Where A = degree of positive impact of an order shipped on time
B = limit of negative impact of a late order

This simulation considers that an order shipped on-time has a positive impact on order volume of 20%, while a late order has a negative impact of 40%. Since the on-time shipment variable is either zero or one, setting A to 0.6 and B to 0.6 achieves this effect. (For more information, please refer to the explanation of this variable later in this section.)

As an example, if we assign a value of one to the relative turn time and the order is shipped on-time, then customer satisfaction = (0.6*1 + 0.6)*1 = 1.2, which is equivalent to a 20% positive impact on order volume. On the contrary, if the order is late, then customer satisfaction = (0.6*0 + 0.6)*1 = 0.6, which is equivalent to a 40% negative impact on order volume. The relative turn time multiplies the effect of the on-time shipment, introducing both outcomes into the calculation of the customer satisfaction level. For this simulation, the relative turn time varies between 0.5 and 1.5; this is further explained later in this section.

Order Inflow. The order inflow multiplies the impact of all the variables affecting the incoming order volume. Variables that affect the incoming order volume are average orders, relative price, sales aggressiveness, and customer satisfaction. The result determines the order volume for the each differential time (one day) of the simulation. The order inflow is defined by the following equation:

Average Orders*(1/Relative Price)*Delay(1 + Sales Aggressiveness,2,1)
*Delay(Customer Satisfaction,3,1)

The delays of the incoming variables are defined in the order inflow equation.

Production Backlog. The production backlog is a conveyor belt-type stock that contains the sub-model.

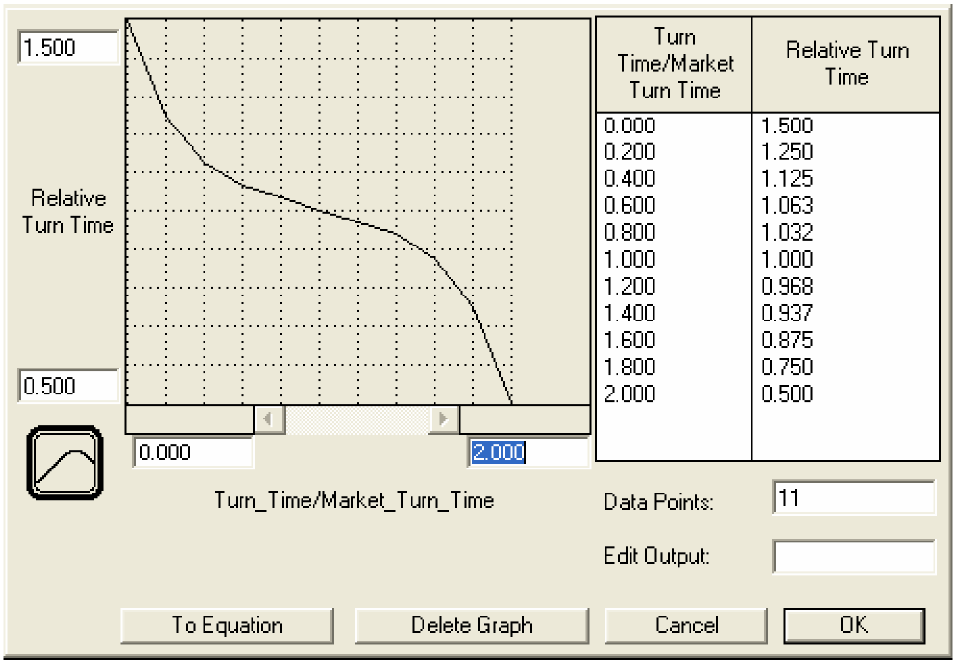
Shipments. The shipments outflow completely depends on the sub-model, and is therefore described in the sub-model section.

Turn Time. Little's Law defines turn time as the inventory in the production backlog divided by the shipment rate, as shown in the equation below:

Production Backlog/Shipments

Market Turn Time. This variable incorporates the average turn time of the market. It is usually well estimated by the sales team, according to the requests of their customers and their knowledge of the conditions that customers are getting from the competition.

Relative Turn Time. The relative turn time is a variable defined with a range of 0.5 to 1.5, intended to approximate the impact of the turn time when compared to the market turn time on customer satisfaction. Figure 16 defines this relationship graphically:



Turn Time/Market Turn Time	Relative Turn Time
0.000	1.500
0.200	1.250
0.400	1.125
0.600	1.063
0.800	1.032
1.000	1.000
1.200	0.968
1.400	0.937
1.600	0.875
1.800	0.750
2.000	0.500

Data Points: 11

Edit Output:

Figure 16. Relative turn time

A turn time lower than the market turn time will have a positive (> 1) impact on customer satisfaction. If the turn time equals the market turn time, then the effect is neutral (= 1). If the turn time is higher than the market turn time, then the impact on customer satisfaction is negative (< 1). The shape of the curve indicates that, when the turn time is competitive (meaning near the market turn time), the effect on customer satisfaction stays near neutral within a narrow range. However, as the turn time moves farther away from the market turn time, the slope of the curve is steeper, increasing the impact on customer satisfaction exponentially. For example, if a print shop has turn times of one or two days over or under the market turn time, then the volume of orders should not vary much. On the other hand, if the turn times are 15 days over the market turn time, orders would most likely plummet. If the turn times are 15 days under the market turn time, orders would most likely rise steeply.

Target Turn Time. Target turn time is also a decision variable. It enables the user to determine the desired turn time that is promised to the customers by the sales force. The actual turn time is then compared to the target turn time for every order to determine if the order has been shipped on-time. A high target turn time improves the on-time service, but decreases the production schedule pressure within the sub-model. The range for this variable is 0.1 to 2.0 months.

On-time Shipment. On-time shipment is a binary variable. If the turn time for an order is less than or equal to the target turn time, then the value is 1. In all other cases, it is 0, indicating a late order. The following equation defines this variable:

$$\text{if Turn Time} \le \text{Target Turn Time then 1 else 0}$$

The impact of this variable on the level of customer satisfaction is also assumed to be binary, with a significant direct impact. The orders shipped on-time increase the customer satisfaction level by 20%. Late orders, on the other hand, decrease the customer satisfaction level by 40%. The higher relative impact of the late orders corresponds to customers' expectation to be served on-time. Late orders are usually punished drastically, while on-time orders do not necessarily bring in more orders on all occasions.

Throughput. Throughput is a variable used only for graphing purposes. It reports one of the main metrics related to productivity—the output per unit of time. For the simulation, it reports the number of orders shipped per month. The goal of the simulation is to maximize the throughput.

Average Turn Time. The average turn time is also a variable used for graphing purposes. It provides the average turn time of the orders shipped daily. The average turn time is appropriate when used to evaluate the turn time of orders within a short time frame (for example, one day.) When considering longer time frames (for example, one month or one year), the average turn time should not be used, as since it is likely that the distribution of turn time is non-normal.

Stock and Flow Diagram and Variable Description

The stock and flow structure of the print production sub-model was also developed in the iThink™ software. As shown in Figure 17, the sub-model includes the plates flow related to the prepress process and the paper flow related to the press and postpress processes.

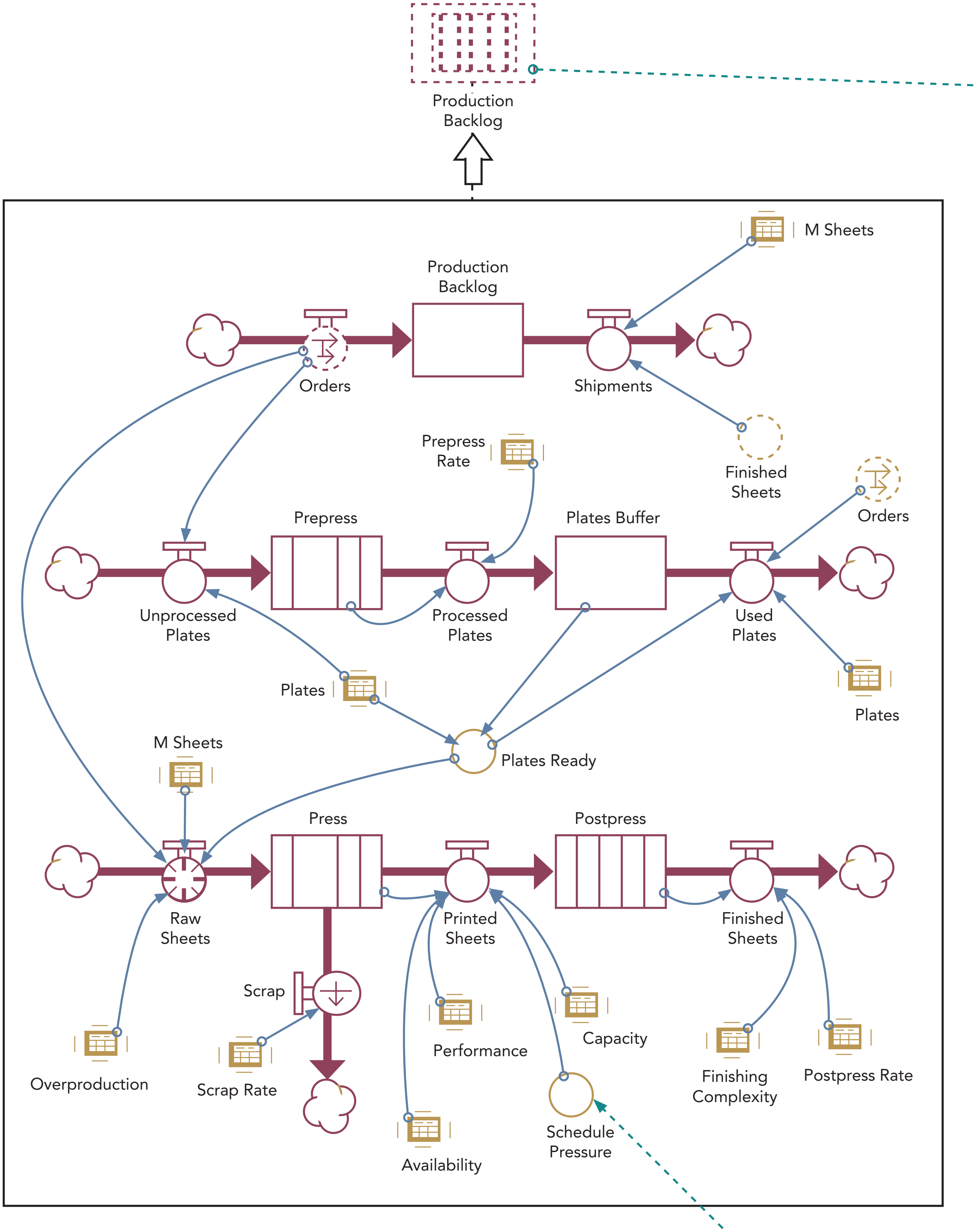


Figure 17. Print production sub-model in iThink™

Unprocessed Plates. Unprocessed plates is a flow variable that activates with each order. It is defined by the following equation:

Orders*Plates

Plates. The plates variable is used to input the average number of plates used per order. This average is calculated from the statistical data of the print shop, or it is related to the number of colors per order.

Prepress. Prepress is a conveyor stock that represents the time spent in the prepress process.

Prepress Rate. The prepress rate is an input variable of the average or estimate number of plates processed per month at full prepress capacity.

Processed Plates. Processed plates is the outflow of the prepress process and the inflow of the plates buffer stock. It represents the transit time of each plate in the prepress stock, as calculated by the following equation:

Prepress/Prepress Rate

Plates Ready. The plates ready variable is a binary variable that indicates whether or not there are plates ready to use in the plates buffer in order for the press process to start. It is defined by the following statement:

If Plates Buffer > Plates then 1 else 0

Plates Buffer. The plates buffer is a stock that acts as a buffer between the prepress and press processes. It accumulates processed plates from prepress, then disposes of them after they are used by the press process. If this stock is empty or has fewer plates than the average plates needed by the press process, then the press process will not start.

Used Plates. The used plates flow is the outflow of the plates buffer stock. It represents the disposal of plates after they are used by the press process. This outflow is calculated by the following statement:

If Plates Ready = 1 then Plates*Orders else 0

M Sheets. The M Sheets variable is used to input the average thousands (M) of sheets needed per order. This average is calculated from the statistical data of the print shop according to the standard sheet size.

Overproduction. Overproduction is an input variable for the average percentage of sheets used for scrap and setup. It is usually a production planning policy decision.

Raw Sheets. The raw sheets flow represents the inflow of sheets into the press process. It is calculated by the following equation:

Orders*M Sheets*(1 + Overproduction)*Plates Ready

Press. Press is a conveyor stock that represents the time spent in the press process.

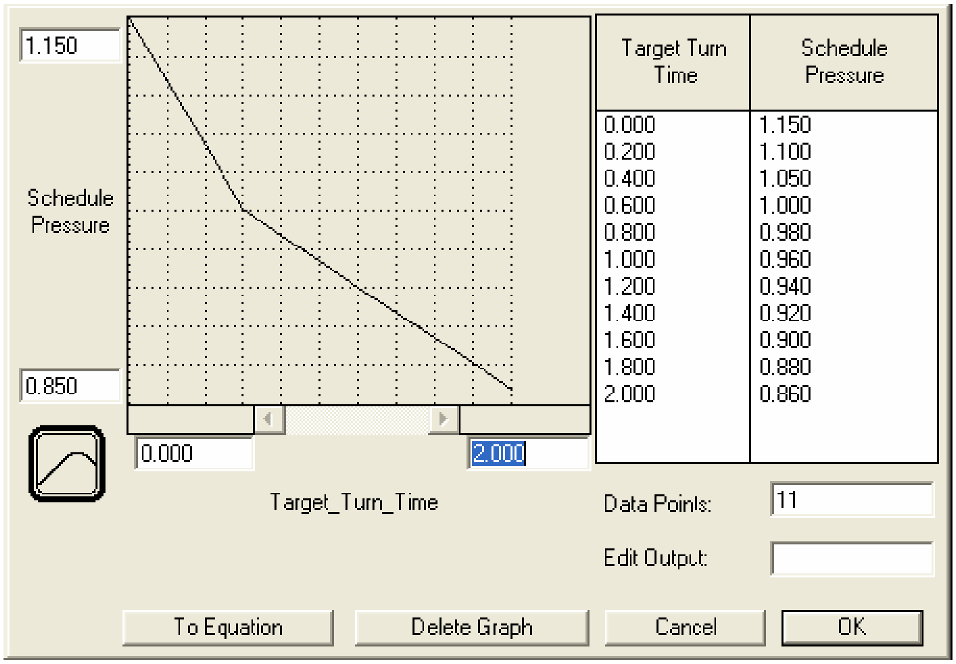
Scrap. Scrap represents the leakage of sheets from the press process due to scrap. This outflow is a fraction of the press stock and is determined by the scrap rate.

Scrap Rate. The statistic or estimate of the press scrap rate is calculated as the percentage of scrap sheets needed by an order.

Availability. Availability is an input variable of the press metrics that indicates the ratio of run time to total planned press time. The run time can also be calculated by subtracting the setup time and downtime from the total planned press time.

Performance. Performance is an input variable of the press metrics that indicates the ratio of the average press speed achieved to the maximum rated press speed. Printers commonly state that they often do not achieve the maximum rated press speed indicated by the press manufacturers. This represents a loss of the maximum capacity of the press.

Schedule Pressure. Schedule pressure is the only variable incorporated from the capacity balancing feedback loop presented in Phase 2. This variable describes how variations of the target turn time affect the real output of the press process. The assumption here is that the press process capacity adjusts to a certain degree (± 15%) in order to achieve the target turn time promised to customers. This happens in real production environments when the press process output is augmented with the use of overtime. This also occurs when the press process output is diminished due to a relaxed mood assumed by the press operators when the schedule pressure is low or to some other factor. Figure 18 illustrates this variable graphically.



Target Turn Time	Schedule Pressure
0.000	1.150
0.200	1.100
0.400	1.050
0.600	1.000
0.800	0.980
1.000	0.960
1.200	0.940
1.400	0.920
1.600	0.900
1.800	0.880
2.000	0.860

Data Points: 11

Edit Output:

Figure 18. Schedule pressure

Capacity. Capacity is the aggregated maximum thousands of sheets of all presses that can be printed per month, according to the maximum rated press speed indicated by the press manufacturer. The assumption that every job can be printed on a single run on a press is used in order to simplify the calculations and to eliminate the difficulty of aggregating the capacity for presses with different number of colors. The aggregate capacity can be calculated by determining a standard sheet size, then adding up the capacity of all presses according to the standard sheet size. For example, suppose a print shop has six presses:

a) Two 14x20" 2-Color, rated at 7,000sph;

b) Three 20x28" 5-Color, rated at 12,000sph; and

c) One 28x40" 6-Color, rated at 15,000sph.

First, the standard sheet size is determined. In this case, the standard sheet size selected is 20x28". Next, a factor by area is determined for the other sheet sizes: 0.5 for the 14x20" and 2 for 28x40". Lastly, the aggregate capacity for the standard sheet size is determined by this formula:

Aggregate Capacity = (Q1*F1*R1 + Q2*F2*R2 + … + Qn*Fn*Rn)*P

Where: Qn = quantity of presses type "n"
Fn = factor by area of the presses type "n" to the standard sheet size
Rn = manufacturers' maximum rated press speed in thousands of sheets per hour (Msph) of the presses type "n"
P = planned production hours per month

The planned production hours may be calculated from historical data or may be estimated using 25 working days per month and two 8-hour shifts per day for a total of 400 hours. Note that, for simplicity, the number of colors of each press is excluded from the formula. The total aggregate capacity of this example is calculated below:

Aggregate Capacity = (2*0.5*7 + 3*1*12 + 1*2*15)*400 = 29,200

Printed Sheets. The printed sheets flow is the outflow of the press process and the inflow of the postpress process. This flow is different from all the other process outflows as it is not governed by a simple process rate. Instead, the press rate is calculated using the press metrics that are commonly monitored at a print shop. The printed sheets flow represents the transit time of each M sheets in the press stock, as calculated by the following equation:

Press/Availability*Performance*Capacity*Schedule Pressure

Postpress. Postpress is a conveyor stock that represents the time spent in the postpress process.

Finishing Complexity. Finishing complexity is an input variable that indicates the degree of complexity of the postpress process of a certain print shop, depending on its product line and equipment. The finishing complexity level is "high" if the order requires three or more separate postpress activities, "medium" if it requires one or two, and "low" if done inline. The following assumption is used to determine the aggregate finishing complexity level: It takes twice as long to complete a "high" level order than a "medium" level order, and twice as long to complete a "medium" level order than a "low" level order. The following factors are used in order to calculate the weighted average:

Low = 2.0, Medium = 1.0, and High = 0.5

Postpress Rate. The postpress rate is an input variable of the average or estimate number of M sheets processed per month at full postpress capacity, considering only medium finishing complexity level orders.

Finished Sheets. The finished sheets flow is the outflow of the postpress process. It represents the transit time of each M sheets in the postpress stock, calculated by the following equation:

Postpress/Finishing Complexity*Postpress Rate

Shipments. The shipments flow is the final outflow of the production backlog stock and indicates the rate of orders being shipped per month. It is the key outflow, since it depends on the whole dynamics of the print production sub-model and, at the same time, determines the turn time per order for the calculation of the critical reinforcing loops of turn time and reliability. The shipments flow is determined by the following equation:

Finished Sheets/M Sheets

The shipments rate, therefore, is the finished sheets outflow of the paper flow divided by the average thousands of sheets per order (M Sheets) to determine how many orders are finally shipped to the customers.

Severe Testing

Two important variables from different areas of the model have been selected for the severe testing. Each variable is tested at their defined minimum and maximum levels and the results are analyzed for proper logic and correct behavior of the model. Two sets of graphs are used to analyze the results: performance metrics and order metrics. The performance metrics consist of throughput, on-time shipment, and average turn time. The order metrics show the behavior of the order inflow, the production backlog, and the shipments outflow. Both graphs summarize the time series behavior of key metrics that govern the model for the whole 48 months of simulation.

Both graphs present three different variables. The X-axis has the time of the simulation in months. The Y-axis represents the value of the variables at each time. To interpret the graphs correctly, review the range of values for each variable on the Y-axis. Note that each variable has different ranges, and the ranges may change from simulation to simulation. Therefore, a curve that appears to be higher than another may actually be lower, depending on the range. This function of adjustable ranges has been selected so that the graphs can adapt to multiple simulations and scenarios.

Average Orders. Average orders have a significant impact on the behavior of the model. It is also feasible to anticipate what happens when a print shop is out of orders or when the orders exceed the capacity by tenfold. The first test consists of running the model with no incoming orders per month. Consequently, both the throughput and average turn time are zero; this is illustrated in Figure 19. The on-time shipment is undefined if no orders are shipped.

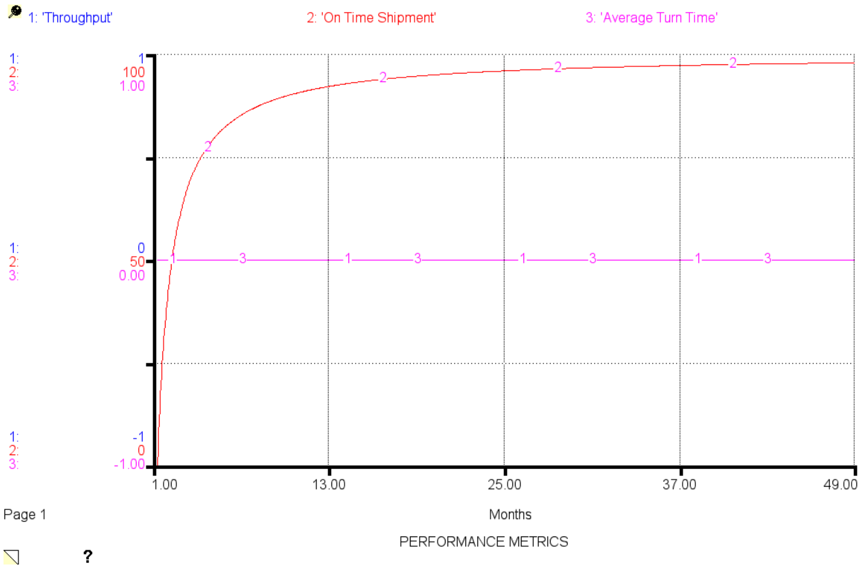


Figure 19. Zero incoming orders - performance metrics

As shown in Figure 20, the level of orders, production backlog, and shipments stays consistently at zero. This first test is successful, since the model behaves within logic.

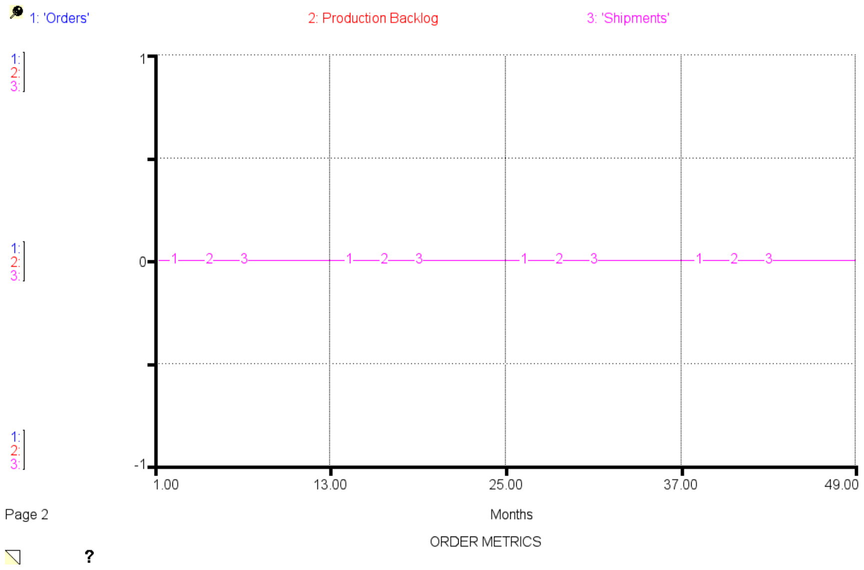


Figure 20. Zero incoming orders - order metrics

On the other extreme, the test consists of 100,000 average incoming orders per month. This clearly exceeds the capacity of the print shop being simulated. The model also behaves properly under this scenario. As shown in Figure 21, the throughput overshoots and collapses immediately after the first month, the on-time shipment collapses to 0% immediately, and the average turn time increases periodically during the overshoot and collapse periods.

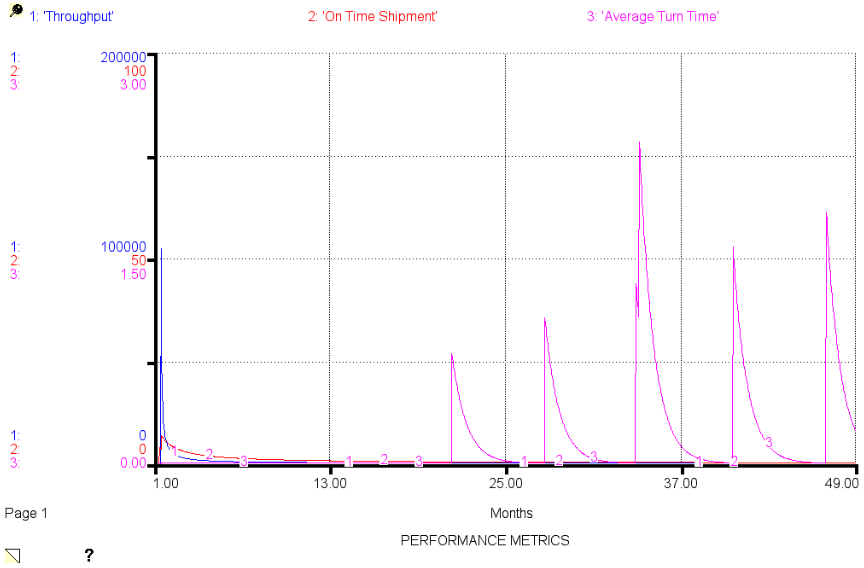


Figure 21. One hundred thousand incoming orders - performance metrics

The order metrics also behave accordingly. After the first three months, the orders collapse due to the poor service levels. As shown in Figure 22, the production backlog increases consistently (due to the lack of capacity), and the shipments overshoot and collapse periodically.

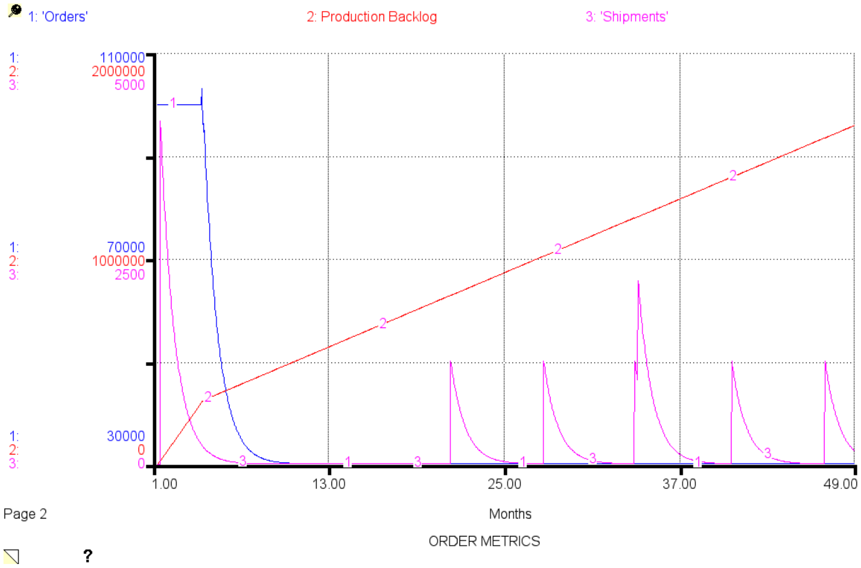


Figure 22. One hundred thousand incoming orders - order metrics

Press Capacity. This test consists of the extreme of having zero press capacity (zero presses) and the extreme of having the capability of printing one billion sheets per month (huge capacity).

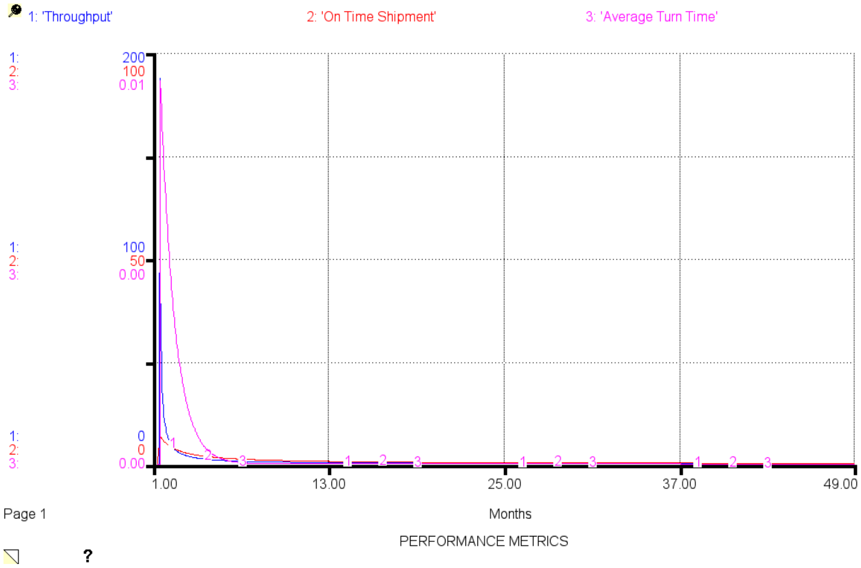


Figure 23. Zero press capacity - performance metrics

As shown in Figure 23, for the scenario of zero capacity, the model assumes infinite transit time within the press process; consequently, after the first month, every performance variable goes to zero.

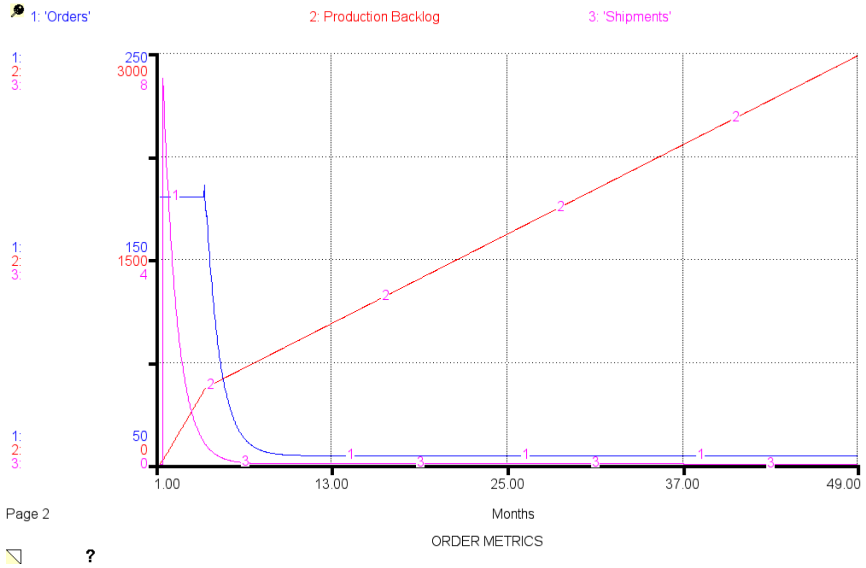


Figure 24. Zero press capacity - order metrics

On the order metrics, the incoming orders collapse towards zero, the shipments collapse to zero, and the production backlog grows consistently since no orders are being printed. The system keeps receiving a minimum amount of orders due to the average incoming orders that are calculated during the setup of the simulation. Figure 24 illustrates these order metrics for zero press capacity.

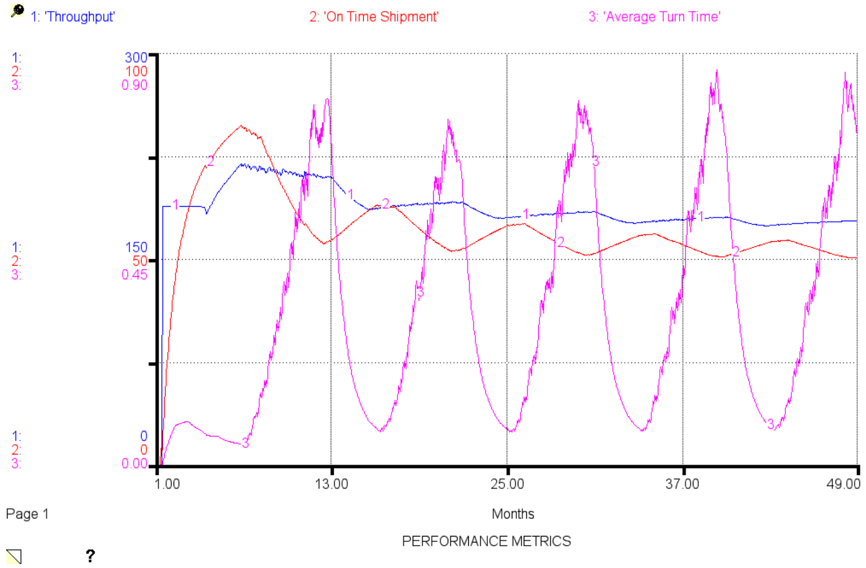


Figure 25. Huge press capacity - performance metrics

On the other extreme, the simulation is run with a huge press capacity of one billion sheets per month. As shown in Figures 25 and 26, both the performance metrics and the order metrics behave very similarly when compared to previous runs with normal press capacity. Only marginal improvements are achieved.

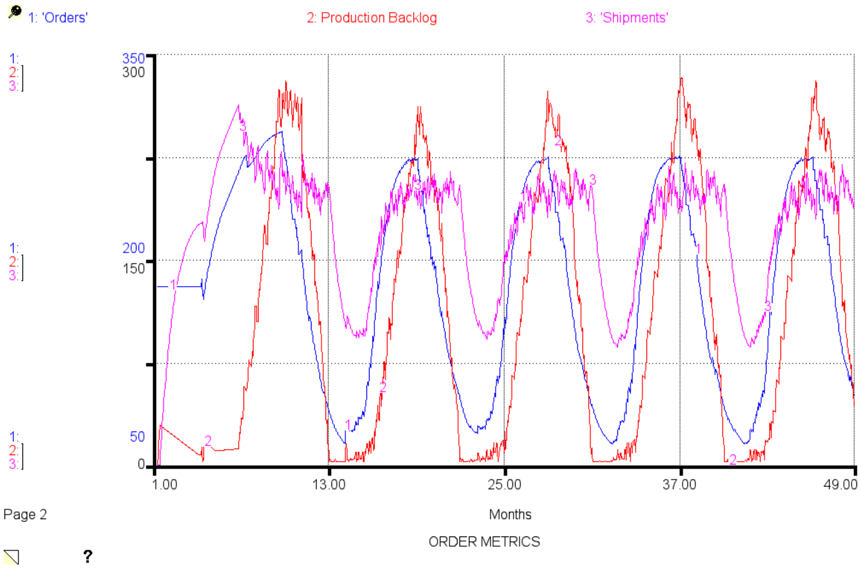


Figure 26. Huge press capacity - order metrics

The improvements hit an immediate limit when the constraint moves from the press process to the postpress process. This is also consistent with logic that indicates that the constraint process limits the maximum output of the whole system. Once the additional press capacity surpasses the capacity of any of the other processes, adding more press capacity brings no additional throughput since the press process is no longer the constraint. The constraint topic is further discussed and developed during Phase 5.

Turn Time. The turn time test is not conducted as a part of the severe test, but as a test to check the common distribution of the turn time of printing companies. Experience and statistics indicate that most print shops have a binomial distribution when analyzing the turn time of multiple orders during a long period of time, such as over one calendar year. This behavior results from any of the following situations: some orders are processed as rush orders for major customers, with very short resulting turn times. Other orders are processed near the target turn time that is promised to normal customers. Also, there are a small percentage of orders that have issues, and these require a significant amount of time before being shipped. Due to those situations, the distribution of the turn time has a binomial behavior with one peak near zero, another peak near the target turn time, and a small number of orders with long turn times. The distribution of a normal simulation run was graphed to test this behavior. This distribution is shown in Figure 27.

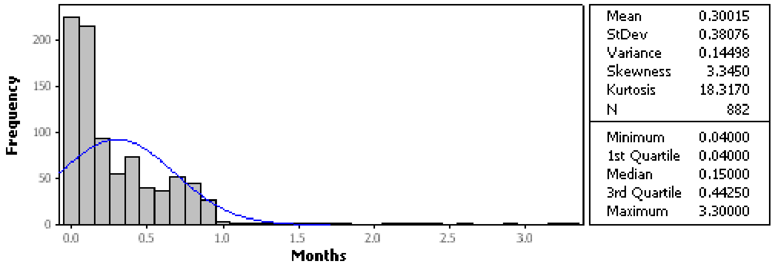


Figure 27. Distribution of turn time

The distribution has the largest peak near the zero value, which indicates that several orders have been processed very quickly, mainly as a result of very low production backlogs during this simulation. The second peak near 0.4 months is consistent with the target turn time selected for this run. This indicates that several orders have been shipped near the date promised to customers. The rest of the orders have been shipped with longer turn times and show lower frequencies, consistent with the fact that some orders have significant delays. The correct performance of the model during this test indicates that the proper dynamics have been captured and correctly reproduced. This is a significant support of the model's validity, since the behavior of this key metric is critical for the model output as it regulates the two main reinforcing loops. Even though the binomial behavior of this distribution is not very strong, a distribution skewed to the right is also a common dynamic of production processes that contain separate sub-processes. For printing, the clearly defined and independent sub-processes of prepress, press, and postpress behave according to the dynamics of a third-order delay (Sterman, 2000), as orders have variable wait times at each process depending on the backlog at each process and capacity constraints.

The severe tests are successful, proving the model's consistency under extreme conditions. To run these tests, a set of estimated values and parameters of an ordinary printing company were loaded into the model. The fact that the model behaves adequately using these values is another factor confirming that the model is ready for use. Once the model is trustworthy and the metrics are defined, the last phase of policy design and evaluation can take place.

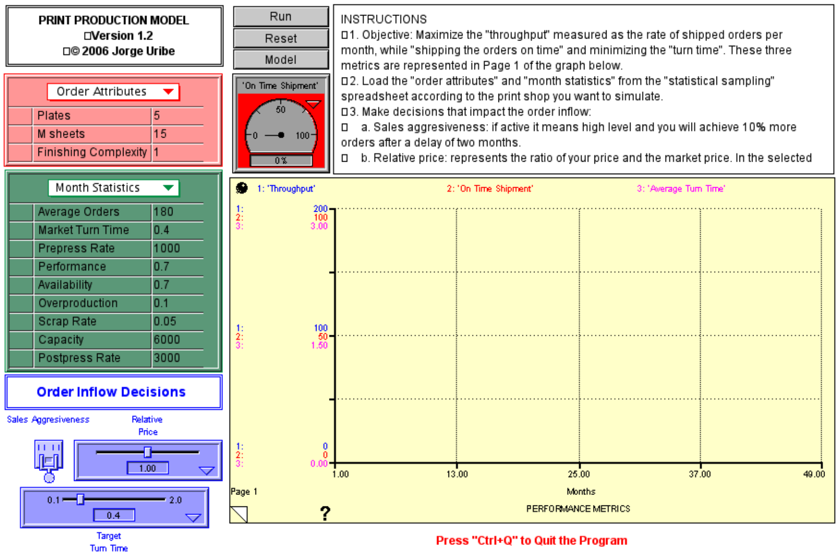
Phase 5. Policy Design and Evaluation

The final phase consists of using the model for policy design and evaluation. Once the model is tested and ready to use, data from any company can be loaded, and the model can run under the existing policies and practices to establish the current baseline, also known as the "status quo scenario." Then, new policies and decisions can be made, and the model is run again. Better results imply improvement, and worse results indicate the need for adjustments. At this stage, the model becomes a great learning tool and a powerful simulator for developing entirely new strategies, structures, and decision-making rules.

Before starting, it is essential to understand how to use the model, interpret the results, and load the statistical data needed. Only then can common scenarios related to the industry be simulated. The first scenario works under an aggressive sales strategy: sell the most you can, no matter what. The second scenario is based on productivity improvements focused on the press process only. The third scenario is related to the trend of shrinking order size and increased frequency of orders. Lastly, a mixed strategy scenario based on synergy, productivity, and growth of the whole system is presented to show how good overall results can be achieved.

Using and Interpreting the Model

As shown in Figure 28, the model runs directly from a control panel designed for easy input of data and decisions. On the left, the statistics on order attributes and monthly data are entered. The order attributes have either already been measured by the print shop intended to be simulated, or they can be sampled statistically from past orders. Order attributes indicate the average plates per order, the average thousands of sheets per order, and the finishing complexity level. Monthly data can also be previously measured, statistically sampled, or estimated. Monthly data includes the average orders per month, the market turn time, the prepress rate, the press metrics (i.e., performance, availability, overproduction, scrap rate, and capacity), and the postpress rate. On the bottom left side, decisions affecting the order inflow can be made. The switch of sales aggressiveness can be turned on or off to change from a low to a high level, and vice versa. The relative price slider can be modified to increase or to decrease the company's price in relation to the market price. Finally, the target turn time offered to the customers can also be modified to lower values (attracting more orders) or to higher values (guaranteeing an improved percentage of orders shipped on time.)



PRINT PRODUCTION MODEL
☐Version 1.2
☐© 2006 Jorge Uribe

INSTRUCTIONS
☐1. Objective: Maximize the "throughput" measured as the rate of shipped orders per month, while "shipping the orders on time" and minimizing the "turn time". These three metrics are represented in Page 1 of the graph below.
☐2. Load the "order attributes" and "month statistics" from the "statistical sampling" spreadsheet according to the print shop you want to simulate.
☐3. Make decisions that impact the order inflow:
☐ a. Sales aggresiveness: if active it means high level and you will achieve 10% more orders after a delay of two months.
☐ b. Relative price: represents the ratio of your price and the market price. In the selected

Order Attributes	
Plates	5
M sheets	15
Finishing Complexity	1

Month Statistics	
Average Orders	180
Market Turn Time	0.4
Prepress Rate	1000
Performance	0.7
Availability	0.7
Overproduction	0.1
Scrap Rate	0.05
Capacity	6000
Postpress Rate	3000

Relative Price: 1.00
Target Turn Time: 0.4

Figure 28. Control panel

The buttons on the top control some actions within the simulation. The run button runs the model for three months each time it is pressed. Decisions and policies may be changed every three months, replicating managerial or Board of Directors' meetings that modify the direction of the company. The reset button is used when a new scenario needs to be simulated. The reset button returns all variables to their original values and clears the graphs. The model button shows the model structure within the iThink™ software.

Below the buttons is a status indicator of the on-time shipment performance. The status indicator is green if the performance is above 80%, yellow if it is between 50% and 80%, and red if it is below 50%.

Lastly, the time series graphs in the bottom right corner show the measured outputs of the model. Page 1 shows the performance metrics: throughput, on-time shipment, and average turn time. The objective of the model is to maximize the "throughput," measured as the rate of shipped orders per month, while "shipping the orders on time" and minimizing the "turn time." Page 2 shows the order metrics: incoming orders, production backlog, and order shipment. These graphs represent the main stock and flow structure of the model from where the variations of the order backlog (due to variations of the book-to-bill ratio) can be appreciated. Managing the level of the backlog is a key element for achieving the main objective of maximizing throughput while keeping turn time under control. Page 3 represents the print processes metrics: prepress, press, and postpress. The print processes metrics show what is happening at the sub-model level within the production backlog stock. This graph is useful to identify which process is the bottleneck that limits the output of the whole system.

Status Quo Scenario: Baseline

In order to improve, the current baseline needs to be determined. This level represents the scenario "status quo." This is usually not the best strategy, but, surprisingly it is not the worst scenario, either. The spreadsheet (shown in Table 2) is used to input and to calculate the data of an imaginary print shop that serves as an example for the policy design and evaluation phase. The same calculations and input need to be completed when simulating any print shop in particular. The data captured in the spreadsheet is then used as the input data for the model within the control panel. The order column is a set of random numbers used for selecting the orders for the statistical sampling.

Table 2. Statistical sampling spreadsheet

STATISTICAL INFORMATION							
ORDER SAMPLING					MONTH STATISTICS		
Sample	Order	Plates	M Sheets	Finishing Complexity			
1	205	5	20.0	High	Average Orders	180	
2	639	2	5.0	Low	Market Turn Time	0.40	
3	581	8	2.0	Medium	Prepress Rate	1000	
4	287	3	21.0	High	Performance	0.70	Press Metrics
5	358	5	91.0	Medium	Availability	0.70	
6	457	6	23.0	Medium	Overproduction	0.10	
7	143	12	2.0	Low	Scrap Rate	0.05	
8	162	11	1.0	High	Capacity	6000	
9	655	6	3.0	Medium	Postpress Rate	3000	
10	153	7	5.0	Medium			
11	141	3	8.0	Medium			
12	412	3	43.0	Medium			
13	238	1	7.0	Low			
14	539	6	1.0	High			
15	112	4	27.0	High			
16	949	5	18.0	Medium			
17	134	3	21.0	Medium			
18	881	5	4.0	Medium			
19	080	5	9.0	High			
20	250	5	11.0	High			
21	072	4	3.0	High			
22	010	5	35.0	Low			
23	958	3	1.0	Medium			
24	983	4	44.0	High			
25	032	4	3.0	High			
26	739	4	6.0	Medium			
27	021	2	1.0	Low			
28	807	7	19.0	Low			
29	694	8	11.0	High			
30	297	5	6.0	Medium			
Averages		5.0	15.0	1.0			

After loading the data into the model from the spreadsheet, the model is executed for the 48 months of the simulation. The results of the status quo scenario or baseline are presented in Figure 29.

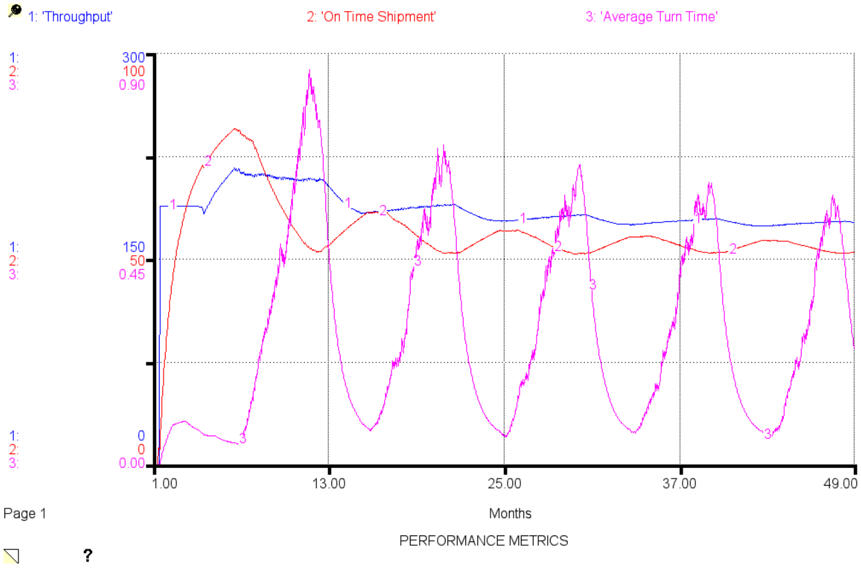


Figure 29. Status quo scenario - performance metrics

The throughput behavior is very stable during the whole simulation (around the level of 180 orders per month.) The on-time service metric ended the simulation at a level of 52%, which definitely needs improvement. Lastly, the average turn time is far from stable, fluctuating from low levels of 0.04 months (1 day) to 0.83 months (21 days). Usually, customers and the sales team ask for a standard and fixed turn time. The dynamics of the print shop in this scenario show that this is not the case, as the turn time fluctuates according to the variations of the production backlog.

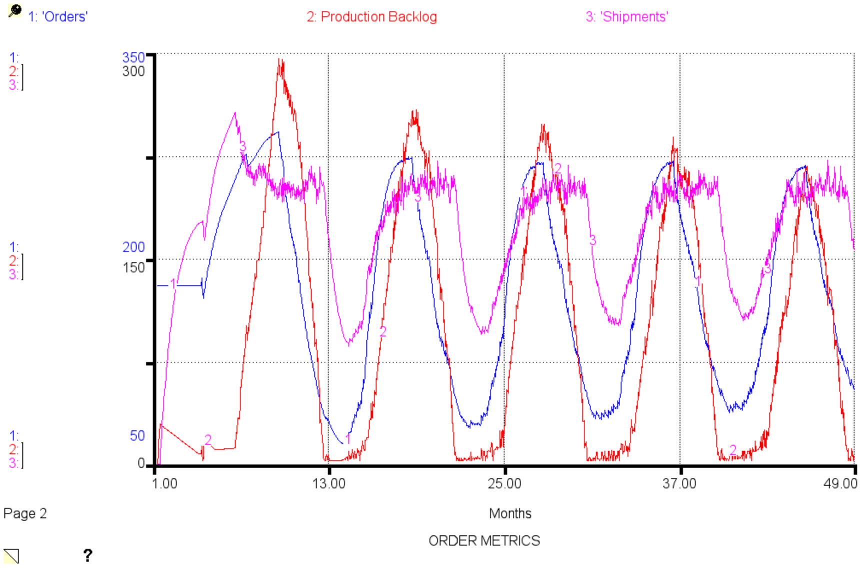


Figure 30. Status quo scenario - order metrics

Figure 30 represents the order metrics. The incoming orders fluctuate consistently with the fluctuation of the turn time and on-time service metrics. This indicates that poor service performance directly affects incoming orders. When the service levels improve, the order level also improves. However, the lack of flexible capacity means that the shop cannot respond fast enough to the higher number of orders, causing the service level to drop again. The shipments fluctuate less, due to reaching a maximum level at 256 orders. This is controlled by the production backlog, which acts as a buffer.

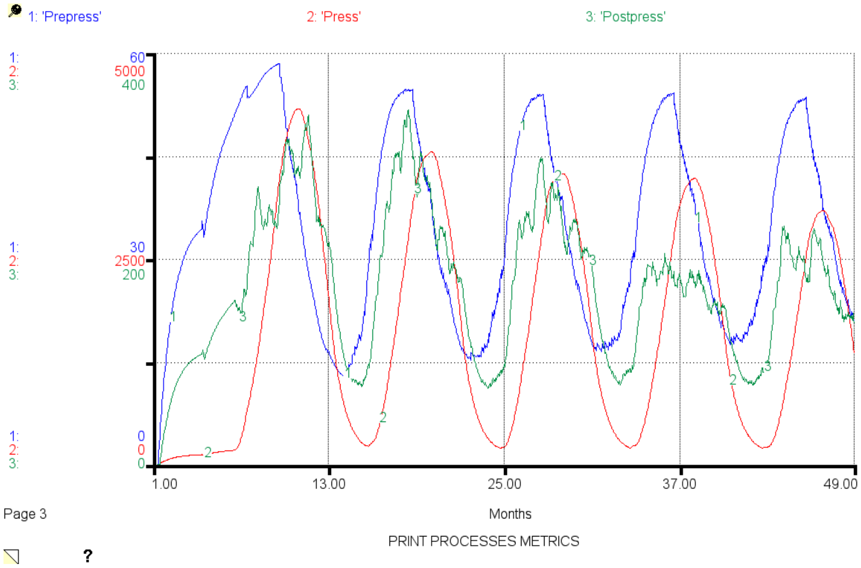


Figure 31. Status quo scenario - print processes metrics

Figure 31 shows the behavior of the stocks related to prepress, press, and postpress processes. In this case, the press process represents the bottleneck, since higher amounts of orders accumulate and wait in line for the press process. The press process has a similar behavior to the prepress process, but lags behind it by two months.

Aggressive Sales Scenario

The status quo scenario sets the current situation: a throughput of 180 orders per month, poor on-time service level at 52%, and a large fluctuation of turn time between 1 day and 21 days. The current performance is not good, and customers definitely expect better service. An alternative solution seems to be to sell much more by executing an aggressive sales strategy. The strategy consists of selling as much as possible by aligning the sales force to the aggressive mood (in the model, the sales aggressiveness switch was turned to "on"). This brings in 10% more orders after a two-month delay. This aggressive strategy is accompanied by a 15% price discount and an offering of a shorter target turn time—0.2 months (5 days) instead of the standard 0.4 months (10 days). Figure 32 shows the results achieved after running the model for 48 months.

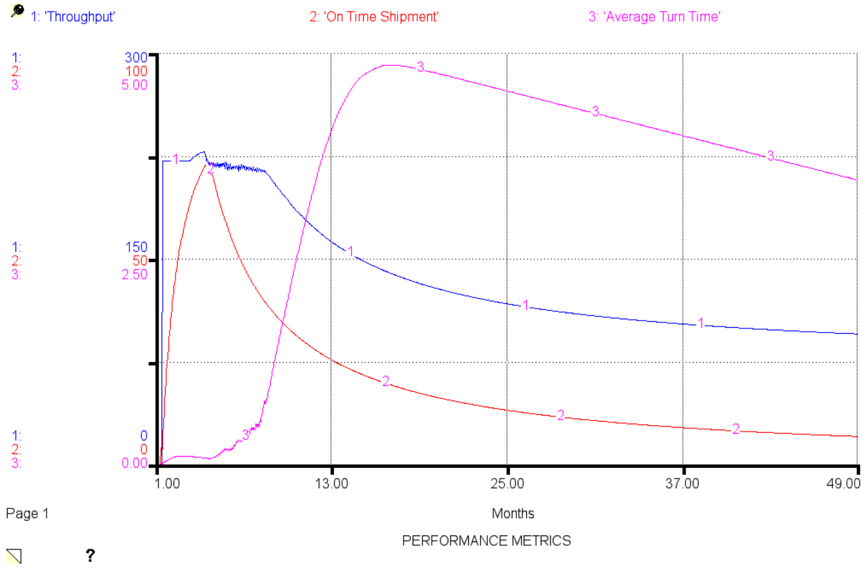


Figure 32. Aggressive sales scenario - performance metrics

Throughput had a good start, increasing to 228 orders per month . However, the capacity of the plant was not able to handle the increased order volume. On-time shipments collapsed to 7%, average turn time grew to an uncontrollable maximum level of 4.86 months, and throughput decreased continually to end the simulation at only 95 orders per month. The poor results during this scenario show what is likely to happen if an aggressive sales strategy is not followed with the proper execution of orders due to capacity constraints. The lower throughput than the status quo scenario shows how exceeding capacity has a considerable negative effect on service levels, causing sales to drop significantly.

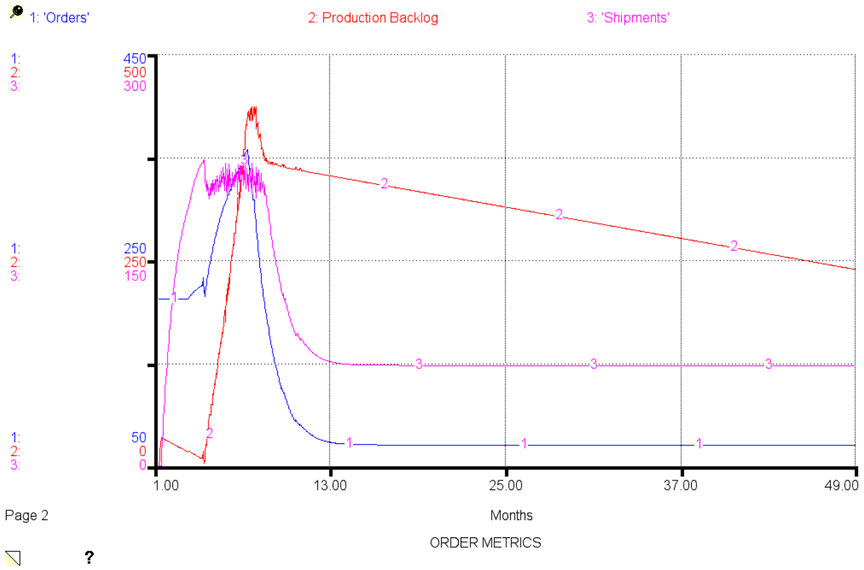


Figure 33. Aggressive sales scenario - order metrics

Figure 33 shows how the orders start increasing at the third month due to the aggressive sales strategy. The shipments are not able to keep pace with the orders, and the production backlog drastically increases, affecting the performance metrics of on-time shipment and average turn time. After Month 7, the orders collapse, and the production backlog diminishes slowly at the stabilized shipping rate of 73 orders per month.

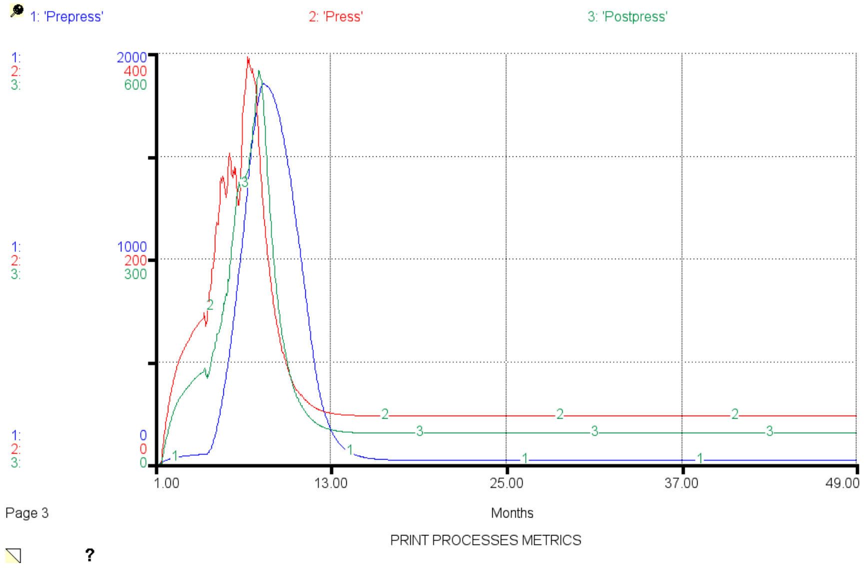


Figure 34. Aggressive sales scenario - print processes metrics

As shown in Figure 34, all the print processes drastically increase, due to the higher order volume, then collapse as the orders stop coming in. Finally, they stabilize for the rest of the simulation. The aggressive sales scenario was not successful, and its performance was worse than the performance of the status quo scenario. Ergo, an aggressive sales strategy should be executed only **after** the operations are prepared and ready in advance of larger order volumes. If this is not achieved, service levels will suffer so much that the end result is a significant drop in orders from which it is very difficult to recover.

Press Productivity Improvement Scenario

This scenario is widespread in the printing industry. It is common to work hard on the productivity of specific equipment—usually a printing press. The logic behind this scenario is that, by increasing the output of the press, the whole output of the print shop will increase. Focusing specifically on the print process also serves to filter the problems of other areas and work on what is called the "circle of influence:" if you can only impact the press process, then focus on that specific process. For this scenario, we use the assumption that a continuous improvement project focused on the press process has been executed properly. The first improvement is on press speed, increasing the performance level of the press from 70% to 90%. This means that the press now runs at 90% of the maximum design output indicated by the press manufacturer. Second, the setup time and downtime has been decreased, bringing the availability of the press to 80% from 70%. This means that the press is running and producing good product for 80% of planned production time. Lastly, the scrap rate has been decreased from 5% to 3%. These results imply very good improvements that should result in an increased output. The model was run for 48 months under this scenario with the following results.

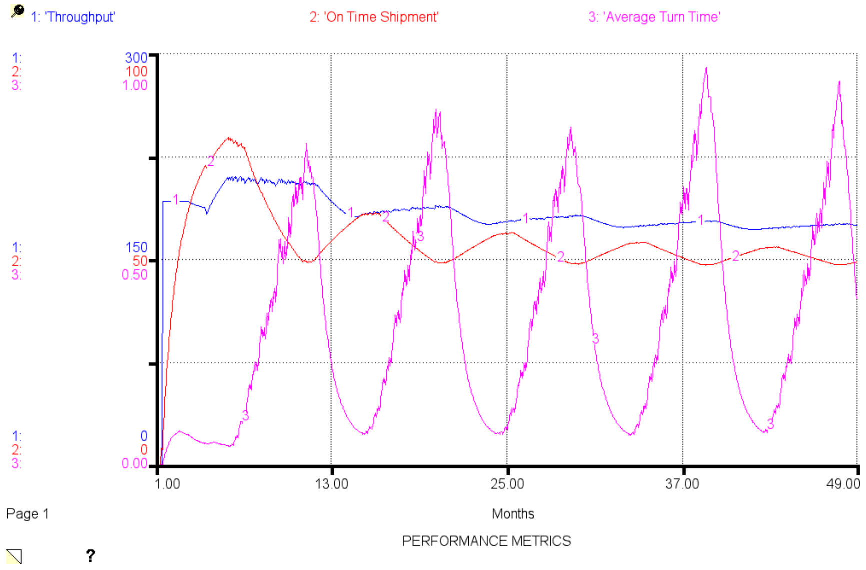


Figure 35. Press productivity improvement scenario - performance metrics

Figure 35 shows that, surprisingly, after the press improvements, the performance is very similar to the status quo scenario. The throughput stabilized at levels around 180 orders per month, the on-time shipment did not improve, and the turn time continues to be volatile. Have the improvements been lost? The following graphs will provide additional information to understand what occurred.

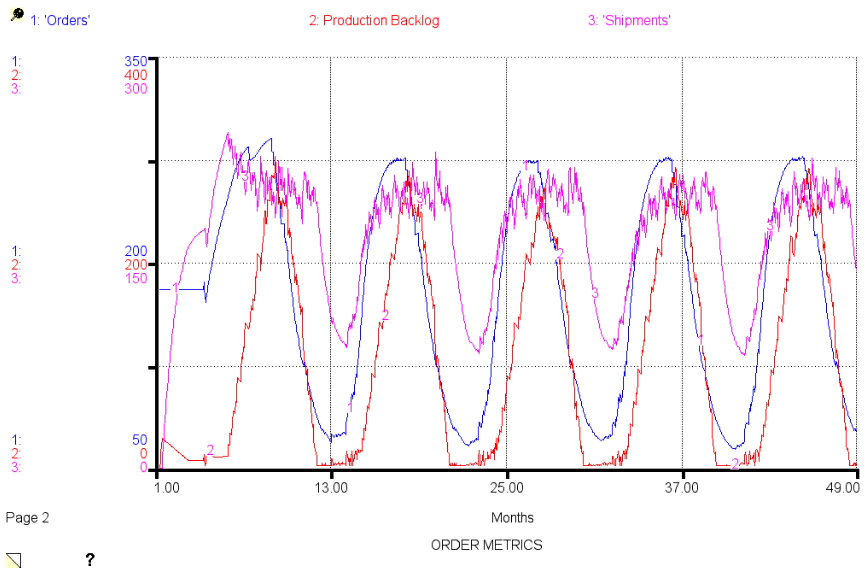


Figure 36. Press productivity improvement scenario - order metrics

Figure 36 shows the order metrics. Their behavior is also very similar to the status quo scenario; the orders and the production backlog fluctuate as the shipment rate continually reaches a maximum output near 210 orders per month. The press improvements have not produced a significant impact on the production backlog and shipment behavior. However, these metrics do not explain why the improvements were ineffective.

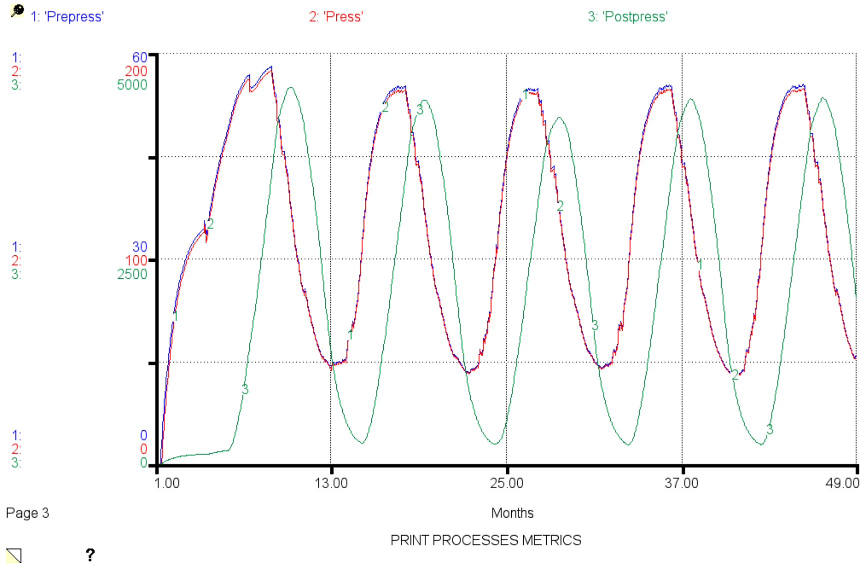


Figure 37. Press productivity improvement scenario - print processes metrics

Figure 37 does show a difference between the status quo scenario and the press productivity improvement scenario. In the status quo scenario (shown in Figure 31), the constraint process is the press process. This process limits the total output of the system. However, after the press improvements, the output of the press process increased to such a level that the constraint has moved from the press process to the postpress process (as shown in Figure 37.) As the constraint moves, the postpress process now limits the output of the system, and this is why the improvements were seemingly lost. Many times in print shops, projects that are too narrowly focused do not improve the financial situation of the company. This represents an effect similar to the one presented above: real productivity improvements need to have an impact upon the throughput of the whole system, and just on one specific process.

Shrinking Order Size Scenario

One of the most common trends in today's printing industry is related to shrinking order sizes and the increased frequency of orders. It is regularly discussed how orders are much smaller than what they used to be, yet they are also more frequent. This is a result of two major factors: first, that very few companies wish to pay inventory holding costs when their printed inventory is likely to become obsolete very quickly; and second, that today's information systems have enabled the print industry to produce product more quickly, reducing the benefits of having inventory even more.

For this scenario, we will assume that the average order size decreases by half, passing from 15,000 sheets per order to 7,500 sheets per order. The frequency of incoming orders duplicates from 180 orders per month to 360 orders per month. Therefore, the total incoming volume in sheets per month stays the same, enabling a comparison with the status quo scenario. Another effect to consider is that, as the frequency of orders increases and their size decreases, the percentage of time spent in the setup of presses in comparison to run time is significantly higher. To capture this effect, the availability of the press process has been lowered from 70% to 50%. The model was run for 48 months under this scenario with the following results.

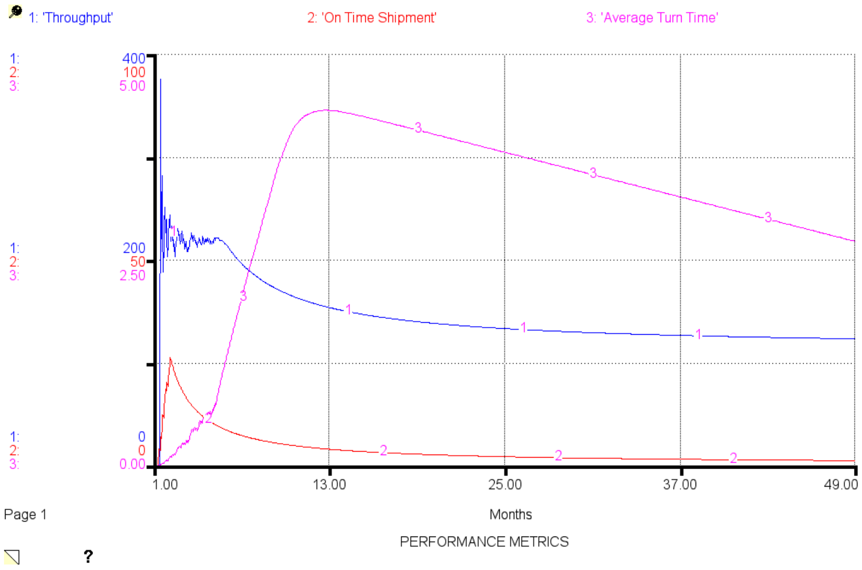


Figure 38. Shrinking order size scenario - performance metrics

The overall performance under this scenario is very poor. The throughput collapses quickly, then stabilizes at a level of 130 orders per month. The on-time shipment is under 25% for the whole simulation. The average turn time escalates to 4.32 months, then declines slowly. It is clear that, without modifying any of the parameters, the company is not able to meet the needs of the new market condition, and its performance is much worse than the status quo scenario.

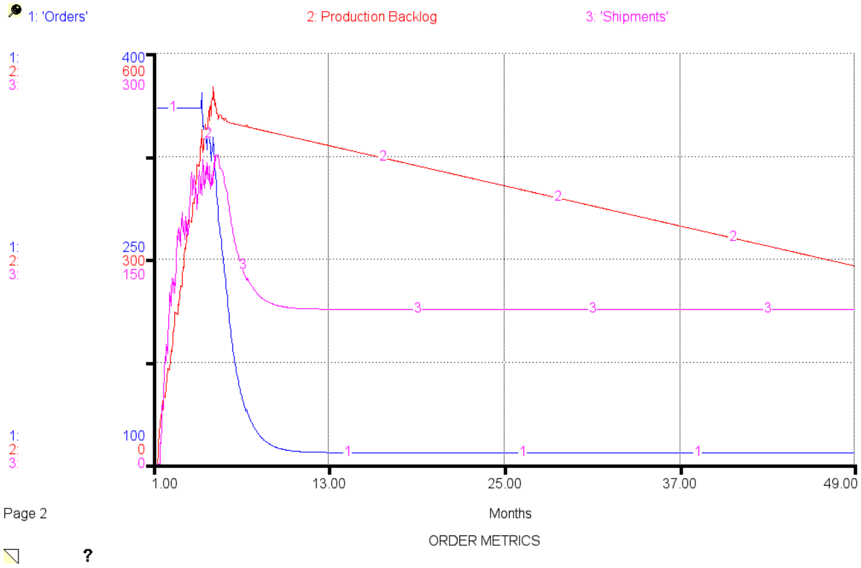


Figure 39. Shrinking order size scenario - order metrics

Figure 39 shows the order metrics. The incoming orders start at a very high rate due to the new market reality with more frequent orders. However, shipments hit a maximum point of 226 orders, with a constantly increasing production backlog that affects both on-time shipments and average turn time. After the fifth month, orders collapse, and the system never recovers.

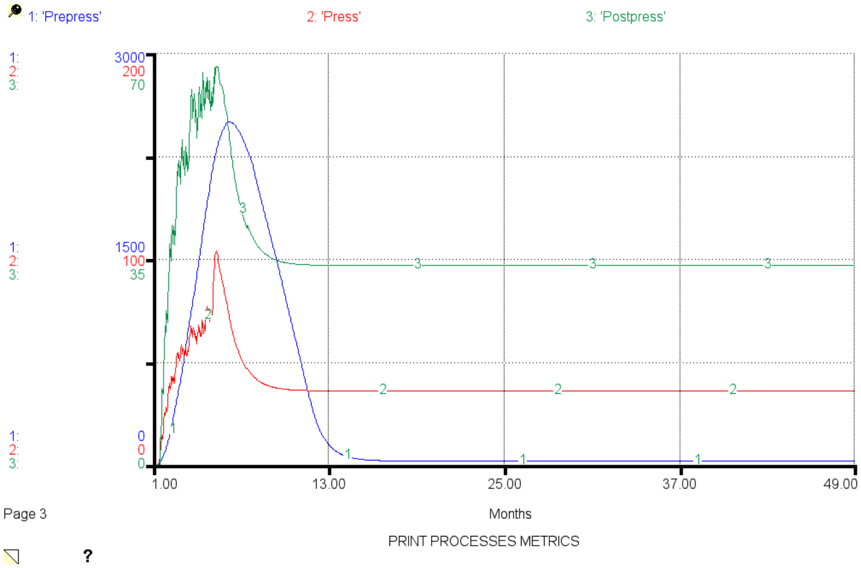


Figure 40. Shrinking order size scenario - print processes metrics

Up until this point, there is no indication as to what is driving this poor performance. Again, the behavior of the sub-model within the production backlog has the answer. In this case, the higher frequency of orders has had a significant impact on the prepress process, which then becomes the constraint limiting the output of the whole system. This is shown in Figure 40. The prepress process is not able to handle the additional demand, and the whole system has suffered the consequences. A takeaway from this scenario is that, to better deal with the current trend of shrinking order sizes, it is important to focus on the front end processes such as prepress, as this department now has to handle many small orders that take as much time to process as do large orders.

Synergy Scenario

Most systems improve under synergistic and adaptive strategies that enable sustainable and long-term growth. It is important to achieve stability, then implement continuous improvements, and finally, grow at a pace where sustainable results can be obtained in order to break the oscillation pattern of the status quo scenario. The status quo scenario provides an idea as to the volatility of the current system. The first strategy implemented is to achieve stability by regulating the incoming orders. At the start of the simulation, the relative price is raised by 15%, and the target turn time is increased from 0.4 months (10 days) to 0.6 months (15 days). These changes provide a lower level of orders and lower customer service expectations. Figure 41 shows the results of the simulation after one year under the stability strategy: 91% on-time shipment, throughput of 225 orders per month, and average turn time stabilized at the level of 0.04 months (1 day).

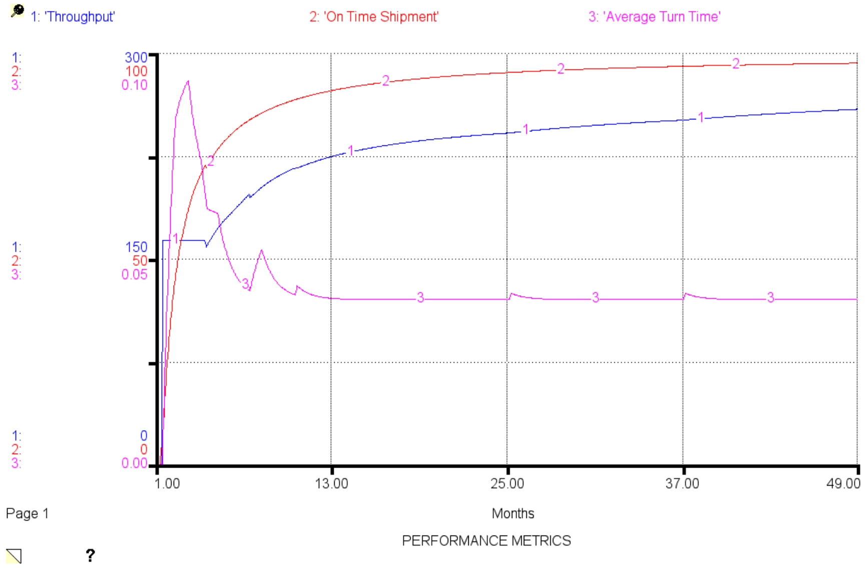


Figure 41. Synergy scenario - performance metrics

Meanwhile, it is assumed that a productivity improvement project has started during the first year. It provides a couple of improvements that have an impact on the system for the second year on, accounting for the time delays related to continuous improvement projects. First, the setup time and downtime for the press process are decreased in combination by 10%, which implies that the availability of the press process increases from 70% to 80%. Second, the scrap rate is improved to 3%. Due to the scrap rate reduction, the overproduction rate can be lowered to 5% for the rest of the simulation, adding some valuable press time. The strategy for the second year (after achieving stability during the first year) is to maintain a good level of on-time shipments, due to the successful implementation of the productivity improvements. Figure 41 shows how the on-time shipment continues to improve up to a level of 95%. This brings more orders into the system for a throughput of 242 orders per month, all while maintaining the average turn time at a stable rate.

After the system has been stabilized and the first round of improvements successfully implemented, growth is the next step. For the third year, the relative price decreases by 5%, and the target turn time decreases to 0.4 months (10 days). The system continues to respond well, with higher throughput of 251 orders per month and on-time shipments of 97%. The fourth year has the company ready for more growth through some aggressive price and service targets. The relative price drops an additional 5%, and the target turn time drops to 0.2 months (5 days). The system continues to improve, but starts showing a plateau that limits growth at the throughput level of 259 orders per month.

The limits to growth indicate that an overly aggressive growth strategy can bring the system to a point of sudden collapse that requires significant time for recovery. The aggressive sales switch is also tested during Years 3 and 4 as part of the growth strategy, but the 10% step increase in orders is difficult to handle by the system even after the stability and productivity improvements were achieved in Years 1 and 2. If the aggressive sales switch is required, then this strategy must be executed after a significant increase in capacity of the print production processes, taking into account the time delays related to purchasing, installing, and learning to use new equipment.

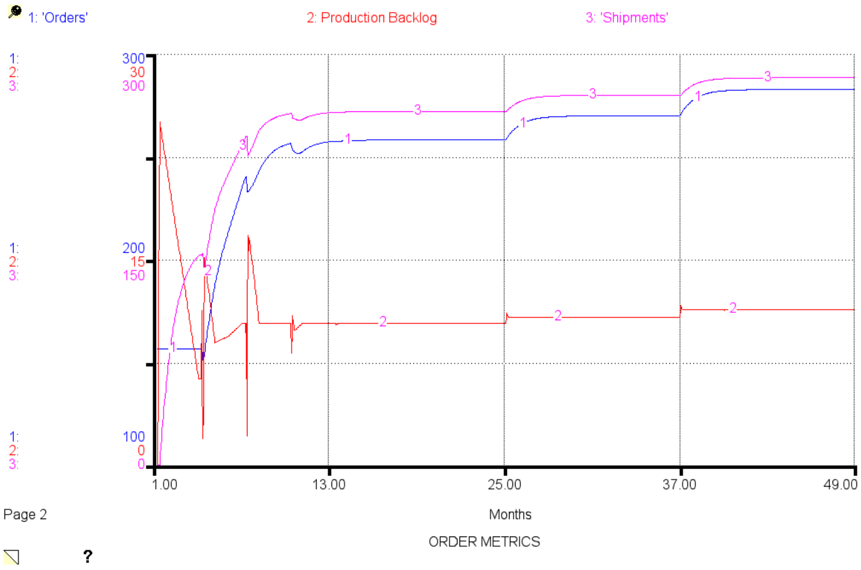


Figure 42. Synergy scenario - order metrics

Figure 42 shows the results of the order metrics under the synergy scenario. The production backlog is volatile at the start, but soon stabilizes at a level around 10 orders. Then, as orders grow, shipments grow together, therefore maintaining the production backlog under control. A stable production backlog provides excellent on-time service and average turn time performance, and is the key to a well-managed print company.

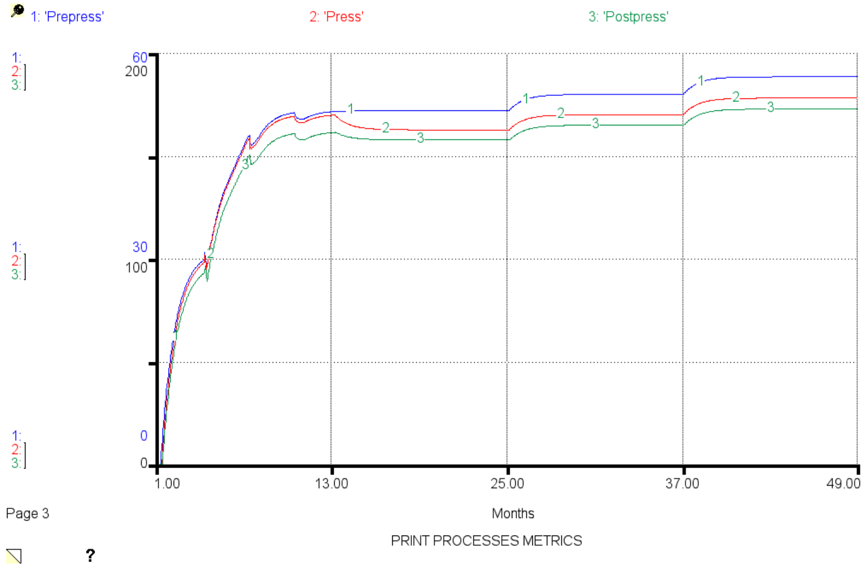


Figure 43. Synergy scenario - print processes metrics

Lastly, Figure 43 shows the results of the print processes under the synergy scenario. Ideally, all processes should be aligned in order to maximize the throughput of the whole system. The productivity improvements related to the press process are able to increase the output to match the postpress process. The prepress process also works at the required output level, and the orders are processed under synchronized conditions. Waste is reduced, as no work from the upstream processes is backlogged, and the flow achieved maximizes the throughput that the system may provide given its capacity constraints.

Under synergistic initiatives from such key areas as finance (relative price), sales (aggressive or sustainable), and operations (target turn time and productivity), great results are achieved for the whole system, even with fixed capital and labor resources. The overall throughput increases from 176 orders per month under the status quo scenario to 259 orders per month under the synergy scenario. This represents a 47% productivity increase for the whole system.

This is just one example of an improved scenario against the status quo scenario. Model users may run multiple additional scenarios that, in many cases, may show better results than the synergy scenario. The dynamic model is hard to predict, and therefore users should learn by experimentation in a simulation such as this with the benefit of zero cost, as opposed to costly real life experiences.

Chapter Seven – Summary and Conclusions

A computer simulation model using system dynamics was successfully created. With proper statistics, any print shop can be simulated, and the current state of the company may be defined. By trial-and-error, the correct path for higher productivity is indicated and learned. The model proved to be simple, ample and flexible, and comprehensive. Its simplicity lies in the limited feedback structures, representing how the production backlog affects the turn time of the orders processed and, at the same time, how customer satisfaction reinforces the system. By presenting the workflow through the main print processes (prepress, press, and postpress), the model shows sufficient amplitude and flexibility to adapt to any print company, no matter its size, specialization, or technology. The model also conceptualizes the whole system involved in a print shop. It comprehensively captures variables related to areas like sales, finance, and operations.

Once a fully functional version of the model was available, five different scenarios were simulated in order to learn from different strategies, as compared with the current state. The first scenario, "status quo," followed the strategy of no changes in order to set a baseline for the other scenarios. The status quo scenario reflected an oscillating behavior as company performance varied related to the utilization of fixed capacity. The overall on-time shipments were poor, and the turn time fluctuated significantly throughout the four years of simulation.

The second scenario was referred to as "aggressive sales," representing a fast-growth strategy and the philosophy of "sell as much as you can." Lowering prices, setting the sales force in an aggressive mood, and offering short turn times created a very high order volume that was sustainable only in the short term. The system collapsed and was not able to recover to the levels of the status quo scenario.

The third scenario, "press productivity improvement," focused solely on productivity improvements for the press process. High local improvements were achieved on the press process: performance (press speed) increased by 20%, availability (effective run time) increased by 10%, and the scrap rate was reduced by 2%. However, the overall impact of these improvements on the whole system was limited, as the constraint of the production system shifted from the press process to the postpress process. The final results were equivalent to the status quo scenario, indicating the apparent loss of the press productivity improvements.

The fourth scenario, "shrinking order size," represents a common trend in today's printing industry. For the simulation, the average order size was cut by half, while the order frequency was doubled. In this case, the constraint shifted to the prepress process, which limited the output of the whole system. The results were poor, as the throughput under this scenario stabilized at a lower level than the status quo scenario. As the orders shrank in size and their frequency increased, the pressure moved upstream, where there is no difference in the processing time of an order, regardless of its run length.

The fifth and last scenario, "synergy," provided a productivity increase of 47% against the baseline set by the status quo scenario. This increase was reflected in the higher throughput of the whole system while keeping capital and labor resources constant. Therefore, the full benefits were only able to be achieved by the correct and timely execution of different policies. After the implementation of a strategy combining stabilization in the first year, press process improvements in the second year, growth in the third year, and consolidation in the fourth year, the final on-time shipments increased to 97%, and average turn time stabilized. The key was the combination of decisions pertaining to finance (relative price), sales (aggressive or sustainable), and operations (target turn time and productivity), which took the oscillating and apparently uncontrollable system to a whole new level of productivity and service.

This model sets the ground for multiple possibilities of further studies. Case studies may be developed with real data from printing companies that are willing to share their statistics and who decide to implement the path indicated by the model. Another possibility is to link several basic model structures together in order to simulate the dynamics of a print conglomerate that controls several printing plants. Scenarios such as centralized order processing and optimization among the multiple plants may be tested. Lastly, stochastic modeling may be achieved by running the key rates of the simulation (incoming orders and process rates) as probability distributions, instead of fixed average rates. This would correlate better with real life situations, while unveiling tougher challenges for optimal performance.

References

Anupindi, R., Sunil, C., Sudhakar, D., Van Mieghem, J. A., & Zemel, E. (1999). *Managing business process flows*. Upper Saddle River, NJ: Prentice Hall.

Bäck, A., Lehtonen, T., Karttunen, A., Kuusisto, M., & Launonen, R. (1998). Evaluation of printing production in networks by means of computer simulation models. *Advances in Printing Science and Technology, PIRA-IARIGAI, 24*, 177-190.

Bauer, C. (2005, April). Pocketing more profits. *Printing Impressions, 47*, 44-46.

Bellander, M. (1998). Workflow bottlenecks and problems influencing production management needs in commercial printing. *Proceedings of the Intergrafika Conference, Croatia*, 30-44.

Bellander, M., Handberg, L., & Stenberg, J. (1998). Workflow analysis in commercial printing – methods and results. *Advances in Printing Science and Technology, PIRA-IARIGAI, 24*, 163-176.

Cost, F., & Daly, B. (2003). *Digital integration and lean manufacturing Practices of U.S. printing firms* (PICRM-2003-09). Rochester, NY: Printing Industry Center at RIT.

Dennis, P. (2002). *Lean production simplified*. New York: Productivity Press.

Dickenson, R. (2003, March). PIA sets the table. *Printing Impressions, 45*, 52.

Forrester, J. (1961). *Industrial dynamics*. Waltham, MA: Pegasus Communications.

Gehman, C. (2003). *Print production workflow: A practical guide*. Paramus, NJ: NAPL.

Hoover, S. (2000, October). Sheetfed productivity: picking up the pace. *American Printer, 226*, 42-46.

Imai, M. (1997). *Gemba kaizen: A commonsense, low-cost approach to management*. New York: Mc Graw Hill.

JDF: An ambitious end-to-end standard. (2005, October). *American Printer*, *230*, 42-43.

Kasdorf, B. (2003, March-April). Publishing lean and mean. *Booktech Magazine, 6*, 8.

Kelly, S. (2002, April-May). It's all about productivity growth. *Canadian Printer, 110*, 30.

Kipphan, H. (2001) *Handbook of print media: Technologies and production methods.* Berlin, Germany: Springer.

Lean Enterprise Institute. (2004). *Lean lexicon: A graphical glossary for lean thinkers.* Brookline, MA: Lean Enterprise Institute.

Merit, D. (1992). *Excellence in scheduling print production*. New York: Don Merit.

Millet, G., & Rosenberg, R. (1992). *Primer for graphic arts profitability*. Colorado Springs, CO: Millet Group.

National Association for Printing Leadership (NAPL). (2004). *The 2004-2005 state of the industry report*. Paramus, NJ: NAPL.

Njezic, Z., Ziljak, V., Pap, K., & Svilicic, B. (2003). The stochastic model of simulation of a virtual printing-house. *Advances in Printing Science and Technology, PIRA-IARIGAI, 29*, 163-171.

O'Brien, K. (2000, October). Productivity: dollars, not donuts. *American Printer, 226,* 8.

Olsson, M. (1998). Towards more effective work flows. *Advances in Printing Science and Technology, PIRA-IARIGAI, 24*, 153-161.

Peacock, M. (2004, September). Saving time impacts the bottom line. *Printweek, 31*.

Pellow, B., Sorce, P., Frey, F., Oslon, L., Moore, K., & Kirpichenko, S. (2003). *The advertising agency's role in marketing communications demand creation* (PICRM-2003-05). Rochester, NY: Printing Industry Center at RIT.

Poyssick, G., & Hannaford, S. (1996). *Workflow reengineering*. Mountain View, CA: Adobe Press.

Ritchie-Dunham, J., & Rabbino, H. (2001). *Managing from clarity: Identifying, aligning and leveraging strategic resources*. Chichester, England: John Wiley & Sons.

Roth, J. (2004, December). Sales are rising, but productivity challenges remain. *American Printer, 234*, 18-32.

Senge, P. (1990). *The fifth discipline: The art and practice of the learning organization*. New York: Doubleday/Currency.

Sinapse Graphic International. (n.d.). *Simulators and software for the graphic arts: SHOTS*. Retrieved July 10, 2005, from http://www.shotsim.com/products/shotsim/shotsim000.php

Sterman, J. (2000). *Business dynamics: Systems thinking and modeling for a complex world*. Boston: Mc Graw Hill.

Ward, G. (2004, May). Making a difference: future as Donnelley sees it. *Printing World, 22.*

Womack, J., & Jones, D. (2003). *Lean thinking: Banish waste and create wealth in your corporation*. New York: Free Press.

Appendix: List of Equations

```
☐ Cummulative_OTS(t) = Cummulative_OTS(t - dt) + (OTS_Rate) * dt
  INIT Cummulative_OTS = 0
   INFLOWS:
      OTS_Rate = On_Time_Shipment
○ 'Average_Turn_Time' = SMTH1(Average_Turn_Time,1)
○ 'On_Time_Shipment' = (Cummulative_OTS/time)*100
○ 'Orders' = SMTH1(Orders,1)
○ 'Shipments' = SMTH1(Shipments,1)
○ 'Throughput' = THROUGHPUT(Shipments)
○ Average_Orders = 180
○ Average_Turn_Time = CYCLETIME(Shipments)
○ Customer_Satisfaction = (0.6*On_Time_Shipment+0.6)*Relative_Turn_Time
○ Market_Turn_Time = .4
○ On_Time_Shipment = if Turn_Time <= Target_Turn_Time then 1 else 0
○ Relative_Price = 1
○ Sales_Aggresiveness = 0
○ Target_Turn_Time = .40
○ Turn_Time = Production_Backlog/Shipments
⊘ Relative_Turn_Time = GRAPH(Turn_Time/Market_Turn_Time)
  (0.00, 1.50), (0.2, 1.25), (0.4, 1.13), (0.6, 1.06), (0.8, 1.03), (1.00, 1.00), (1.20, 0.968), (1.40, 0.937), (1.60,
  0.875), (1.80, 0.75), (2.00, 0.5)
▥ Production_Backlog = Production_Backlog'
   INFLOWS:
      Orders =
      Average_Orders*(1/Relative_Price)*Delay(1+Sales_Aggresiveness*0.1,2,1)*Delay(Customer_Satisfac
      tion,3,1)
   OUTFLOWS:
      Shipments = Shipments'
    ☐ Plates_Buffer(t) = Plates_Buffer(t - dt) + (Processed_Plates - Used_Plates) * dt
      INIT Plates_Buffer = 0
       INFLOWS:
          Processed_Plates = CONVEYOR OUTFLOW
           TRANSIT TIME = Prepress/Prepress_Rate
       OUTFLOWS:
          Used_Plates = If Plates_Ready = 1 then Plates*Orders' else 0
    ▥ Postpress(t) = Postpress(t - dt) + (Printed_Sheets - Finished_Sheets) * dt
      INIT Postpress = 0
       TRANSIT TIME = varies
       INFLOW LIMIT = INF
       CAPACITY = INF

▥ Prepress(t) = Prepress(t - dt) + (Unprocessed_Plates - Processed_Plates) * dt
  INIT Prepress = 0
   TRANSIT TIME = varies
   INFLOW LIMIT = INF
   CAPACITY = INF
   INFLOWS:
      Unprocessed_Plates = Orders'*Plates
   OUTFLOWS:
      Processed_Plates = CONVEYOR OUTFLOW
       TRANSIT TIME = Prepress/Prepress_Rate
▥ Press(t) = Press(t - dt) + (Raw_Sheets - Printed_Sheets - Scrap) * dt
  INIT Press = 0
   TRANSIT TIME = varies
   INFLOW LIMIT = INF
   CAPACITY = INF
   INFLOWS:
      Raw_Sheets = Orders'*M_sheets*(1+Overproduction)*Plates_Ready
   OUTFLOWS:
      Printed_Sheets = CONVEYOR OUTFLOW
       TRANSIT TIME = Press/(Availability*Performance*Capacity*Schedule_Pressure)
      Scrap = LEAKAGE OUTFLOW
       LEAKAGE FRACTION = Scrap_Rate
       NO-LEAK ZONE = 0%
☐ Production_Backlog'(t) = Production_Backlog'(t - dt) + (Orders' - Shipments') * dt
  INIT Production_Backlog' = 0
   INFLOWS:
      Orders' = Orders
   OUTFLOWS:
      Shipments' = Finished_Sheets/M_sheets
○ 'Postpress' = SMTH1(Postpress,1)
○ 'Prepress' = SMTH1(Prepress,1)
○ 'Press' = SMTH1(Press,1)
○ Availability = .7
○ Capacity = 6000
○ Finishing_Complexity = 1
○ M_sheets = 15
○ Overproduction = .1
○ Performance = .7
○ Plates = 5
○ Plates_Ready = If Plates_Buffer > Plates then 1 else 0
○ Postpress_Rate = 3000
○ Prepress_Rate = 1000
○ Scrap_Rate = .05
⊘ Schedule_Pressure = GRAPH(Target_Turn_Time)
  (0.00, 1.15), (0.2, 1.10), (0.4, 1.05), (0.6, 1.00), (0.8, 0.98), (1.00, 0.96), (1.20, 0.94), (1.40, 0.92), (1.60,
  0.9), (1.80, 0.88), (2.00, 0.86)
```

R·I·T

Printing Industry Center
An Alfred P. Sloan Foundation Center

Rochester Institute of Technology
College of Imaging Arts and Sciences
55 Lomb Memorial Drive
Rochester, NY 14623
Phone: (585) 475-2733
http://print.rit.edu