12-14-2001

Constraint-Based Supply Chain Inventory Deployment Strategies

David Jay Stremler

Recommended Citation

Stremler, David Jay, "Constraint-Based Supply Chain Inventory Deployment Strategies" (2001). *Theses and Dissertations*. 1163.

https://scholarsjunction.msstate.edu/td/1163

CONSTRAINT-BASED SUPPLY CHAIN INVENTORY DEPLOYMENT STRATEGIES

By

David Jay Stremler

A Thesis
Submitted to the Faculty of
Mississippi State University
in Partial Fulfillment of the Requirements
for the Degree of Master of Science
in Industrial Engineering
in the Department of Industrial Engineering

Mississippi State, Mississippi

December 2001

CONSTRAINT-BASED SUPPLY CHAIN INVENTORY DEPLOYMENT STRATEGIES

By

David Jay Stremler

Approved:

Stanley F. Bullington
Professor and Graduate Coordinator
Department of Industrial Engineering
Mississippi State University
(Director of Thesis)

Allen G. Greenwood
Associate Professor of Industrial Engineering
Department of Industrial Engineering
Mississippi State University
(Committee Member)

Kimball E. Bullington
Assistant Professor of Management
Middle Tennessee State University
(Committee Member)

A. Wayne Bennett
Dean of the College of Engineering
Mississippi State University

Name: David Jay Stremler

Date of Degree: December 14, 2001

Institution: Mississippi State University

Major Field: Industrial Engineering

Major Professor: Dr. Stanley F. Bullington

Title of Study: CONSTRAINT-BASED SUPPLY CHAIN INVENTORY
DEPLOYMENT STRATEGIES

Pages in Study: 96

Candidate for Degree of Master of Science

The development of Supply Chain Management has occurred gradually over the latter half of the last century, and in this century will continue to evolve in response to the continual changes in the business environment. As organizations exhaust opportunities for internal breakthrough improvements, they will increasingly turn toward the supply chain for an additional source of untapped improvements. Manufacturers in particular can benefit from this increased focus on the chain, but the gains realized will vary by the type of supply chain. By applying basic production control principles to the chain, and effectively using tools already common at the production line level, organizations address important supply chain considerations. Both the Theory of Constraints and the factory physics principles behind the Constant WIP concepts focus on the system constraint with the aim of controlling inventory. Each can be extrapolated to focus on a system whose boundaries span the entire supply chain.

ACKNOWLEDGEMENTS

I would like to take the opportunity to thank the many people behind this research effort. I would like to thank my committee members for their time and guidance which have definitely contributed to the completion of this thesis. My graduate advisor, Dr. Stan Bullington, has helped guide me through the IE program and the thesis work with timely, sage and patient advice. The Industrial Engineering faculty at Mississippi State University as a whole has offered support and guidance in my studies. I would also like to thank Joan Mead at the Maury Oceanographic Library, who, it seems, can find just about anything through interlibrary loan. Behind the scenes, my wife, Sylvia, has provided the motivation and support that have kept me focused throughout my studies, while my kids have persistently reminded me to “do my homework.”

TABLE OF CONTENTS

CHAPTER

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Supply chain management has evolved over the latter half of the last century. During that time, the business landscape has changed considerably and supply chain management has evolved in parallel with these influences. By the new millenium, mass customization, increased customer expectations and fiercely intense competition characterized the marketplace and chain versus chain competition became a significant factor in marketplace success. As organizations have shifted toward optimizing the extended enterprise in an increasingly dynamic business environment, supply chain management has shifted its focus to inventory visibility in the chain. More readily observable than other parameters, inventory is an important indicator of system performance and the impacts of uncertainties from various sources. As these organizations continually refine the management of supply chains, regardless of the maturity of the approaches developed, managing inventory throughout the chain remains a critical competitive factor for the supply chain. As such, continual refinement of the strategies used to manage and reduce inventory in the chain is essential.

Problem Statement

As the scope of the enterprise expands, managing the supply chain has emerged as the most difficult and expensive aspect of the extended enterprise. Supply chain management has extended the application of traditional inventory control methods over a broader scope [1]. At the same time, production control methodologies have also been applied to the new, larger and more complex problems encountered. These approaches have varied from the extremes of pure push systems, such as Material Requirements Planning (MRP), to pure pull systems, such as kanban. Between these extremes, other methodologies have developed. Two of these approaches, Constant Work-in-process (CONWIP) and Theory of Constraints (TOC), focus on the system constraint as a means of managing and ultimately reducing the system WIP, and share many similarities in their approaches to managing the constraint. Surprisingly, though, the literature comparing these two methodologies, particularly in the context of supply chain management, is very limited. Further, direct evaluations of these two methods, even at the production line level, have not been encountered.

Research Objectives

This research focuses on two main objectives:

1) to provide a more comprehensive overview of the development of today's supply chain management (SCM), with particular emphasis on the importance of SCM to the manufacturer; and

2) to discuss the applications of CONWIP and TOC in the supply chain environment.

The thesis begins with a more detailed discussion of supply chain management. After developing the background of SCM, the discussion focuses on the impact of supply chain management on manufacturers and the results obtained through increased focus on the supply chain. A brief discussion of supply chain structure and its objectives provides a context for later analysis. After presenting a simple definition of supply chain management that conveys the focus on chain inventories (while encompassing the key concepts found in the numerous definitions in use in the literature today), this section of the thesis concludes with discussion of the role of inventory in the supply chain.

Before discussing the specifics of the constraint-based methods, the next section of the thesis will begin with a brief discussion of a typical, organizational-level production control system and how that system is applied across the extended enterprise at the supply chain level. This section will then detail the applications of the TOC and CONWIP. While there is some literature that discusses the applications of TOC, the literature discussing the application of CONWIP to SCM is fairly limited. As such, this section of the thesis will examine the current and potential applications of these methods to SCM. The basics of each approach will be examined, including a discussion of how these methods can be expanded from the scope of the individual organization to the extended enterprise. The application of both methods in the supply chain environment will focus on the three structures described by the V-A-T Analysis outlined by TOC. The first is described by TOC as a divergent or “V” structure. In this flow, product families diverge at specific points [2], resulting in a large number of retailers. In this case, members of the supply chain can function in several pipelines [3], so this structure produces the challenges of material allocation and postponement of customization at the divergent points. The second structure to be examined is described by TOC as a convergent or “A” structure. In this structure, a number of raw materials and components are processed and assembled into a few finished products. This structure presents the challenges posed by synchronizing arrivals at assembly operations. Lastly, the T-structure will be examined. In this structure, there are many components and assemblies produced through separate routings that are combined to create a wide variety of finished products. This increased complexity of this structure stems from the combination of convergent and divergent control points, plus fairly unique routings with low product volumes which more closely resemble a job shop [2]. Any additional assumptions or concepts that cannot be directly applied to the supply chain environment will also be discussed.

CHAPTER II

THE DEVELOPMENT OF SUPPLY CHAIN MANAGEMENT

Through the latter half of the twentieth century, economic factors, technology changes, and changes in the marketplace forced American business practices to evolve. The timing and sequence of these events shaped today's supply chain management. The first roots of supply chain management can be traced to the 1940s. While these changes shaping supply chain management began slowly at first, a period of continuous change has persisted since the 1960s, with the rate of change accelerating as time progressed. In the late 80s and 90s, organizations moved beyond an internal functional focus to a process focus which transcended functional boundaries [4]. The methods and principles developed in these "process improvement years" transitioned from a process level, to the enterprise level, and then to the supply chain level, extending process improvement techniques to the inter-enterprise, demand driven, and resource constrained supply chain environment [5]. During this transition, business structures have continually shifted from vertically tall and functionally aligned to horizontal, process oriented and customer-focused [6]. This natural progression shaped the conceptual framework of supply chain management to meet the needs of businesses in today's market, and continues to evolve in response to new changes in the global market of tomorrow.

The changes contributing to the evolution of supply chain management began with the establishment of a theoretical foundation based on the 1940s introduction of linear programming. This provided the basic mathematical techniques for formulating and solving problems in the areas of resource allocation, distribution, and transportation [7]. Adding to this theoretical base, the Forrester industrial dynamic effect first described the amplification of demand when moving from the market to raw material suppliers [8]. There was little change in economic, market, and technological factors throughout the 50s, and for the remainder of the 1950s and into the 1960s, most companies answered the economy's demand for goods with an operations strategy focused on mass production as a means to realize low cost per unit. While this approach allowed little flexibility in process or product [9], American businesses did not have much concern about inventories in the supply chain [4]. The 60s did, however, mark the beginning of a period of continual change, and began a trend throughout the 60s of focusing on integrating material handling equipment to form systems [10], heralding the significant influences of changing competition in the next decade.

Technology had the most significant impact at the start of the 1970s. By the late 60s and into the 70s, mainframe computers introduced the first significant technological influence in the development of supply chain management. With this new computational capability, the theory outlined by linear programming could now be applied to industry problems [7]. The impacts of technology became more significant in the 1970s. While personal computers of the day more resembled "expensive typewriters" [11], the technology encouraged broad use of the transactional tracking concept (then known as Online Transaction Processing (OLTP)) with a tremendous impact on business operations. Companies able to monitor transaction processes provided better customer service and gained the competitive edge over other companies [12]. But the mass production legacy of the 60s persisted through the 70s as well. Many companies designed their manufacturing and distribution systems to respond to a mass market, and these companies produced, for the most part, large volumes of uniform products that were sold through defined wholesalers and retailers. These systems continued to focus on minimizing costs with little concern for flexibility [13], with equipment optimization remaining the major emphasis through the decade [14]. But it was not long after the start of the decade that economic pressures forced this focus to change. For the first time, economic pressures began to shape the path embarked upon by American business, and the influences of these economic pressures were a significant change from the previous decade. Increased foreign competition, most notably, forced American business to place greater emphasis on cost and quality [9]. The economic pressures of the two oil embargoes increased the inflow of foreign goods, which renewed companies' efforts to focus on cost reduction. Manufacturers saw their power in the supply chain eroding, and were forced to look toward service for competitive advantage, though this new focus centered on the manufacturer's (not the customer's) view of service. Further, high transportation costs in heavily regulated industries (like trucking and railroads) produced tremendous economic pressure on companies, with transportation costs alone accounting for up to 70% of logistics expenses (compared to 57% today). High fuel prices and interest rates forced an increased awareness of transportation and inventory expenses, in contrast to the general lack of concern about inventory in the supply chain in the 1960s [4]. This heightened awareness increased interest in operational improvements in different areas and began increasing competitive pressure. As management of materials remained the constraint in the 1970s [15], companies merged production planning, material requirements planning, shop floor scheduling and purchasing into an emerging materials management. This merging aimed to improve delivery performance, inventory levels and manufacturing costs [5]. Companies began overhauling warehouse layouts and route structures [4], with facility integration, including many of the systems in warehousing and manufacturing, forming an early version of supply chain management [10]. As the decade closed, companies' measurements continued an emphasis on cost and functions [4] rather than processes. While the momentum of change had increased over the 60s, companies remained focused on mass production and cost reduction [13].

Increasing competitive pressures in the marketplace marked the start of the 1980s. World-class organizations focused on lower cost, but higher quality products that were more reliable [9]. For the first time, companies' focus on the mass market began shifting to "local marketing" [13]. In response to the increase in competition, US manufacturers diversified product lines [3]. At the same time, the confluence of different trends in management accelerated the change. Organizations adopted "advanced management techniques" (such as Total Quality Management (TQM), Just-in-time (JIT) manufacturing and distribution, design for manufacturability (DFM), and flexible manufacturing systems (FMS)) [3] as management looked beyond issues of labor and asset utilization [15] to line optimization. While line optimization dominated the 80s [14], new management philosophies also challenged many of the traditional tenets and contributed to the intensifying competitive environment. Companies considered inventory a liability rather than an asset, lead-time became an important factor in creating customer value, and the inadequacies of traditional cost accounting surfaced [3]. Companies' increased cost focus led to the merging of distribution and transportation cost management with materials management to form an integrated logistics concept that enabled improvements in operational performance across multiple plants and distribution centers in large organizations [5]. But technology and the economy also significantly influenced the business landscape of the 80s. Spreadsheet technology introduced in that decade evolved into a user-friendly logistics planning tool used in most industries [7]. Progressive manufacturers and distributors began to exploit technology like bar coding and scanning, UPCs and electronic data interchange (EDI). This new technology not only began to standardize business practices [4], but companies converted variable costs to fixed by purchasing new manufacturing technologies as well [3]. Economic and market pressures played more significant roles in shaping the 80s through a combination of events. Deregulation in transportation produced "unprecedented" price and service competition among trucking companies and railroads. Companies felt even greater pressure to improve with continued foreign competitive pressure as inflation and interest rates soared, while at the same time consumer demands rose and the power of large shareholders increased [4]. These companies recognized the need to control critical inter-organization activities, but these activities were "managed by ownership" through vertical integration, which also benefited the organization by matching assets in the supply chain [16]. By the end of the 1980s, retail channels began to emerge. Big retailers replaced regional chains, gaining more influence in the supply chain that these large retailers used to negotiate better prices based on volume with better terms from the manufacturers [4].

The integration of customer service with mass customization and rapid delivery characterized the overall trend through the 90s, and, as the focus shifted from line to plant optimization [14], a company's ability to react to demand variability became a differentiating competitive factor [9]. But management efforts to increase customer satisfaction using reengineering for improving internal processes overlooked the need for both internal and external changes [17]. Companies realized that functional excellence does not equate to business excellence, which can only be achieved through superior business coordination [13]. During this decade companies recognized that supply chain management is "an enabler of competitive advantage" [18], a result of a decade of the most significant, fast-paced change yet. The impacts of economic, technological, and marketplace changes in this decade can be summarized by five specific trends: 1) focus on increasing revenues, 2) product commoditization, 3) growing customer demands, 4) globalization, and 5) e-commerce [4, p. 17].

1) Focus on increasing revenue. While cutting costs was still important in the 1990s, the major focus of companies shifted to increasing company revenue [4]. To this end, companies pursued better business coordination as a means to realize organizational excellence [13]. This had a significant impact on the market, changing the competitive environment very early in the decade. While companies managed inter-organizational operations of the 1980s "by ownership," that was no longer an option for companies of the 90s. The

vertical integration strategy carried high risk, reducing flexibility by locking companies into specific technologies and decreasing the company’s focus on core competencies through unmanageable expansion. By the mid 1990s, the vertical integration trend of the previous decade had, for the most part, reversed itself in that 60% of the mid 80s vertical acquisitions into new fields were later divested [16]. About the same time, large international companies began dominating manufacturing and increased focus on core competencies [19]. But companies could not use operations improvements and cost reduction [20] to remain competitive in the fast-paced business environment. The “world class” company model in the latter half of the 90s highlighted the need for an agile enterprise able to merge flexibility with delivery, cost, quality and dependability [9]. Further, companies could no longer afford the capital investment needed to maintain competitive advantage through inventory [21]. Instead companies recognized the importance of the link between inventory and manufacturing [20] and began to strive for increased productivity (from existing capacity) while reducing work-in-process (WIP) inventory. Manufacturers in the supply chain began the transformation to extended enterprises [22] while improving their ability to provide reliable delivery with low inventory [21]. This marked a definitive move toward an integrated supply chain where the enterprise began striving to meet customer needs [23]. By the end of the 1990s, the tremendous pressure on CEOs to produce strong earnings and increase shareholder value continued [4]. The key for these CEOs was the increasing of asset productivity "in the context of pull distribution," a significant change from the push systems of the past [22].

2) Product commoditization. Through the 90s, companies were forced to find new ways to differentiate products [4]. Product life cycles decreased and the number of products produced increased [9]. The marketplace had changed, and customers demanded individual customization, pressing for more sophisticated products with new technology [19], requiring more flexibility from manufacturers. This need for flexibility required manufacturers to shift from long production run focus to modular customized assembly [4]. By the end of the decade, customers evaluated suppliers more on the services offered than on the products alone as "quality became a standard of performance, not an option." [4, p. 51-52]

3) Growing customer demands. The marketplace changed yet more as the customers of the 90s fueled the move toward "mass customization" [19] with demands for more variety, better quality and greater service (based on reliability and response time) [9]. By the mid-1990s, organizations encountered continuous pressure to produce high quality products to meet customer needs in shorter time [23]. The view of quality from the customers' perspective became important as companies responded more readily to customer demands [15]. In doing so, power shifted toward the customer, blurring traditional roles in the supply chain [24] and "squeezing" manufacturers to deliver better customer service at lower cost [13]. Customers

of the 90s also set the definition of "acceptable performance," in many cases raising standards over a ten-year period, while in other, more competitive industries, customers redefined standards almost annually. By the end of the 1990s, "mega retailers" controlled the major distribution channels with their purchasing power, and manufacturers shifted toward make-to-order strategies for better customer responsiveness. This move called for even greater organizational flexibility on the part of the manufacturers [4], again addressed by a shift in focus from long run production to modular, customized assembly.

4) Globalization. Throughout the 1990s, more and more US companies began to source and sell globally [4] as the result of changes in technology, the market and the economy. More technically advanced products also required more resources, further driving companies toward global resource acquisition. As a result, manufacturing became more global, dominated by large international companies, and large final assemblers in the chain began concentrating on core competencies. Often "non-core" functions were outsourced to others in the supply chain, creating more opportunities. But these factors did more than just increase competition. The very nature of the competitive environment changed from individual companies competing to competition between different supply chains [19]. By the end of the 1990s, the global market transected geographical boundaries as many tariffs were eliminated [11], and global competition became the "norm rather than the exception" [26]. Companies focused on global approaches to sourcing, transportation,

marketing and manufacturing based on pull concepts [22]. "Dynamic alignment" replaced the vertical alignment of the late 80s [27] as partnerships and manufacturer alliances replaced vertical integration strategies [13]. The dynamic alignment introduced "functional shiftability" to the supply chain, which increased effectiveness by synchronizing efforts within the chain while streamlining the chain and increasing speed to market [28]. But the trend toward vertical de-integration through outsourcing greater percentages of manufactured components [1] increased the reliance on others in the supply chain. Manufacturers had to work more closely with supply chain members as product quality depended more and more on external inputs. These "non-competing collaborations" helped manufacturers increase their leverage with customers [13], further developing chain versus chain competition.

5) E-commerce. The pace of technological developments increased dramatically in the 1990s, producing product innovations and manufacturing process improvements [9]. The explosive growth in distributed processing and small computer power [1] in the late 80s and into the 90s made supply chain optimization systems possible for even the largest companies [7]. At the same time, high-powered, networked PCs with e-mail and internet access made e-commerce possible [11]. In many industries, e-commerce challenged the status quo and influenced the ways in which trading partners interacted [4]. This made the challenge of "making supply meet demand" even greater [21], and created a new challenge in managing the information flow

> associated with the material flow. Companies began using the internet and telephone to go directly to customers, bypassing wholesalers and retailers [4], resulting in a declining number of wholesalers. In some industries, wholesalers were all but eliminated, though in manufacturing about 60% of products were still marketed through wholesalers in the late 90s [28]. But the most significant impact of e-commerce is in business-to-business interactions, which are growing even faster than retail e-shopping. This is particularly true for heavy manufacturers where e-commerce applications focus on the transfer and processing of electronic documents (such as invoices, shipping notices and purchase orders). In this capacity, the internet "could become the ultimate driver of supply chain efficiency" [4, p. 27-28].

Overall the 1990s brought about more change than any of the previous decades. While market and technology factors played the most significant role, economic factors were still important in shaping the more recent developments in supply chain management. By the end of the decade, the trends toward vertical de-integration through outsourcing and increased attention to vendor certifications continued [1].

Impact on Manufacturers

Now, in the new millennium, manufacturers continue to face challenges of "increasing intensity and complexity" [26]. Competition between supply chains had already emerged in the 90s [19], and will continue in this decade [4] as the new focus moves toward optimizing the extended enterprise [14]. Companies now need to develop more integrated approaches to business to avoid suboptimization [26] in the context of the supply chain. For manufacturers, "life on the supply chain will only get tougher" [4, p. 22] as the dynamic business environment, characterized by demand uncertainty [13], market expansion and increased supply chain competition, continues to challenge companies [4]. Mass customization is already here as companies scramble to meet more stringent customer requirements [29] while performing "a highwire balancing act…to reduce costs, achieve flexible manufacturing, and provide ever-higher customer service levels" [30]. For manufacturers, there are several very compelling reasons to take note of the potential improvements to be realized through supply chain management:

1) Increasing customer demands. As stated by George Bevis, late Executive Vice President of Tennant Co., "The objective of a manufacturing company is to manage the flow of inventory to satisfy customers' needs" [31]. But customer demands are increasing now and will continue to increase, requiring constant measurement and operational changes to ensure continued cost effectiveness [4]. Efficiency is still important, but responsiveness to changing market conditions is now much more important [32, 33]. Manufacturers need to better anticipate customer demand for quicker response. This applies equally to manufacturers of consumer goods as well as those manufacturers who need to anticipate product failure and replacement part availability to support repair and service industries [34]. In either situation, the inevitable disparity between inventory and sales will require the manufacturer to make costly changes to production schedules or let customer service suffer [13]. As more companies look toward new methodologies like Just-in-time (JIT) manufacturing, more realize the need for just-in-time information to support those changes [35], and that information is held in the

supply chain. In the end, the companies that continue to meet customer demand the fastest will survive, while those companies that do not will lose market share [36].

2) Increasing competition. The first thing to happen in the face of increasing competition is that "everyone else" improves. The result: the rate of change in almost every industry's supply chain is accelerating [4]. As discussed above, manufacturers realized in the early to mid 1990s that their business practices were obsolete and began looking externally (e.g., benchmarking and best practices) [14]. Many discrete manufacturers began reemphasizing "quality management" with more of a focus on improving both the factory and supply chain performance while improving quality [37]. After spending the last ten years optimizing plant operations [29, 38], almost all manufacturers now meet market demands for consistent product quality regardless of industry [39]. Manufacturers can no longer compete on improved quality, efficiency and improved yield [14]. Since incremental improvement is all that remains within the plant [29, 38], companies must look for further cost reductions in the supply chain [40]. This outward focus shifts emphasis toward improving processes to increase the speed of product flow to the customer [39, 41], ensuring that products are high quality, made right the first time, and provided with ever decreasing lead time [20]. To this end, managing the flow of goods from end-to-end (raw materials to point of sale) is essential to remaining competitive in the market. More recent efforts to consolidate and streamline the supply chain have improved the effectiveness of the supply chain (increasing responsiveness and decreasing cost). At the same time, the challenges on the plant floor have increased with shorter production runs, more changeovers, diversified product lines,

more complex packaging, and more frequent schedule changes [36]. This means greater flexibility with less tolerance for rework or missed deliveries [37, 39] with increased financial pressure such that large capital investments in inventory are not practical, and inventory reductions are needed in part to increase the availability of capital [35].

3) Supply chain structure. Manufacturing is traditionally furthest from the customer in the linear supply chain model:

Manufacturer --> Wholesaler --> Retailer --> Consumer

Figure 2.1: Traditional Linear Supply Chain Model [28, p. 2]

As such, the manufacturer and raw materials suppliers are the most sensitive locations [42] to the Bullwhip effect, the "systematic distortion" that occurs as demand information (gathered and transmitted through the supply chain) moves away from the end consumer [43]. The Bullwhip effect creates excessive WIP, poor use of capacity, long customer backlogs, and increased expediting costs [1], which all propagate through the supply chain. In the 1950s, Jay Forrester demonstrated the impacts of this amplification, then termed the "acceleration principle," showing that a 10% change in rate of sale at the retail level can result in a 40% demand change for the manufacturer [42]. When this occurs, the variability must be buffered by inventory, capacity or time [1]. While this remains a concern for all manufacturers, those who have begun streamlining their supply chain have most likely undertaken steps to mitigate or eliminate the Bullwhip effect. But for many manufacturers the structure of the supply chain has already changed. The most important change in supply chain structure is the domination of the retailer in the chain, even in those chains with the historically biggest manufacturers. As different retailers have different approaches, the business environment for manufacturers is much more complex [44]. But manufacturing remains a key operational component [14, 15] and the most important single element on which supply chain performance depends is still the basic production process [37]. The characteristics of the factory drive the amount of inventory held in the entire chain, "and the ability to reduce in-plant response time is key to reducing the level of inventory required to support customer delivery expectations" [45]. This is especially significant for heavy manufacturers (such as aerospace, defense, industrial products and transportation equipment) for whom balancing the material flow through a complex network of resources on the shop floor is key. For these manufacturers in particular, the delivery of items is highly dependent on timely arrival of many manufactured parts at assembly points. Many of these parts are processed in manufacturing environments characterized by large amounts of dissimilar work at shared resources, large product variety and changing product mix (which in turn requires proper capacity allocation and scheduling), all of which impact timely arrival [46].

4) Challenges old and new. Manufacturers are still "besieged" by constantly changing priorities, forecast errors, late deliveries, product specification problems, and material flow disruptions that constrain operational capabilities and increase performance variability [17]. Poor management of this variability results in product obsolescence, unbalanced supply and demand, low customer retention and lost revenue (through lost opportunities) [47]. Managing a supply chain well has always been important [48], and

the traditional concepts (low cost, high quality) developed up to and including the 90s are still important in addressing many issues facing manufacturers. But the circumstances now are vastly different, and manufacturers face an environment of continuing change that is forcing a focus on agility and integration [14]. Managing the supply chain well is now critical as JIT and other trends push the burden of keeping inventory up the supply chain [48]. At the same time, the functionality of older manufacturing applications does not support the emerging requirements of the supply chain, increasing the uncertainty facing manufacturers [14] and reinforcing the need to integrate. The rules of the game are different; “the new rule is that there are no rules,” forcing manufacturers to transform from single entities to members of their supply chain [38].

The bottom line is that manufacturing is expected to do more, incur more cost and risk, and take more time to keep business. Retailers use the clout derived from their buying power and “exhaustive knowledge of what is selling at the checkout counter” [4, p. 22] to leverage continually lower prices and better service from their suppliers in return for large volumes. The message to manufacturers: “comply or die” [4, p. 22]. While many manufacturers realize their role has changed, most still maintain a dated view of the supply chain. Though many companies have global production, stocking, and distribution, few have global inventory visibility [49]. But manufacturers are starting to seriously embrace integration for the benefit of the supply chain [29]. As they realize that traditional marketing and distributing approaches are too slow to react [50], manufacturers need to shift from “push” to “pull” systems to drive down inventory, reduce warehousing requirements, and improve customer service [14].

Results of Increased Focus on the Supply Chain

For success in the long run, a supply chain must perform as well as its nearest competitor in the worst case [4]. Achieving this success means that companies in dynamic industries (which includes almost all industries today) must organize for functional integration [13]. At the same time these companies must increase profits, which is more easily accomplished through decreased fixed asset investment rather than increased sales volume [28]. For many of these companies, the key to realizing the needed improvements is supply chain management. Supply chain management is interpreted as many things, but, most importantly, it has evolved in response to the changing business environment. As such, supply chain management addresses the key elements of integrated planning and control needed for the global operations of companies today [26]. And as it has evolved, supply chain management has made its mark through the financial and operational results obtained by companies in a variety of industries.

Even though supply chain improvements are not cheap, the financial impacts can be significant. A 1997 study by Pittiglio, Rabin, Todd and McGrath (PRTM) found that best practice companies spend 3 to 6% of revenue on supply chain management. This is a significant investment considering the standard net profit in most industries is 0.02% of sales [28]. But the benefits are even more staggering with a potential return of as much as 7% of annual revenue. That means that strict management of the supply chain can save a $600 million company as much as $42 million annually [38] while improving a company’s asset performance by 15 to 20%. At the same time a company can reduce costs and increase cash on hand, potentially boosting its stock price by 20% or more [51]. The study also found that leading companies have a 40 to 60% advantage in “cash-to-cash” cycle time, the time for cash to flow back into the company after it is paid out for production material. Another multi-industry benchmarking study conducted by management consultant A. T. Kearney in 1996, showed that closer relationships with suppliers could reduce purchasing costs by an average of 12%. Since a manufacturer’s largest expense is frequently purchasing with 20 to 80% of total revenue spent on goods and services from suppliers, this reduction is significant. Further, one third of those companies studied expected additional reductions of 11 to 40%, while yet another third expected further reductions greater than 40% [25]. On the other hand, companies choosing not to make this investment could lose twice the potential return (up to 14%) in costs due to inefficiency [52]. And supply chain management continues its evolution and refinement. A 1999 benchmarking study by Performance Measurement Group (PMG) found that best-in-class performance in total supply chain costs was down 27% from 1995 levels. The leading companies of North America, Europe and Asia have cut supply chain management costs to 4 to 5 % of sales, while the median performers spent 9 to 11% of sales. Not surprisingly, the survey results showed a strong statistical correlation between market leadership in supply chain management and superior financial results. Market leaders not only reported profits 75% higher, but companies with strong supply chain management performance also reported 60 to 100% better asset utilization [53].

The benefits derived from supply chain management can also be seen in the operational improvements in companies in a variety of industries. The 1996 A. T.

Kearney report also showed that the companies studied decreased product development time by an average of 62%. During the same year auto suppliers reported a 20% improvement in inventory turns and a 72% reduction in error rates. In 1997, the US Department of Commerce stated that manufacturers had cut inventory by 9% since the 1980s, a savings of $82 billion passed on to customers and shareholders [28]. KPMG Consulting and the J. L. Kellogg School of Management conducted a global supply chain study (also in 1997) based on 451 responses from 24 countries in 8 different industries including: automotive, chemical, consumer goods, electronics and industrial. In this study, 42% of respondents had lowered inventories since the last year, and 52% forecasted lower inventories over the next three years [54]. The 1997 PRTM study mentioned above found that companies with solid supply chain systems had 60% fewer days of inventory, which resulted in better cash flow and more working capital. Further, the top performers in this study had higher productivity per employee [38] and achieved greater flexibility in meeting customer demand [38, 52], achieving 20% increases in production in less than 2 weeks while “fair to middling” companies needed up to four months to match that increase [52]. The individual benefits for some companies have been tremendous. Samsung’s supply chain management efforts halved average inventories from $3.6 billion [55]. Apple is another success story. Asset problems (such as having too much inventory) produced a $1 billion loss in 1997. At the end of that fiscal year, the company held 5 weeks of inventory ($437 million) with 10 inventory turns per year. By the end of the next fiscal year (September 1998), the company reduced inventory to 6 days (an 80% reduction). By December 1998, inventory levels dropped to

$25 million for a total reduction of 94% in fifteen months. By 1999 the company had increased inventory turns from 10 to 180 [56]. But big revenue is not the key to success. Nabisco, the $8.1 billion food manufacturer, carried $260 million in inventory (96 days) in 1999 as the company lacked a single focus on the supply chain [57]. This is in sharp contrast with Delphi, who supplies the Alabama Mercedes plant with 2 days of inventory [58].

Despite these successes, supply chain management had not yet reached widespread application in the 1990s. By 1996, only about 25% of the 500 largest manufacturing companies had started to formulate a supply chain management strategy [50]. At the same time there was still a tremendous potential savings. Retailers in soft goods and general merchandise industries had achieved $13 billion in annual savings out of a projected $102 billion in 1997 [52]. Even as late as 1998, waste in larger auto industry manufacturing supply chains amounted to 20 to 30% of costs [59]. But supply chain pressures are forcing manufacturers to rethink business practices [14], and necessitate continued change to meet evolving expectations. As stated by General Electric CEO Jack Welch, “If the rate of change inside an organization is less than the rate of change outside, the end is near” [4, p. 9]. For companies in this decade, supply chain management targets the challenges facing today’s business.

Defining the Supply Chain and its Objectives

Before continuing discussions about the supply chain, it is important to first establish some definitions of supply chain terms and outline the goals of the supply chain. As defined by Swaminathan, Smith and Sadeh:

> "A supply chain can be defined as a network of autonomous or semiautonomous business entities collectively responsible for procurement, manufacturing, and distribution activities associated with one or more families of related products" [60, p. 607].

Within a supply chain, Bhaskaran further defines a pipeline as " the stream of information, materials, components, and assemblies that are associated with a particular product or tight family of products" [61, p. 634]. Based on this concept, the supply chain in total consists of all the pipelines within it [61]. The latter definition emphasizes that the supply chain entities are linked by opposite flows of information and material. Together these concepts define the supply chain across a wide range of situations from co-located entities of the same organization to globally dispersed entities represented by numerous organizations. Given this conceptual structure of a supply chain, a number of supply chain objectives can be identified [62]:

1) agility to accommodate changes,
2) reduction of the inventory costs,
3) minimal response time to the market (through chain-wide inventory and production management),
4) smoothing supply chain dynamics to reduce fluctuation in demand signal, and
5) stability in supply chain dynamics for better forecasting of capacity requirements and product quality.

Based on the supply chain definition and goals, there are four major decision areas which impact the supply chain:

1) location (of production facilities, stock points, and distribution centers)

2) production (product line, actual production facilities and distribution centers used)
3) inventory deployment strategies (such as push versus pull) and control policies (order quantities, reorder points and safety stocks)
4) transportation decisions (mode, shipment sizes, routing and scheduling).

Each of these considerations has both strategic and operational elements, though most inventory management methods focus on the operational perspective since these decisions impact day-to-day operations [63].

A Simple Definition of Supply Chain Management

The purpose of supply chain management has really been constant since its very beginnings. Supply chain management is an enabler, a tool to achieve a company's goal. In simplest terms, a company's goal is to "make money" [64]. But the manner in which supply chain management approaches have changed to reach that goal continues to change with the business environment. By the beginning of this decade, the definition of supply chain management is all but clear, as reflected by the number of definitions to be found in use. But supply chain management is most simply defined as "the overall systemwide coordination of inventory stocks and flows" [1, p. 582]. Though simple, this definition fully encompasses many key points that define the context for discussing supply chain management issues.

- "Overall": A reality of business today is that companies must optimize the operating variables that affect financial measures as these ultimately impact shareholders [5]. As such companies must manage all events and activities, before and after manufacturing [20], that are involved in the delivery of goods and services to the market [26]. In this sense, the "overall" nature of supply chain management includes functions found across the organizations in the chain, from financial to human resources to workflow functions [23]. More specifically, this would include sourcing, manufacturing (production and assembly), marketing, sales, order entry and tracking, distribution, delivery [65, 66] and product development [26]. This provides a comprehensive view of factors influencing costs in each organization in the chain.

- "Systemwide": The "systemwide" perspective expands the early 90s boundaries of the enterprise, focusing now on the whole supply chain [65]. Instead of using a push philosophy based on forecasts of customer demands, supply chain management extends the "concept of a pull driven environment where the customer actually drives demand" [15], customer focus being the great potential benefit [67]. As the focus expands from an individual enterprise to the supply chain, planning functions have moved "beyond the four walls of the firm" [22]. The assets of the system now include equipment (as before), plus suppliers and partnerships [67] available to organizations in the supply chain as they strive to optimize the system [4]. As organizations strive to eliminate "inefficiencies out of the entire chain from source to consumption" [68], the entire supply chain changes to optimize its position in the market. This "dynamic alignment" [27] is key to maintaining the competitive advantages of the chain.
- "Coordination": The dynamic aspect of the supply chain is key as supply chain management is not an environment of static control and measurement [10]. On the

contrary, supply chain management aims to coordinate all links in the supply chain to maximize the speed and predictability of delivering goods to the customer. The relative value added by different links varies for different markets [69], and each organization has its own supply chain [21], requiring that each chain continually evaluate its market demand and partner capabilities. “Coordination” in the context of supply chain management goes far beyond the management of materials and stocks of the 70s and 80s as the increasing challenge for companies is matching material flow with the associated information flow [70]. The coordination and sharing of information is key in reducing risk and cost in the supply chain [22]. The biggest challenge for manufacturers remains optimizing the increased communications while moving to collaborative enterprises [71].

- “Inventory stocks and flows”: As stated by David Glass, CEO of Walmart, “The two most important things we can do are manage inventory and lower expenses” [28, p. 149]. Manufacturing results in inventory, and even Make-to-Order (MTO) companies face inventory issues in dealing with WIP [20]. System dynamics cause the majority of inventory found at every stage in the chain, most of which is totally unproductive in improving efficiency or delivery performance [45]. Therefore, inventory control is a key element in supply chain management [72]. The objective extends beyond just reducing inventories to ensuring that the purpose of inventories is met with minimal cost [1]. The challenges facing companies in this next decade will continue to intensify. In the face of these pressures, supply chains must strive for continuous inventory flow and achieve greater inventory visibility along the entire chain [22].

> The supply chain needs to continue to focus on inventories, not only ensuring the availability of product, but providing an optimal customer service level while managing all costs [74].

Overall the supply chain management of today differs greatly from traditional MRP with an emphasis on pulling goods through the chain based on both customer orders and chain constraints [46]. Today's supply chain management brings a greater visibility of material flows that results in better defined manufacturing schedules and improved customer service. The focus on inventories concentrates on replacing costly inventory with relatively inexpensive information [49]. But supply chain systems are more than just software. These systems are based on a new business philosophy and the application of technology, and are changing the way that manufacturers operate and interact with the supply chain [38].

The Role of Inventory in the Chain

The most common problems in the supply chain include coordinating inventory and capacity to maintain customer service levels. The decisions regarding inventory are important to the whole supply chain as the entities are "highly interdependent," and the impacts from improving performance, increasing quality, or decreasing costs [75] are felt throughout the chain. Inventory decisions impact the supply chain at almost every stage as raw materials, work-in-process (WIP), semi-finished or finished goods. As the central, common issue in the supply chain, inventory is a symptom of problems in the chain, and improvements in manufacturing can only be measured "in the context of inventory's performance" [20]. The primary purpose of these inventories is to buffer against uncertainty [63] arising from demand, process and supply [75]. But the main drivers for inventory are forecast error and system dynamics, with system dynamics serving as the primary driver. As demonstrated by Forrester in *Industrial Dynamics* (1961), even with zero forecast error a 3 stage supply chain has two week time delays between stages. A single 10% increase in order rate in this system causes a 50% increase in demand at the factory 2 weeks later, and the system continues to oscillate for 15 months in response to that single event. While the majority of inventory in the supply chain is completely unproductive in improving performance [45], the cost of these inventories is substantial, with the holding costs of inventory running as high as 20-40% of the inventory value [63]. As such, inventory is an "unwise approach to dealing with highly changing market demand and short life cycles" [75]. In the context of the supply chain, inventory is the most significant hidden cost where the largest savings can be realized [50].

Within the supply chain, there are four categories of inventories, each with different reasons for its existence. It is important to understand the function of each type such that any supply chain improvements undertaken focus on the purpose of each type of inventory [1], and to strive to make the inventory flow in each pipeline both continuous and visible across the entire chain. The four categories of inventory are:

1) Input Materials Inventory (IMI) – this is conceptually identical to raw materials inventory (RMI) at the plant level that Hopp and Spearman have defined as components, subassemblies or materials purchased outside the plant [1]. However, the distinction made here is that IMI originates from outside an individual pipeline such that the "system view" of the supply chain

considers "raw materials" as materials entering the pipeline. A mere extrapolation of the raw materials concept from the plant to the supply chain would actually entail tracking the change in inventory "status" from one entity to the next in the pipeline. Viewed as IMI, this material always enters the pipeline from an external source, and its characteristics are identical to raw materials inventory. This differentiation in nomenclature becomes more important in later analysis. At the production line level, raw materials inventory is a "necessary evil" that cannot be eliminated completely even using JIT techniques. The three main factors impacting RMI size are batching, variability, and obsolescence (due to changes in demand or design) [1]. These characteristics are expected to extend to IMI in the supply chain environment.

2) Work-in-transit (WIT) – this is analogous to work-in-process (WIP) inventory, which is defined in the plant environment to include all jobs released to a production line that have not arrived at an inventory location [1]. At the chain level, work-in-transit takes a slightly different perspective in that it includes all jobs released to a pipeline, a distinction which will prove useful in later analysis. WIT is another element which can be reduced but not eliminated. In a production line, typical WIP levels can exceed the critical WIP level (the lowest WIP level to achieve full throughput under the best conditions) by large amounts (20 to 30 times). The WIP will exist in five states: Queuing (waiting for resources), processing, waiting for batch (delay

for other jobs to complete a process or move batch), moving, or waiting to match (waiting at assembly for other parts to arrive). However, the majority of WIP (more than 90%) can be found in three states: queueing (caused by high utilization and variability in both flow and process), wait for batch (caused by batching for process or transport), or wait to match (caused by lack of synchronized arrival of components as well as flow and process variability) [1]. It is expected that these observations will also apply to work-in-transit inventory at the chain level.

3) End product inventory (EPI) – this is conceptually similar to finished goods inventory (FGI) at the production line level, which is defined as fully processed jobs not yet sold that are held in inventory for customer responsiveness. At the production line level, FGI is typically the result of batch production, forecast errors, production variability (in either timing or quantity), or demand seasonality (FGI held as build ahead inventory). It is essential to view FGI as a whole as these five causes interact [1]. In this case, it is expected that the concept will apply directly from the plant level to the supply chain as end product inventory, though EPI in the supply chain is held by entities nearest the end customer.
4) Spare parts – inventory held to support the production processes.

Of these types of inventory, process and flow variability are important factors in IMI, WIT and EPI inventories at the supply chain level, and subsequent discussions will focus on these inventories specifically. While many of the methods used to address FGI at the production line level can be applied to spare parts [1], the applications of these methods at the supply chain level are beyond the scope of discussion in this paper.

CHAPTER III

PRODUCTION CONTROL PRINCIPLES IN THE SUPPLY CHAIN

The initial focus of production control was to effectively use resources to produce goods in response to consumer demand while creating profit for those investing in the company. Ultimately this is accomplished by reducing the waste in the system by ensuring the coordination of resources, which, after reconciling the conflicting objectives of various parts of the organization, results in production plans and inventory policies for the organization. In this capacity, the production control function interrelates with other functions in the organization, and this interdependency results in decisions in one part of the production control system impacting other areas. At the organizational level, the

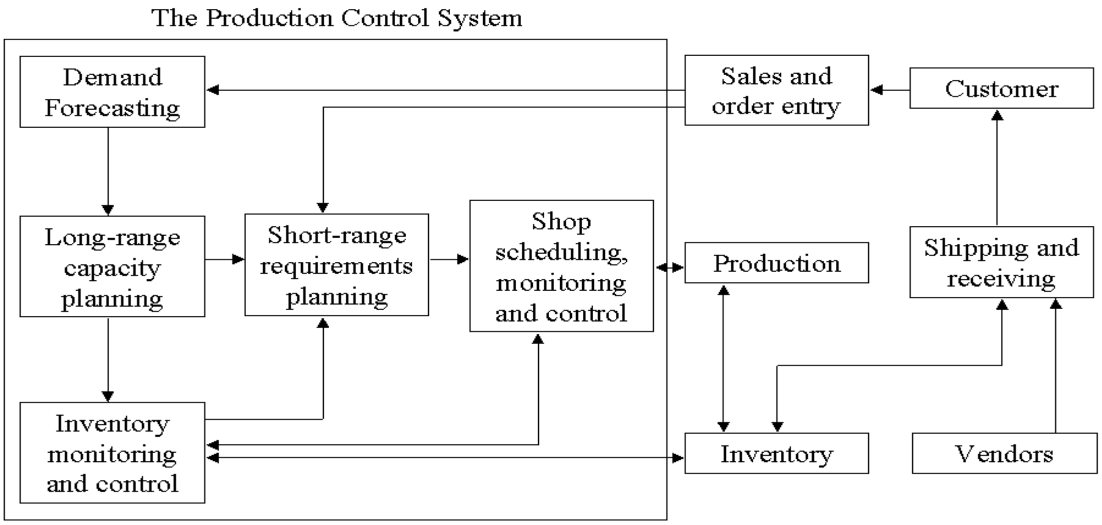

Figure 3.1: Production Control System Relationships and Information Flow [76, p. 4]

production control system starts with the customer. Figure 3.1 provides a simplistic overview of the interactions at this level [76].

When viewed as a hierarchical structure, the production planning and control model includes the elements noted in Figure 3.1 plus some other features. For a pull production system in particular, the hierarchical model specifically addresses WIP levels, while again emphasizing the interdependencies of the different elements of the production control system. Figure 3.2 illustrates this model.

Both of these models indicate that, regardless of the mechanism used (e.g., pull or push) in the system, the basic elements and purpose remain the same. Bedworth and Bailey succinctly defined the production control system and its objectives:

> "The production control activity is a chain of interrelated events that function as a system. The decisions are made for different horizons in time with different degrees of accuracy. Yet they must all occur if the final objective is to be met: that is, to use limited resources effectively to produce goods that satisfy customer demands and create a profit for investors" [76, p. 6].

Interestingly, although this definition was written in the context of the organization, it is just as applicable in the supply chain environment. As organizations expand their view of the system to encompass the supply chain, all of these activities must still take place, though production control activities for the chain may occur at different levels. At the organization level, the basic functions will continue, but the nature and role of these functions will likely change. For example, several organizations in the chain may perform aspects of the same function. At the other extreme, one chain member may take a more prominent role, performing a particular function or functions for other members of the chain. The interactions within the chain's production control system will be more

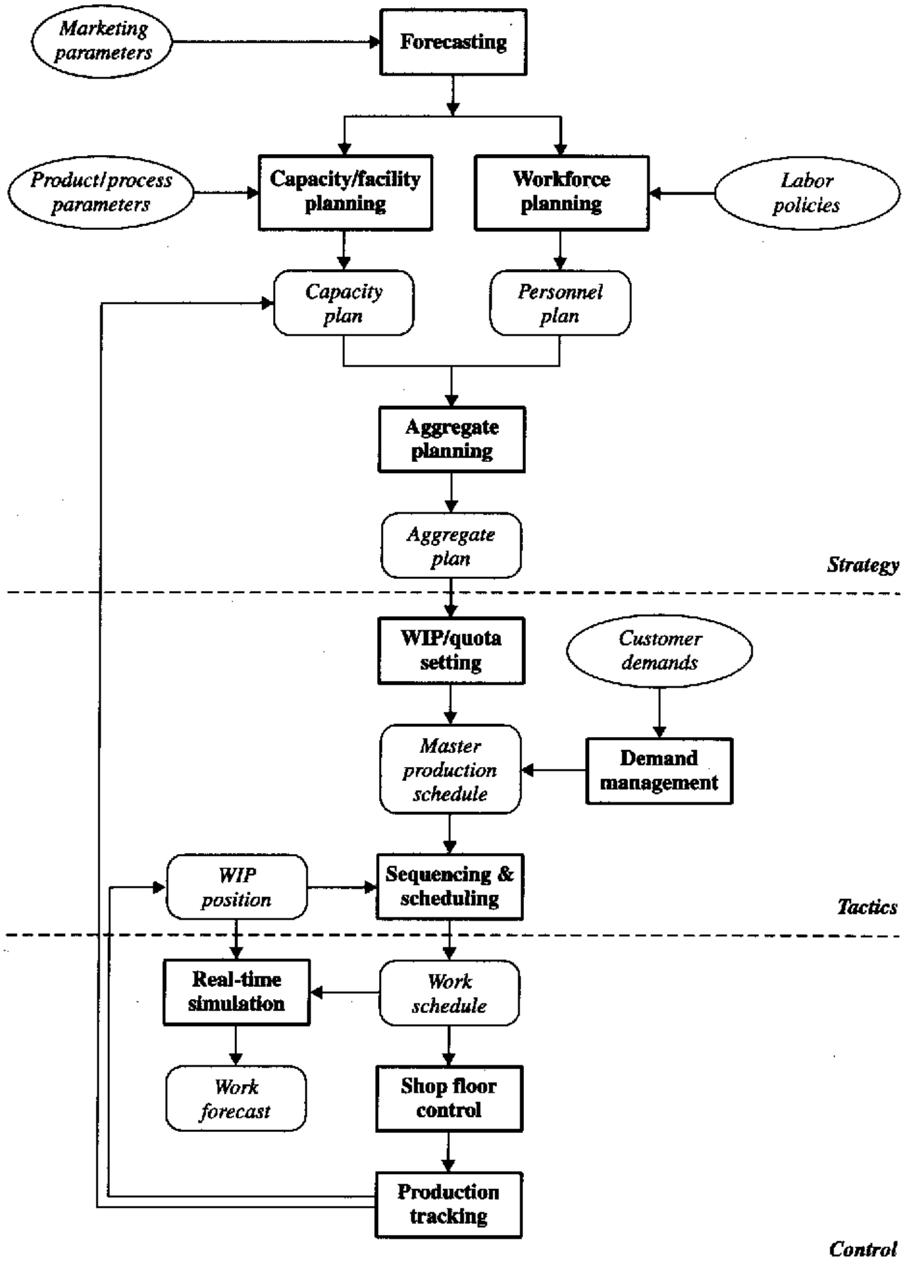

Figure 3.2: Pull Production and Planning Control Hierarchy [1, p. 433]

complex, but the general relationships and interdependencies described in Figures 3.1 and 3.2 remain the same.

An integral part of the execution of production control is the manufacturing system, which, in turn, impacts the manner of control. In this regard, the differences between push and pull production systems should not be overlooked. In a push system, production is scheduled. The release signal comes from outside the system (e.g., a schedule not linked to the status of the process). Such is the case in a Make-to-order (MTO) operation where production is based solely on customer needs, a push system. In a pull system, production is authorized by a signal inside the system which triggers material releases via a change in the process status. A basic stock model is a pull system in that orders are triggered when stock in the system falls below a certain level. A pull system offers several advantages over a push system. First, "a pure push system requires higher average WIP levels to attain a given throughput level" [1, p. 346]. The higher inventory levels, in turn, dilute the effects of disruptions in the system. Second, a pull system limits the maximum inventory before the system is overloaded. The decreases in output when an outage occurs are unavoidable. But the pull system delays releases and prevents overloading. This offers the third advantage, maintaining the flexibility for engineering changes or changes in schedule priorities. The loss of flexibility is an important cushion for reducing the costs of changes and expediting. The fourth advantage is that pull systems time work releases. This prevents congestion and keeps cycle time down to "directly reduce the manufacturing costs associated with holding inventory" [1, p. 345]. Generally, pull systems are more efficient than push systems, requiring less WIP for the same throughput. Again, these concepts were developed and executed at the production line level. However, these same principles can be extended to the supply chain environment [1].

Both the basic concepts of production control and the different methods used to achieve control at the line level in an organization can be extended to apply to the supply chain level. In particular, two approaches, Theory of Constraints (TOC) and Constant Work-in-process (CONWIP), focus on the system constraint to manage and ultimately reduce system-wide inventory. As mentioned earlier, inventory deployment strategies are among the four major decision areas in support of the supply chain goals. These two methods can be extrapolated to the supply chain environment as means to control and strategically deploy inventory within the supply chain, focusing on inventory control as a key element in supply chain management [72]. By doing so, organizations within the chain can strive toward the chain's objectives, while manufacturers specifically can realize some of the potential benefits.

Theory of Constraints at the Production Line Level

The Theory of Constraints was first developed in 1979 as Optimized Production Timetables (OPT), with its current name adopted by Goldratt in 1987. At the shop floor level, TOC uses Drum-Buffer-Rope (DBR), a scheduling methodology, in conjunction with Buffer Management (BM) techniques [3] to execute the production schedule [2]. The focus of TOC is the system constraint, which ultimately determines the system throughput, and the objective is to execute the finite schedule of the constraint. TOC in total consists of three separate components. The first component, logistics, is the most visible element to operations managers, and consists of the scheduling process and V-A-T Analysis. The scheduling process includes the DBR scheduling methodology and BM techniques, while V-A-T Analysis is a means of identifying the general product flow to determine control point and buffer locations. The second component of TOC consists of the five focusing steps and the performance measurement system, and the third component includes problem solving methodologies collectively known as the Thinking Processes [2]. Since scheduling and schedule execution are the main focus, this discussion will center on the first branch of TOC.

Under Constraints Management, control is exercised through five points: 1) the system constraint, 2) points of divergence, 3) points of convergence, 4) the gating operation, and 5) the shipping operation. V-A-T Analysis is a means of classifying production processes to identify general product flow and highlight these control points, as well as the locations for strategic placement of buffers. This analysis is also important in developing an overall systems view. The analysis is based on the Bill of Materials (BOM) and the product routings. At the production line level, there are two types of BOMs. The planning BOM is a summary of the information describing the relationship between components. This is the BOM that is normally used in computer production planning systems such as MRP. This differs from a manufacturing BOM, which describes the actual making of the product from raw materials to finished item. The routing is also needed for analysis of the production process structure, and describes the actual sequence of operations. The routing can also include cycle times, standard hours per operation, and machine center identifications. Regardless of specific content, the routing shows the logical flow of material. The logic structure is derived from the routing and the planning BOM to describe the overall flow of material for a product or product family. The end result of the V-A-T Analysis is the identification of key operations, control points and buffer locations. By focusing management attention in the areas identified, the organization can improve the performance of the system [2].

The name "V-A-T Analysis" is derived from the three most common basic structures observed. The most commonly observed structure is the T-structure, in which the routing consists of sequential steps leading to the finished product as shown in Figure 3.3. In this structure, common components and assemblies which each have their own routings are combined to create many different finished products. The T-structure is actually a special case of the V and A-structures where the initial structure develops into a much broader product line that offers more products with numerous features and options. The critical convergent point in the T-structure is located at the end of the process near the assembly and packing operations, and this control point dominates this structure. In fact, the fabrication and assembly areas are viewed as if they are separate plants. The most recognizable characteristic of this structure is the large number of combinations of finished products generated by a limited number of similar process steps. Other characteristics of this structure include:

- typically found in a make-to-order (MTO) or assemble-to-order (ATO) environment
- excessive WIP and FGI are held to ensure prompt fulfillment of orders when received

- production activities are usually labor intensive and include picking, assembly, and packing operations
- overtime is often used to meet schedules
- misallocation of parts (shifting a common assembly or part of a shipment from one order to another to meet schedules) or capacity is a key managerial problem which often results in additional overtime and misallocations.

Within this structure, a typical V-A-T Analysis would focus attention on the constraint and the convergent operation, as well as the several gating operations that most likely exist [2].

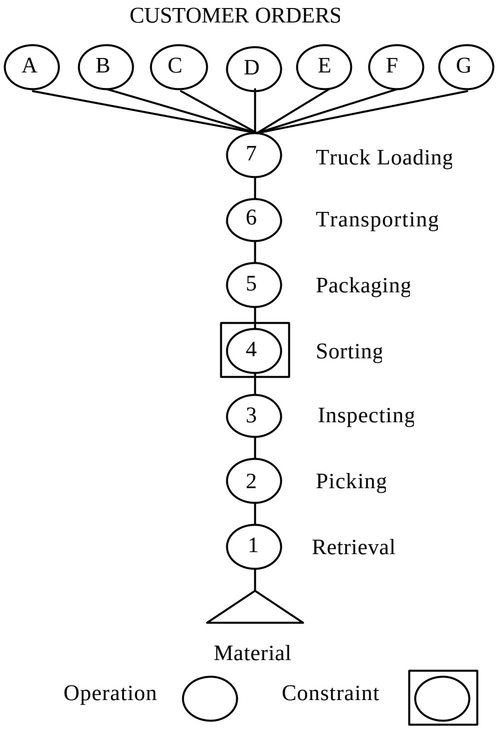

Figure 3.3: T-Structure [2, p. 108]

The V-structure, as shown in Figure 3.4, is the second most common logical structure of production lines. This structure represents a divergent fixed flow, where a product family shares an identical routing and the products differentiate at divergent points. The most significant difference from a T-structure is that a few types of materials (sometimes only one) are used to produce a variety of different products. The divergent points in the V-structure are often the constraints and, therefore the most important aspect of this structure. Equipment is usually expensive with specialized purpose, and dependent setup times can be long. After the divergent operation, the material generally cannot be shifted to production of another product since the customization occurs at that

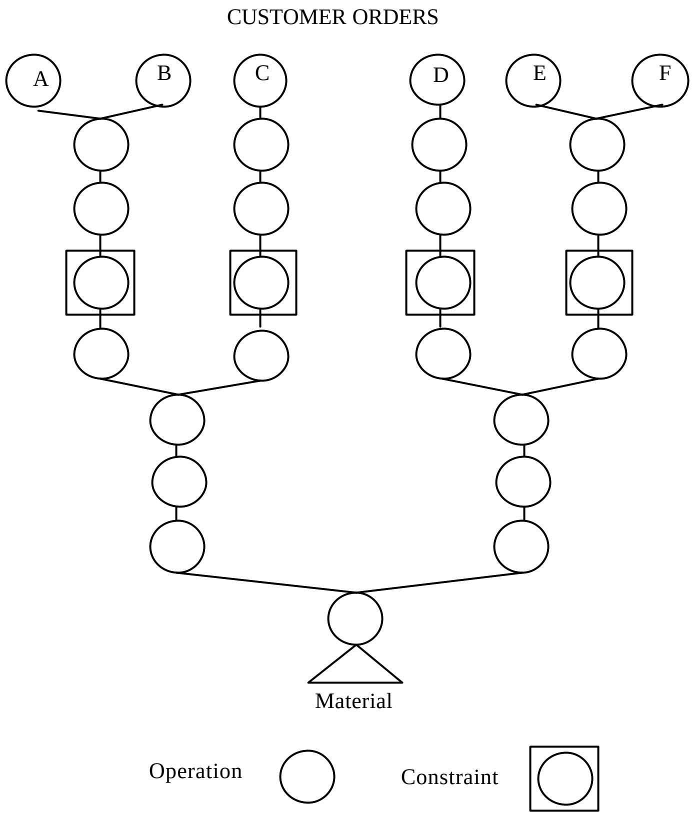

Figure 3.4: V-Structure [2, p.113]

operation. Material allocation at the divergent point is a primary concern as workcenters performing the divergent operation may misallocate material to reduce the setup times required and increase local efficiencies. In this case, misallocations usually involve diverting the entire order quantity. Within this structure, a typical V-A-T Analysis would highlight the constraint, the gating operation (usually only one) and divergent points (if not the constraint) as important control points. Control of the divergent point is based on both the constraint schedule and the customer orders. Where multiple divergent points exist, each must be provided information regarding order priorities and quantities. When long setup times create near constraints, a buffer can be used at the divergent point to allow for process batching to reduce setup times and eliminate the near constraint [2].

The third most common type of structure is the A-structure (depicted in Figure 3.5), which represents convergent flow where many raw materials and/or components are processed or assembled to make a few finished products. This structure typically requires a wide variety of resources. Similar to a T-structure, the A-structure contains convergent points, though these are located at production operations before packing and assembly and can cause misallocation of capacity. An A-structure is also characterized by a large number of dissimilar routings, whereas V and T-structures usually have comparatively few routings. Each order may require a specific sequence of operations that may not be repeated for other products, often resembling a job shop environment in which workers are interchangeable in terms of skills and assignment. Workers are usually reassigned throughout the day as priorities change and a “significant amount of expediting” [2, p. 115] is usually required. Generalized equipment is used for various operations on different parts, requiring long setups for different operations. A V-A-T Analysis of this structure would identify the constraint (though often hard to identify and may often be a specific skill or equipment required for most orders), convergent points, and divergent points as important control points. In this case, convergent point schedules are based on the constraint schedule and the order priorities maintained such that non-constraint parts arrive before constraint parts. A key factor is controlling misallocation of capacity at upstream workstations, where batching to reduce setup times may result in late arrival of parts or assemblies. The divergent points are controlled in a similar manner, using finite

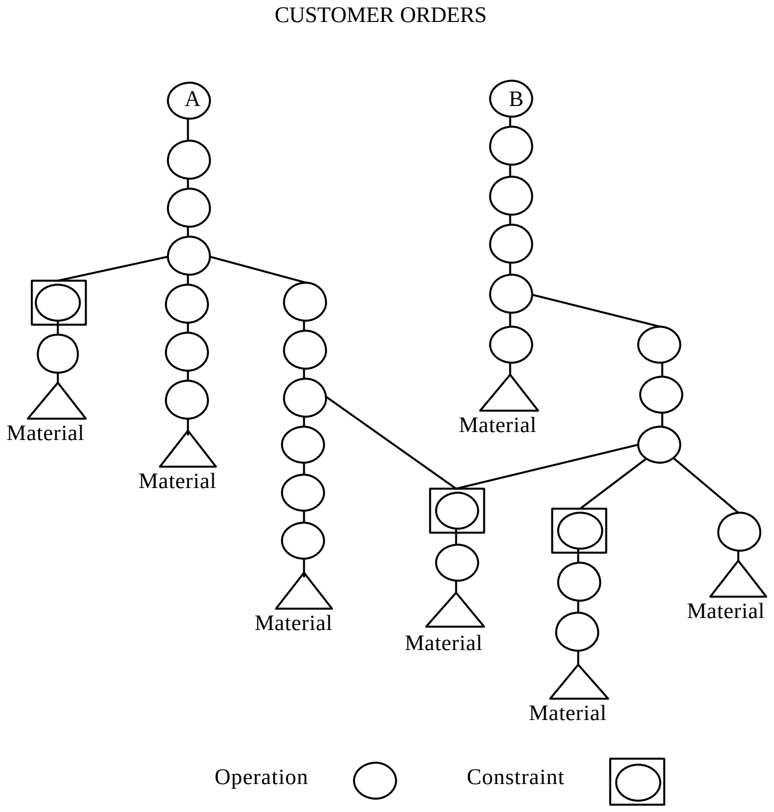

Figure 3.5: A-Structure [2, p. 119]

schedules of actual quantities required to reduce misallocation of capacity and reduce expediting [2].

After identifying the control points through V-A-T Analysis, the other component of the logistics branch of TOC, the scheduling process, is used for managing the production process described by the logical structure. The first portion is the DBR scheduling methodology which uses the control points to manage the system based on “constraint capabilities.” The objective of DBR is to maximize throughput using resource management. In this context, the constraint is any factor that limits the system’s throughput. As such, the constraint could be a physical condition (insufficient capacity at a workstation, or lack of material) or a managerial condition (a policy or procedure). The drum is the rate of constraint production on which the rest of the system is paced. Buffers are intentionally established to protect the system against disruptions due to variation so that throughput is maximized. The rope is the means of communication between the constraint and the gating operation to ensure material release is based on the constraint production rate [2]. It is important to note that the rope is the material release schedule, which is, in turn, based on the expected constraint production rate. In this sense, there is no “pull” interface as found in pure pull systems (e.g., kanban) or in hybrid systems (as a push/pull interface). As such TOC is strictly a “push” mechanism [77]. Its primary advantage over more traditional push systems (like MRP) is the consideration of constraint capacity, thereby representing more of a “paced push” manufacturing system.

In CM, the buffers are specifically located in the system, while most inventory “is removed from all operations except where it provides strategic benefits. This CM approach uses inventory to reduce the impact of statistical variability" [2, p. 98]. The first location is the constraint, which is protected by two buffers. The first is a time buffer between material release and the constraint such that the size of the time buffer is much larger than the sum of the processing times of the operations between these two points [2]. The general "rule of thumb in CM" is to initially establish a time buffer of three [78] to five times [2] the sum of setup and processing times, and then adjust the buffer size during production. The main purpose of this buffer is to ensure that the constraint is continuously supplied. Therefore this buffer should be nearly full most of the time. Another buffer is located after the constraint. This buffer is a space buffer that will prevent the line from being blocked in the event of equipment failure after the constraint, and should remain empty most of the time. Together these buffers serve to isolate the constraint from other workstations. If the sizes of buffers are maintained correctly, the throughput of the line will only be impacted by the statistical variations at the constraint [2], rather than the cumulative impact of variations through the line as in pure push systems.

The second buffer location is the assembly operation buffer. This is again a time buffer and is intended to protect shipping from internal and external disruptions. For purchased parts, this buffer ensures that variability in delivery does not disrupt the assembly schedule. This buffer also protects assembly from statistical fluctuations in the production of non-constraint parts, which can also disrupt the assembly schedule. This buffer also isolates the assembly operation from variability in the line for parts that are not routed through the constraint (e.g., variability that is not buffered by the constraint buffer) [2].

The last buffer location is at the shipping operation to ensure that shipments are not impacted by variability in the line [2]. With other buffers in place, the variability observed at the shipping operation is only that introduced by the constraint process. This buffer is also a time buffer that is added to the constraint schedule as a forward offset for constraint parts. Parts not routed through the constraint, or "free goods," can be scheduled by one of two methods. In the first method, material release is back scheduled from the shipping time (subtracting an established shipping buffer from the shipping time). In the second method, material release is scheduled to ensure that new constraints are not created in the line, then the shipping buffer is added to determine the shipping time [2].

The second portion of the scheduling process is buffer management, which is the means of executing the production schedule by managing the content of the buffers. Buffer management is explicitly defined as:

> "a process in which all expedition in a shop is driven by what is scheduled to be in the buffers (constraint, shipping and assembly buffers). By expediting this material into the buffers, the system helps avoid idleness at the constraint and missed customer due dates" [2, p. 18].

As discussed earlier, all of the control point schedules are based on the production rate of the constraint. This controls the material release to prevent excess WIP, reduce confusion and expediting, and to minimize misallocation to maintain priorities. The main areas of emphasis in buffer management are the sequencing, sizing and composition of the buffers. Buffer sequencing is based on the constraint such that priority decisions ensure that items with highest margins are scheduled first. The CM margin is the selling price minus raw materials, for which direct labor and overhead are assumed fixed in the short run. Based on this definition of margin, the priority of items at the constraint can be determined by the contribution per constraint minute [2].

The buffer is typically sized so that it remains, on the average, half full. It is composed of the jobs scheduled to arrive in the buffer during that period and includes setups, which are viewed as components in front of the machine center and are sequenced for "processing." The buffer area is managed by dividing it into three regions, which can be physically outlined on the shop floor. Each region represents an equal portion of the total buffer time [2]. Region three of the buffer is essentially the portion of the buffer that can drop to zero inventory with no action required. "Holes" that appear in region two indicate that parts required for the constraint are missing, and these must be located and tracked to ensure the timely arrival in the buffer. Expediting is not required until "holes" appear in region one of the buffer. At that point, missing parts can starve the constraint [78] and impact the output of the constraint (and, therefore, the system). As production occurs, the composition of the buffer changes [2] and the actual sizes of the regions can vary based on the production line's ability to react to these signals [78]. The physical division of the buffer allows supervisors to monitor the buffer for potential problems. As the buffers are monitored, the size of the buffer is decreased until "holes" appear in the regions [2] with the minimum buffer size targeted at a level so that 90% of the parts can be processed without expediting [78]. Improvement efforts can then focus on the causes of these holes as part of the continuous improvement process [2].

When DBR and BM are implemented at the production line level, the result is a system that times material release with the anticipated pace of constraint production. This method focuses on scheduling the system constraint, and using this schedule to drive other components in the production line. Figure 3.6 outlines the conceptual model of DBR and BM in production.

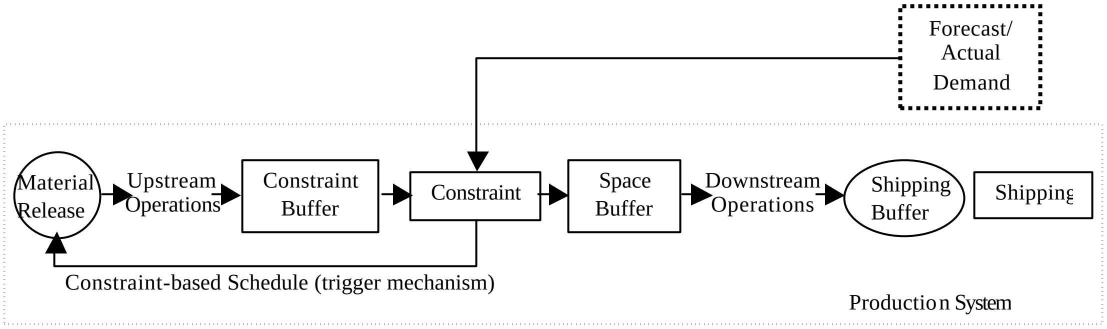

Figure 3.6: Basic concept of DBR and BM in production

Constant WIP (CONWIP) at the Production Line Level

An alternative to the TOC approach to production control is the factory physics approach developed by Hopp and Spearman [1] which is based on the need for a feedback mechanism for an effective production planning and control system. In this approach, the focus is on shop floor control (SFC) which “is where planning meets parts” [1, p. 453]. If well designed, SFC controls the flow of material while making the design and management of the rest of the production planning system easier. In practice, SFC is generally not given enough focus and is perceived as simple material flow control that is dependent on scheduling. Perhaps the varying nature of manufacturing systems, which “makes a uniform SFC module for all applications…impractical, if not impossible” [1, p. 482], contributes to this narrow view. In a broader view, SFC not only controls material flow, but it establishes links between a number of other functions that can be designed into the SFC module of the production planning and control system. The central component of SFC is, in fact, material flow control, which drives material release, workstation sequencing, and material transport. The other functions inherently related to material flow control are:

1. WIP tracking – tracking the location of parts in the line
2. Status monitoring – maintaining the status of the line other than WIP levels (such as manning and machine status)
3. Throughput tracking – measuring output of a line or plant against production goals or customer due dates to anticipate additional manning requirements for production
4. Capacity feedback – using updated information on capacity estimates used to make sure that execution is consistent with planning and monitoring input and output to track actual capacity over time
5. Work forecasting – predicting the arrival time of jobs at specific stations to anticipate and prepare for specific jobs
6. Quality control – monitoring quality at move points (an opportunity for statistical process control (SPC)) and linking to other functions to identify: replacements needed for scrap (coordinated with material flow control), blockages in the line when parts do not move because of quality problems (coordinated with WIP tracking), upcoming potential system delays (coordinated with work forecasting).

Given this range of functions, a SFC mechanism must be tailored to specific manufacturing systems so as to be manageable and effective [1].

The need to focus on SFC is driven by the inevitable difference between the sequence in which work is completed and that in which it is planned. Recognizing that this difference will exist, the aim is to use the schedule as a guide and make changes based on the actual state of the system. The factory physics approach seeks to take advantage of the benefits of both pull and push with the objective of tracking and improving the system throughput. Although capacity ultimately drives system throughput, it is not easily observable. Since WIP is easily observable and robust, it is a better candidate for a control parameter than system throughput, hence the emphasis on a constant limit on the upper bound of system WIP (constant WIP referred to as CONWIP). By limiting WIP levels, system cycle time decreases and throughput increases. At the same time, the limited WIP drives system improvements, as high throughput cannot be maintained at low WIP levels unless sources of variation are identified and eliminated. While pure push systems allow WIP to increase to mitigate the impacts of variation, the WIP limit highlights sources of variability and provides “pressure that promotes continuous improvement” [1, p. 348].

The CONWIP approach is based on the concept that the rate of the line is ultimately determined by the bottleneck. In lines where all parts follow the same routing, throughput is a direct function of bottleneck utilization. A basic CONWIP model entails timing releases with completions to maintain a constant WIP level. This model approximates the real system as long as routings are constant, processing times for all parts are similar, there are no significant setups and flow is linear (no assemblies). Under these conditions, a basic CONWIP line would appear as in Figure 3.7. This basic model is most easily implemented using CONWIP cards to maintain an upper limit on the system WIP, functioning similarly to kanban cards in lean manufacturing systems [1].

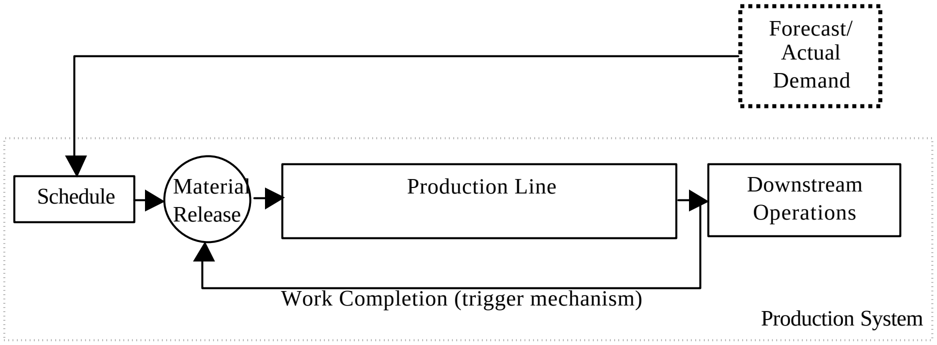

Figure 3.7: Basic CONWIP line

Looking at more complex situations, other CONWIP configurations may be preferred even when the assumptions of the basic CONWIP model apply. One alternative may include designing the line as tandem CONWIP loops or as split loops. Designing the line as tandem loops entails establishing separate CONWIP loops that are separated by buffers. Each loop maintains different WIP levels and can run as linked or unlinked. In linked loops, CONWIP cards remain attached until the jobs leave the interloop buffer so that the condition of one loop impacts the condition of the other linked loops. The configuration might apply to non-bottleneck loops which run at a speed fast enough to keep up with the rest of the line. When CONWIP cards are released when the job enters the interloop buffer, the loops remain unlinked and the buffers between allow these loops to temporarily run at different speeds without impacting each other in the short term. The unlinked configuration may be used, for example, when one loop can be identified as the bottleneck loop. In either configuration, the CONWIP loops will run at a speed that approaches the bottleneck rate over the long term. Such a setup may be desirable for span of control considerations in the organization or to more closely approximate the control achieved by kanban systems by increasing the number of CONWIP loops. The interloop buffers also allow for “passing points” where higher priority jobs can move ahead. In addition, analyzing the system is simplified somewhat as each loop can be analyzed separately. However, there are several tradeoffs. Using a looped configuration is more complex in terms of the implementation and the communication required to support production. Efficiency is also degraded because of the additional WIP and the increased cycle time created by the interloop buffers [1].

The existence of a shared resource across routings also presents a more complex situation for controlling production since incoming work is available from multiple routings. By establishing CONWIP loops before and after the shared resource, parts needed most urgently at downstream workstations can move ahead of other jobs in the buffer. In the loops adjacent to the shared resource, the overall sequence within each loop can be maintained as first-in-system first-out (FISFO) such that production is linked with demand as in a pull system. At the shared resource, jobs can be sequenced by age so that the work needed soonest is completed first. This configuration not only simplifies management of the shared resource, but the routings in this configuration can also be analyzed independent of one another, making the system analysis somewhat more manageable. By relaxing the basic CONWIP assumption of no significant setups, additional control parameters are needed to define the number of parts from one family to process before changing to another family. If the load of the products is fairly constant, the shared resource capacity can be allocated to specific part families based on a level volume of product in the routings. Similar to availability, this method decreases the overall time available for processing parts in each routing, thereby increasing the effective processing time. With a fairly steady volume of products, each routing can be approximated with the basic “conveyor” model. However, the greater the fluctuation in loading on the lines, the greater the variation introduced into the system, with an impact similar to the variability introduced by long, infrequent equipment outages [1].

By further relaxing the basic assumptions, the problem becomes more complex. Such is the case with many product families, where processing times can differ and sequence dependent setups might exist. This situation does not lend itself to control using WIP limits because of the varying processing times. As an alternative, the total amount of bottleneck processing time present in the line can be tracked and used as the trigger for material release. This same approach can be effective where multiple routings exist. However, most manufacturing systems do not resemble simple models and are not always stable, so it is often difficult to identify the bottleneck. For complex manufacturing systems, no production control model “can entirely mitigate the negative effects of highly variable demand” [1, p. 458]. Problems that can arise in applying the CONWIP model are: premature releases, when WIP levels trigger release of materials which are planned beyond a specified future window, and bottleneck starvation, which can occur when downstream machines fail and there is no mechanism to authorize additional releases. The issue of premature releases can be addressed by establishing a specific release window which is used in conjunction with WIP levels to trigger material release. The basic CONWIP method can be modified in a manner similar to the Drum-Buffer-Rope technique which is referred to as the Pull From Bottleneck strategy. This strategy addresses the bottleneck starvation by establishing a CONWIP loop from the beginning of the line to the bottleneck, and using a push strategy for the workstations following the bottleneck. The PFB strategy can then be used for routings through the bottleneck, while non-bottleneck routings are run as CONWIP loops. The non-bottleneck routings can also use the combination of WIP level and release window if the volume is not steady [1].

With the PFB strategy, the location of the push/pull interface, that boundary between the CONWIP loop and the downstream push portion of the line, has important impacts that depend on both customer requirements and the actual production process. By locating the push/pull interface closer to the customer, the customer may perceive better service if there is a noticeable increase in the speed of service. The characteristics of the process are important in that some steps may not lend themselves to the conditions imposed by the interface location. For example, the location of the interface may require that materials reside in a buffer at a specific point in the process, but those materials may not be easily handled or stored for the required length of time. At the same time, the number and location of the divergent points, where customization occurs, must also be considered. If there are very few finished goods produced, locating the interface closer to the customer may be accomplished with a reasonable level of finished goods inventory, whereas a line producing a large number of finished goods would require an interface located further upstream to avoid excessive amounts of inventory. This latter example relies on variability pooling. By locating the interface further upstream, less safety stock is needed to protect the line from disruption due to variability. This delays the customization of the product until specific customer demand exists [1].

Assembly operations introduce a more complex situation because the arrivals must be synchronized to avoid negative impacts on the system. The importance of the assembly operation often necessitates that the requirements for this operation dominate the control of the production in that the final assembly schedule drives the schedule of upstream fabrication operations. The assembly operation will trigger the release of material into the preceding fabrication lines, which are operated as CONWIP loops with specific WIP levels for each. As separate loops, each is separated from the assembly operation by an interloop buffer. The completion of assemblies then triggers material release into the fabrication lines.

General Considerations in Applying Production Control Methods to the Supply Chain

As previously discussed, production control objectives remain the same at the supply chain level, suggesting that similar, if not the same, methods applied to the production line may be applied to the chain environment. The focus at the chain level is the control of production activities by planning and controlling material flow through control points. There are several similarities between these two environments:

1. the line level routing is similar to the supply chain pipeline introduced earlier. This “routing” consists of “machine workcenters” represented by the various organizations in the chain.
2. the constraint is the basis for the system output.
3. the focus is on inventory in the system as a robust control parameter.

There are also several important differences to consider at the supply chain level:

1. there is no planning BOM counterpart in the supply chain environment. While a consolidation of organization level planning BOMs could serve this role if compatible, transportation is an important issue that would not be addressed.
2. at the line level, transportation is not a significant issue, but supply chains are geographically dispersed. The geographical dispersion of activities is considered by viewing logistics as a “production process” [2]. While varying definitions of logistics exist [79], in this discussion the term logistics is used to refer to the transportation network between supply chain activities.
3. contrary to the line level model, setups at the chain level are not considered.
4. the basic definition of “product” or “end product” is also fundamentally different. Customer requirements at the chain level include the “finished product” in a specific place at a specific time. While many quality philosophies emphasize this concept, it is critical to the application of production control methods at the chain level as this differentiates between supply chain pipelines.

The application of constraint-based production control methods parallels the production line level. A simplified supply chain will be used to illustrate the application. In this model, a single physical product is produced and sold through geographically dispersed retailers. Each of the supply chain pipelines is differentiated solely by variations in the transportation "processing time" or capacity, analogous to products routed through a series of shared resources. Implicit in this model are several important assumptions:

1. in lieu of setups, it is assumed that significant retooling of an organization in a supply chain pipeline would most likely not occur. Rather the composition of the supply chain would more likely change when facing a drastic shift in focus or requirements.
2. if transportation "processing" time is not the same or similar, that portion of the channel may require management as a distinct supply chain pipeline.
3. the system constraint(s) can be identified.
4. product volume is steady enough for a stable constraint.

Theory of Constraints at the Supply Chain Level

At the expanded chain level, it is still important to identify the five control points. The application of V-A-T Analysis in the chain environment parallels the application at the production line level. While there is no planning BOM, each control point (constraint, divergent points, convergent points, gating operation and shipping operation) has a counterpart in the supply chain, where shipping is viewed as the last transport process to the customer. Using V-A-T Analysis, the supply chain structure will vary by the type of goods manufactured and distributed by the chain. In each, transportation is depicted as a process by which pipelines differ in either processing time or capacity.

The expendable consumer goods chain (Figure 3.8) is the first type of supply chain to examine. In this type of chain, the distribution link is the most critical, and the distribution network is most likely sophisticated [48], implying larger numbers of retailers. Not only do divergent points largely dominate this structure, but other characteristics of the production line level V-structure also apply. Material after the divergent operation is generally not available to be shifted to another pipeline, though the differentiation has only occurred through transportation “processing” so this portion of the process is more easily reversible. Material allocation at the divergent point remains a primary concern. In this instance, a buffer could be used at the divergent point to allow for risk pooling to reduce downstream risks [79], similar to the approach to long setup times at the line level. However, this strategy would require consideration of the disadvantages of the additional inventory in the chain created by risk pooling. Further, where multiple divergent points exist, each requires information regarding order priorities and quantities. Even though this model is very simplistic with very few divergent points, it quickly becomes fairly complex.

An A-structure is more typical of a durable consumer goods chain as shown in Figure 3.9, where the purchasing component is as critical as a large number of raw materials and component suppliers can be included in the chain [51]. As at the line level, this structure is characterized by the combination of many raw materials or components to produce relatively few finished goods. At the chain level, this structure implies a

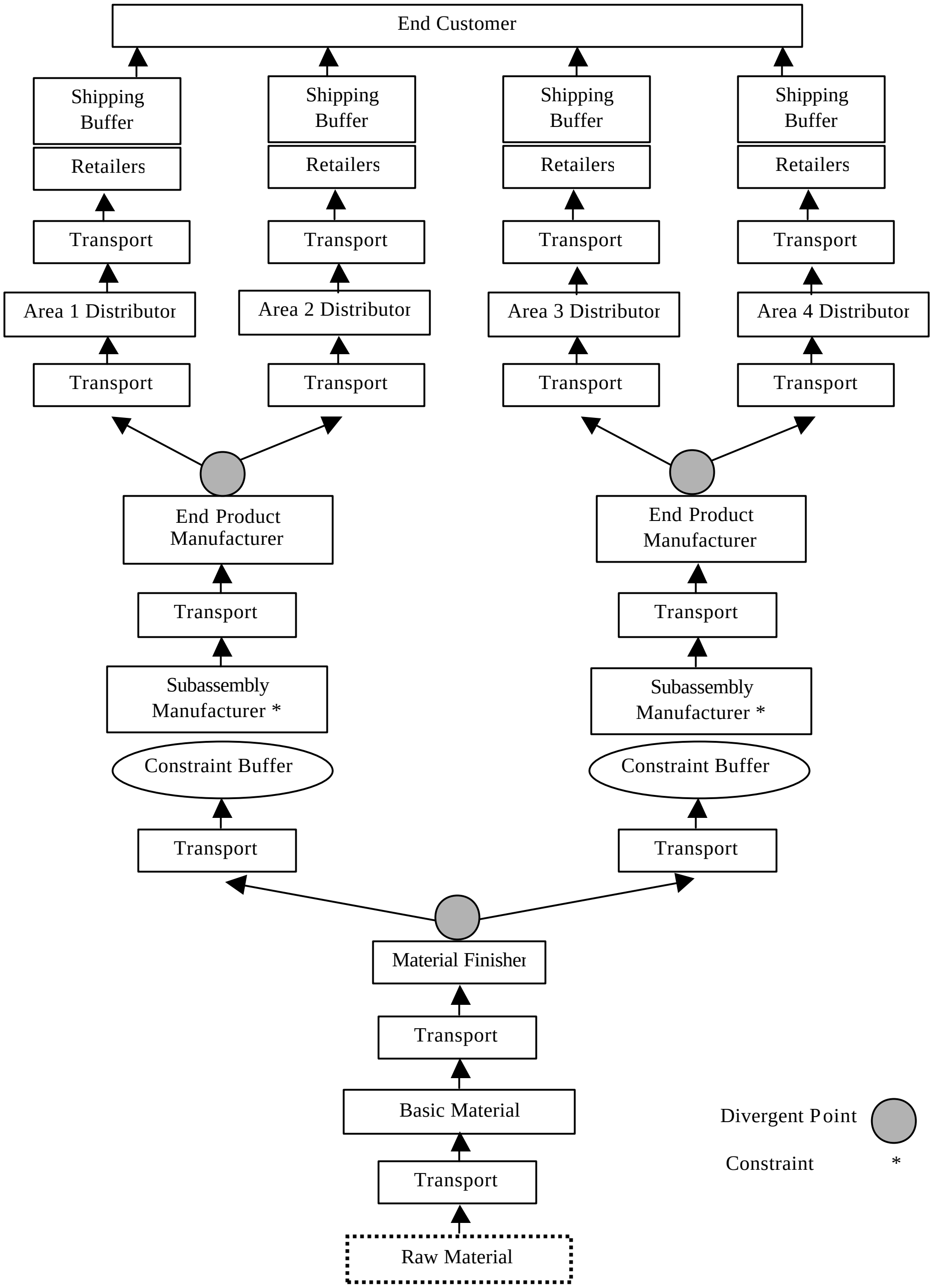

Figure 3.8: Example of expendable consumer goods supply chain employing TOC [2, p. 127 and 3, p. 348]

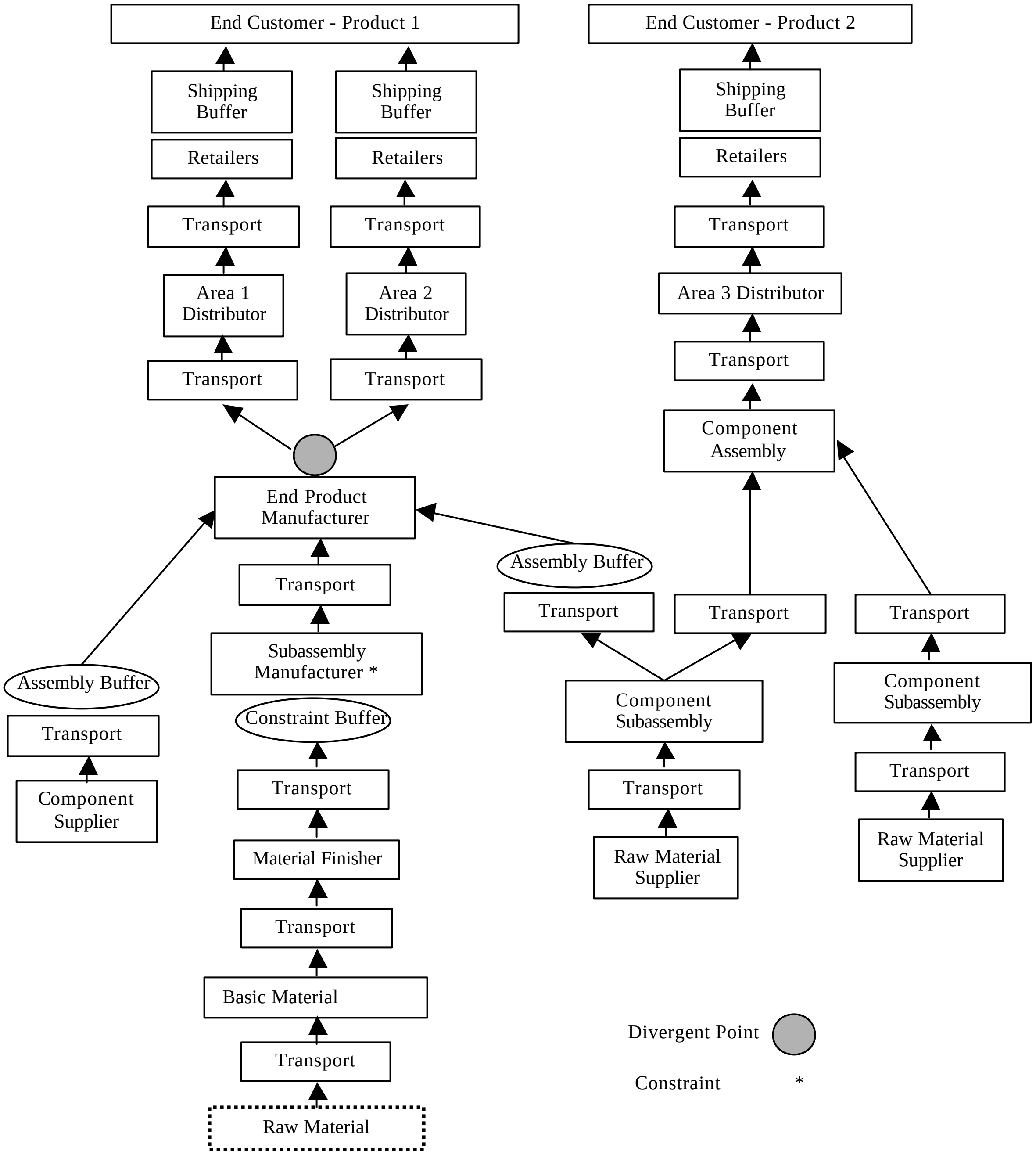

Figure 3.9: Example of durable goods supply chain employing TOC [2, p. 127 and 3, p. 348]

fewer number of retailers than might be found in a V-structure, and involves a larger number of supply chain pipelines that converge. Convergent point schedules are based on the constraint schedule and order priorities must be maintained to avoid late arrival of non-constraint parts because of misallocation upstream. The divergent points are also controlled using finite schedules of actual quantities to reduce misallocation of capacity and eliminate expediting.

The third type of supply chain (shown in Figure 3.10), that producing and distributing complex discrete products [51], would really show characteristics of the A-structures. As the manufacturing of components has a much more significant impact on the chain, the ability of the manufacturing organization to respond quickly without using inventory becomes more important. With still a fairly high reliance on the purchasing components, this type of structure would involve even fewer retailers than the typical A-structure, with a critical convergent point at the end of the process as is characteristic of a T-structure. This convergence point is an essential control point in this chain structure. Heavy manufacturing supply chains (such as industrial equipment, aerospace and defense) would typically involve this structure. Other production line characteristics might also apply, as the chains would typically operate in an MTO or ATO environment and production activities in the manufacturing organization are usually labor intensive. The same operations in these chains could produce a wide variety of combinations for the end product.

Overall, the V-A-T Analysis at the chain level indicates similar control points for analogous structures. The expendable consumer goods chain, with a V-type structure,

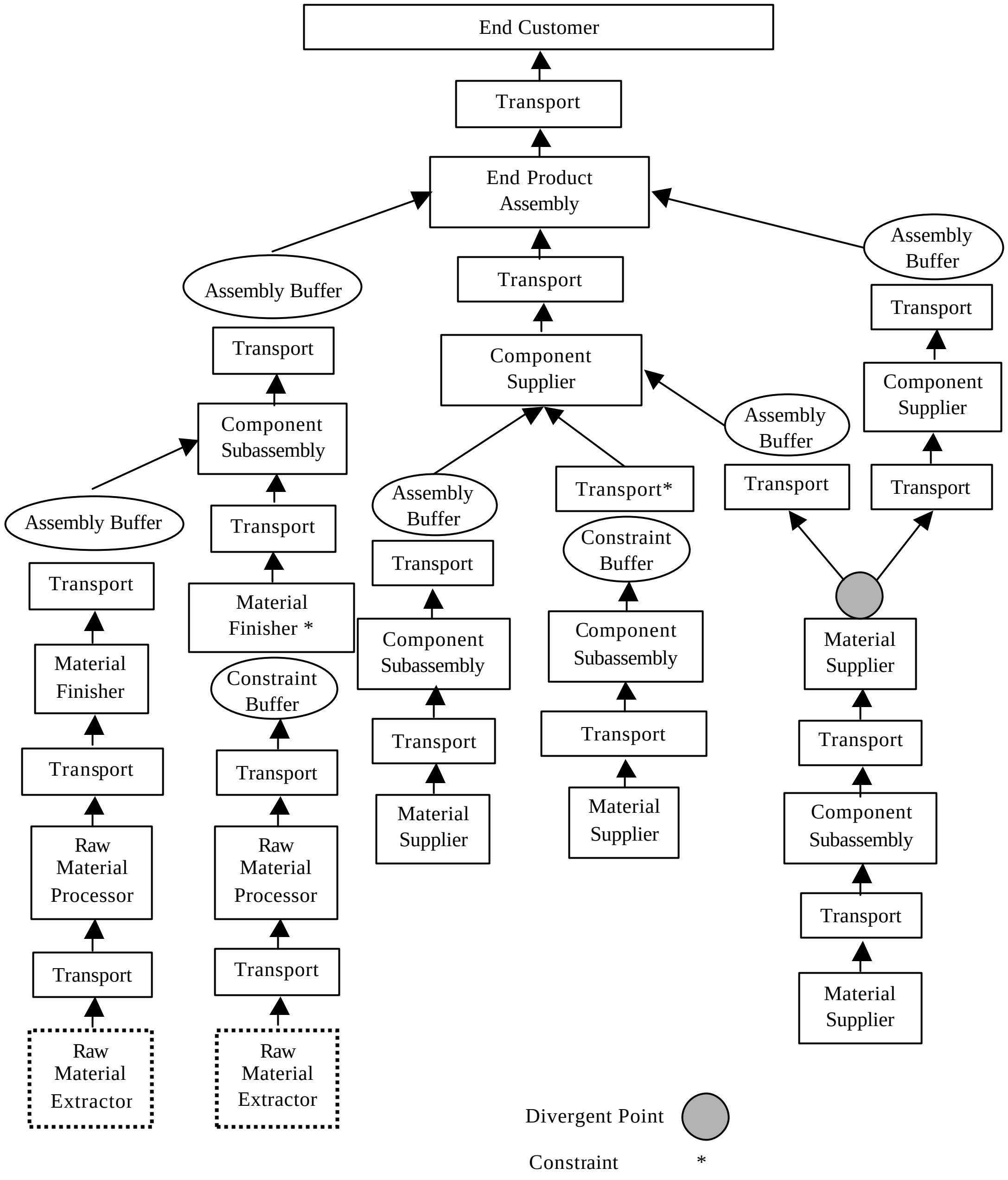

Figure 3.10: Example of complex discrete manufacturing supply chain employing TOC [2, p. 127 and 3, p. 348]

would be controlled through the constraint, the gating operation (usually one), and divergent points (if not the constraints). A durable goods chain, being similar to an A-structure, would be controlled through convergent points which are located before the packing and assembly, the constraint and divergent points. Lastly, the complex discrete products chain would be controlled through several gating operations, the constraint and convergent operations. The application of V-A-T Analysis at the production line and supply chain levels is summarized in Table 3.1.

Table 3.1

SUMMARY OF V-A-T ANALYSIS APPLICATIONS

	Production Line Level	**Supply Chain Level**
Elements	Product Routings	Supply Chain Pipelines
	Planning BOM	No counterpart
Output	Identifies 5 control points, key operations, and buffer locations.	Same; shipping is the last transport process to the customer
Use	Focus management attention on specific areas to improve system performance	Same

In examining the application of DBR to these chain structures, the basic concepts apply fairly directly as shown in Table 3.2. The locations of the various buffers (constraint, assembly and shipping) are consistent with the line level application. The

Table 3.2

SUMMARY OF TOC SCHEDULING PROCESS APPLICATIONS

	Production Line Level	**Supply Chain Level**
Drum	Rate of constraint workstation	Rate of constraint organization
Buffers	Constraint buffers – time buffer before, space buffer after	Same
	Assembly operation buffer	
	Shipping Operation buffer	
Rope	Constraint-based schedule	Same
Buffer Management	Means of schedule execution by managing the content of the buffers	Same

basic concepts of BM also apply. However, several practical issues arise that might impact actual implementation:

1. costs and locations of inventory – a method for determining cost distribution is necessary as inventory is consolidated at specific points in the chain rather than throughout the chain. Further, while not necessarily an issue at the line level, the specific locations of the inventory in the chain would need to be resolved. For example, an assembly buffer between a transport process and an assembly point could be located at the freight company’s destination point facilities or at the assembler’s facilities.
2. determining the buffer size – the actual mechanism for determining buffer size should be determined by function within the chain. However, as indicated earlier, large retailers have used their leverage to dominate the supply chain.

3. distinguishing between Raw Materials Inventory (RMI)/Work-In-Process (WIP)/Finished Goods Inventory (FGI) and Input Materials Inventory (IMI)/Work-In-Transit (WIT)/End Product Inventory (EPI) – supply chain inventory issues must be differentiated from organizational level issues. Since traditional line level categories of inventory (e.g., RMI, WIP and FGI) vary at each stage of the chain as product moves from one organization to the next, supply chain inventory designations (e.g., IMI, WIT and EPI) remain the same throughout the chain. This allows identification of inventory held for supply chain management purposes, making it easier to address issues of inventory cost and control. This also requires exact inventory control, perhaps in near real-time or real-time.
4. increasing complexity – even with a simple example, the model begins to look fairly complex. Relaxing the assumptions could quickly result in a very complex situation with multiple interactions between pipelines and organizations in the chain.
5. achieving Just-In-Time (JIT) information – as information replaces inventory in the supply chain, the need for JIT information becomes increasingly important. In addition to communicating between the chain organizations, data must be reliably transferred.
6. identifying the constraint – it may not be possible to specifically identify the constraint.

7. sequencing across several pipelines – even the most simple structures will most likely involve routing several pipelines through at least one of the same (and perhaps several of the same) organizations. This will require sequencing flow in a manner similar to a shared resource. However, priorities must be communicated across the various organizations, relying on an effective communication network.
8. exploding WIT – just as push systems at the line level can experience a WIP explosion, applying TOC at the chain level presents the possibility of a WIT explosion. The “paced push” aspect of TOC could mitigate this, but the possibility of a WIT explosion still exists.

Regardless of structure, though, the application of the TOC model to the supply chain environment addresses important concerns and provides important benefits, which specifically include:

1. ability to react to change – employing TOC directs the correct information to the appropriate control point, enabling the chain, as a system, to react to changes more quickly.
2. reduction in inventory – strategically locating inventory in the chain, and replacing inventory with information, decreases overall inventory costs throughout the chain.
3. minimal response time to the market – by reducing inventory, overall chain cycle time decreases and responsiveness increases.

4. reduced demand distortion – this is especially important for the manufacturing organization in the chain. By transmitting customer demand directly to the constraint, other activities in the chain are then based on the constraint schedule, eliminating, or at least mitigating, amplification of the demand signal up the chain. This eliminates the need for each link to generate independent forecasts.
5. increased stability in the chain – more predictable demand means more stability in the chain, allowing better forecasting of customer requirements.
6. prevention of starvation – ensures the constraint and the assembly operations are continuously fed.
7. enhanced customer service – by locating the shipping buffer near the retailer, customer service is improved by better response to changing customer needs.
8. defined information flow – identifying specific links which need real-time or near real-time information reduces unnecessary information exchange.

The application of the TOC concept in the supply chain consolidates the flow of information. It creates a more structured forum that both promotes and requires coordination in the chain to succeed. TOC concepts also concurrently address several important considerations which are essential to achieving the objectives of the chain, while producing specific benefits for the manufacturing organizations in the chain. The implementation concerns and benefits when applying TOC to the chain are summarized in Tables 3.4 and 3.5 respectively (pages 81 and 82).

CONWIP Concepts at the Supply Chain Level

In applying the factory physics CONWIP approach to the same structures described in the previous section, the analysis again parallels closely the production line concepts. Examining each structure individually, the CONWIP approach offers more flexibility in the types of strategies available to address concerns in the chain structure. Specifically these strategies include:

1. Basic CONWIP loops
2. Tandem CONWIP loops (linked and unlinked)
3. Pull From Bottleneck (PFB)
4. Assembly loops.

As in the TOC analysis, the first structure to look at is the expendable consumer goods supply chain, again analogous to the V-structure. While many possible configurations exist, one possible approach to this type of chain structure is shown in Figure 3.11. The main focus is on simplicity, as the supply chain environment is already complex enough to manage. More complex controls are only used when absolutely necessary. As such, this structure chain can be most easily analyzed as separate stages divided by the divergent points. As determined in the TOC analysis, this is a logical control point in the CONWIP model as well since these are points of customization in the chain. Since the stages form a serial configuration, it makes sense to look at the stages as tandem CONWIP loops. For each stage, focusing on the most effective means of control (e.g., balancing simplicity and capability), the first stage could operate as a basic CONWIP loop. This loop should operate as a linked loop since it is the non-bottleneck. The interloop buffer is best located at the divergent point to consolidate any inventory held as far upstream as possible (a risk pooling strategy [79]). The second stages of the chain are the bottleneck loops. Both can best be operated using the Pull from Bottleneck (PFB) strategy within this loop, unlinked to avoid disruptions at the constraint due to downstream outages. The interloop buffer is, again, held at the divergent point to postpone customization. The last stage of the pipeline is also operated as a linked CONWIP loop. An EPI buffer at the retailer serves as the push/pull interface, offering better customer service and responsiveness to the end customer.

The next chain structure, the durable goods supply chain, is also divided into stages at the divergent points, and involves the strategy used for assembly operations. The constraint paths shown in Figure 3.12 are the main pipelines with other pipelines that merge considered as non-bottleneck loops. While this structure requires a more complex approach, the focus remains on using the most basic CONWIP tools to achieve effective control. In the Product 1 pipelines, the first loop (from raw material to end product manufacturer) is the constraint loop for that pipeline, so the unlinked PFB loop is again appropriate here. The End Product Manufacturer is the assembly point. Both loops feeding this assembly operate as basic linked CONWIP loops and maintain an interloop buffer that functions similarly to the assembly buffer in the TOC analysis. The Component Supplier at the left of Figure 3.12 is also at the first stage of the pipeline, and could require an IMI buffer upstream to ensure the assembly operation does not starve. This buffer would only be necessary if the loop is unstable or has very long cycle times that might impact the inventory level of the interloop buffer. The interloop buffer

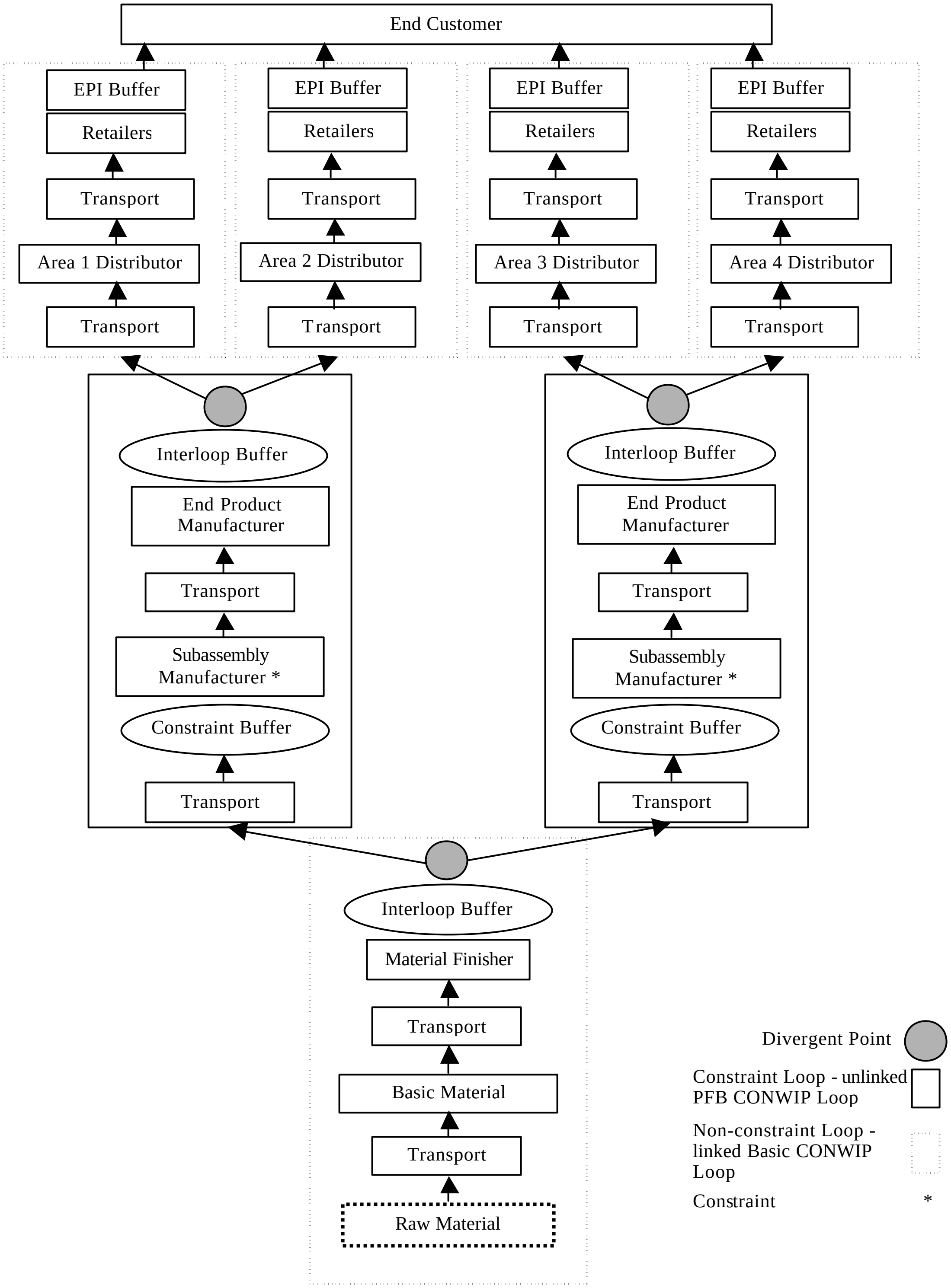

Figure 3.11: Example of an expendable consumer goods supply chain employing CONWIP

preceding the transport operation feeds the loop which converges at the assembly operation. The necessity of this buffer would again depend on the "processing time" and capacity of the transport operation, and would be unnecessary if the transport operation can reliably supply the assembly operation from the interloop buffer at the divergent point preceding the transport operation. If these interloop buffers are necessary, both could be held at the end product manufacturer performing the assembly operation, or at the distribution facilities of the freight company. The End Product Manufacturer is also the divergent point, so the interloop buffer would be maintained there. The second stage the entire constraint pipeline operates as a PFB linked loop with the EPI buffer located at the retailer.

The application of the CONWIP strategies in the complex discrete manufacturing chain in Figure 3.13 employs the same approaches as in the other structures with minor exceptions. Here the constraint loops merge at the End Product Assembly operation. In this case, the center Material Supplier (labeled "Primary Constraint Loop") is the best candidate for the main constraint pipeline since it feeds two assembly operations. The entire loop from Material Supplier to the final transport operation functions as the constraint loop in the pipeline. Since the loop interfaces directly with the End Customer of the Product 1 pipeline would also operate as a linked basic CONWIP loop with an EPI buffer at the retailer, just as in the expendable goods chain. For Product 2, the first stage could begin at either raw material supplier on the right side of Figure 3.12. However, since the raw material supplier feeds a divergent operation that subsequently merges at the next level in both pipelines, this loop is the best candidate for the non-bottleneck

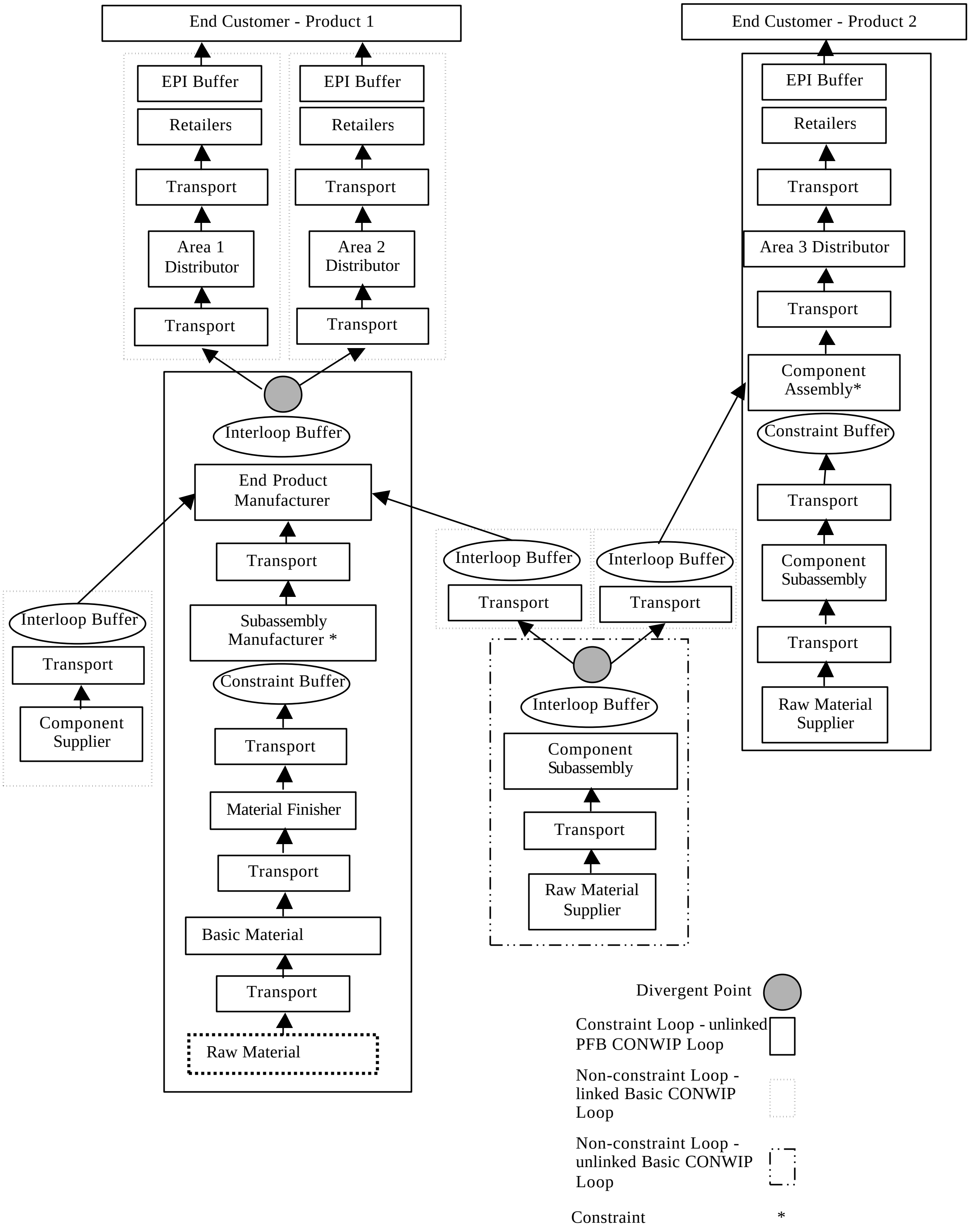

Figure 3.12: Example of a durable goods supply chain employing CONWIP

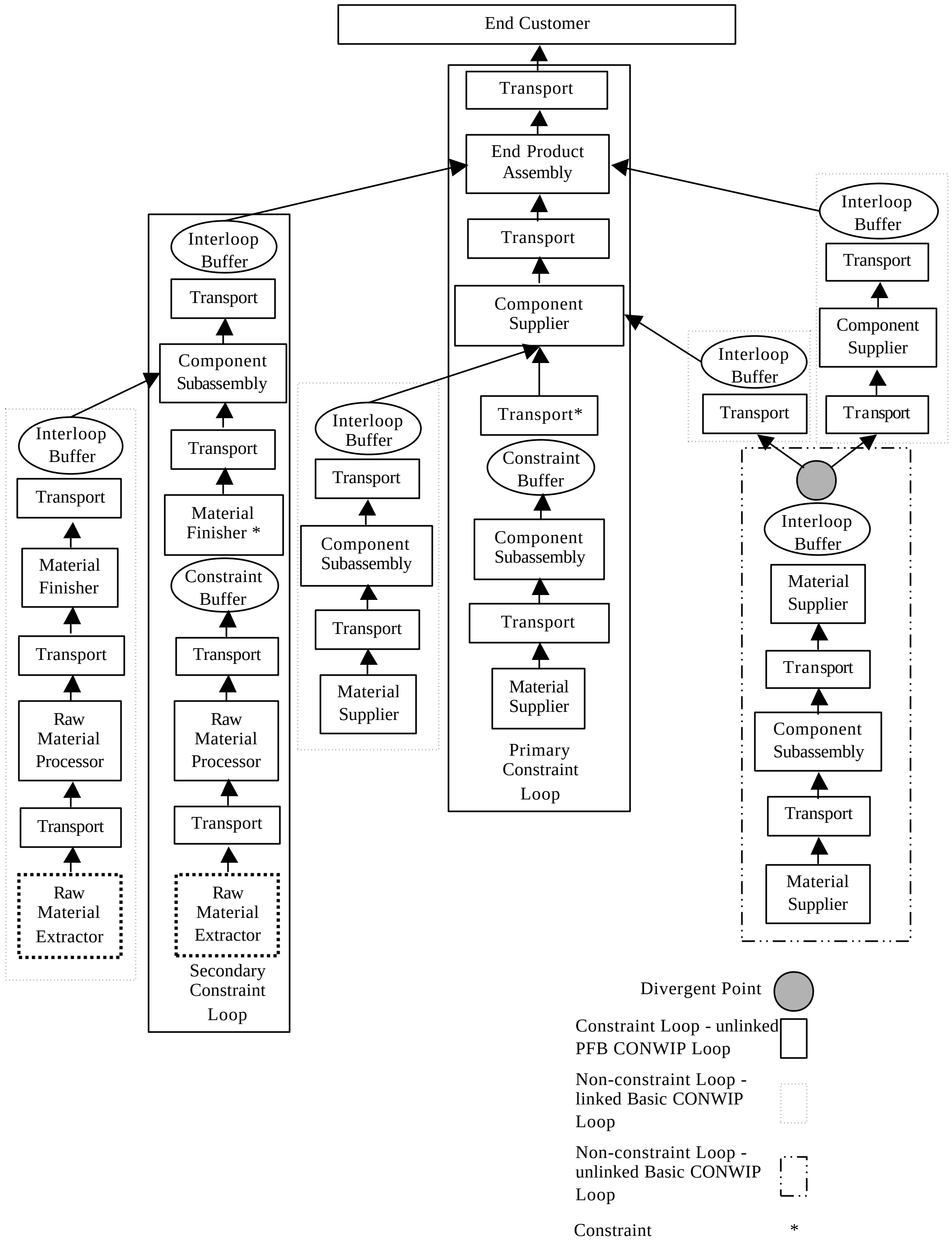

Figure 3.13: Example of a complex discrete manufacturing supply chain employing CONWIP

loop. This could also involve an IMI buffer at the Raw Material Supplier, which, in this case, would most likely be necessary. The interloop buffer held at the Component Subassembly would function as a basic CONWIP loop. The transport operation would hold the interloop buffer, but this buffer could be unnecessary if the transport "processing" time is low with high capacity and low utilization of the transport resource. The constraint loop for Product 2 begins at the Raw Material Supplier on the right side of Figure 3.12. In this case, the first stage extends from the Raw Material Supplier to the retailer. The constraint buffer is maintained at the Component Assembly operation, and (no buffer for such large, expensive items that are most likely MTO), the constraint loop operates as a linked PFB loop. End Customer demand is transmitted directly to the constraint. At the line level, the assembly operation can be used as the trigger for material release. However, in the chain structure, assembly operations in the constraint loop would not function as the material release trigger, but would rely on the constraint as the material release within the constraint loop. While this strategy could be used at the chain level, the existence of two or more serial assembly operations could introduce demand amplification. Typically at the line level the schedule is transmitted back from the assembly operation, subjugating fabrication operations to assembly [1]. In a supply chain with multiple serial assembly operations, transmitting the demand up the chain sequentially through each assembly operation could amplify the demand signal through the Bullwhip Effect, just as when serial links in the chain independently forecast demand. The secondary constraint operates as an unlinked PFB loop which feeds the interloop buffer closest to final assembly. The first stage loop beginning with the Material

Supplier on the right side of Figure 3.13 operates as an unlinked basic CONWIP loop. As discussed in the context of the durable goods chain structure, loops terminating at a divergent point could function as linked or unlinked loops, depending on the processing time of the transport operation, the capacity and the utilization of the transport resource. The remaining loops all function as basic CONWIP loops and each could have IMI buffers at the first link in each pipeline. As mentioned before, the necessity of each IMI buffer should be evaluated based on the transport processing time, capacity and utilization of the transport resource.

Applying the CONWIP principles and strategies to the supply chain is fairly straightforward and the concepts extrapolate well to the expanded system. The application of CONWIP in the production line and supply chain environments is summarized in Table 3.3. In this context, the application of the factory physics model is based on the following assumptions:

1. non-bottleneck CONWIP loops have enough capacity to “catch up” to the constraint loop in the event of an outage in the non-bottleneck loop.
2. the constraint is identified.
3. the assembly operations require a number of components from each supplying non-constraint loop that can be provided without the loop becoming a bottleneck or near-bottleneck.

With these assumptions in mind, using factory physics at the supply chain level brings to light some practical issues that might impact implementation. The first six issues

Table 3.3

SUMMARY OF CONWIP APPLICATIONS

	Production Line Level	**Supply Chain Level**
Basic CONWIP loop	Releases timed to maintain constant WIP	Same; used with linked/unlinked strategies
Linked tandem loop	CONWIP cards released after the next loop accepts the job so downstream loop impacts upstream loop * non-bottleneck loop	Same; interloop buffers held upstream
Unlinked tandem loop	CONWIP cards released as jobs enter interloop buffer so successive loops operate independently in the short term * bottleneck loops	Same * used in conjunction with PFB in the constraint loop with interloop buffers upstream * used to feed interloop buffers preceding assembly operations
Split loop	CONWIP loops before and after shared resources provide a means to reprioritize work in the buffers while maintaining FISFO sequence * shared resource	Potential application but not addressed in this model
Multiple product families	Total bottleneck processing time is tracked/controlled and is used as the release mechanism	Potential application but not addressed in this model
Pull From Bottleneck (PFB)	Prevent bottleneck starvation by establishing a basic CONWIP loop from the beginning of the line to the bottleneck, then using a push strategy downstream.	Same; push/pull interface location balances service level and postponement * used with unlinked tandem loop for constraint with interloop buffers upstream
Assembly Operation	Dominates upstream fabrication operations that are run as separate CONWIP loops with assembly completion as the release trigger	Different; material release not based on assembly completion as serial assembly operations could amplify demand

highlighted by the TOC analysis (pages 65-67) also apply to the application of the factory physics model. In addition, other issues may arise such as:

1. implementing the release feedback mechanism – establishing a mechanism to trigger release across several organizations could be complex and difficult to establish. Systems employing the CONWIP controller concept [1] would simplify this task, but would increase reliance on reliable, real-time or near real-time electronic data exchange.
2. coordinating capacity requirements – there is no “best guess” schedule for coordinating capacity requirements across organizations. From a functional manager’s perspective, this would increase the difficulty of managing resources within the organization.
3. maintaining supply chain inventory levels – in the structures examined, the number of buffer locations increases, especially in the complex discrete manufacturing chain.

The flexibility offered by the variety of strategies in the CONWIP approach provides a number of advantages in addition to those found through the application of TOC (pages 67-68). Specifically:

1. re-prioritizing work in the pipeline – the interloop buffers allow for re-sequencing or re-prioritizing work in the pipeline.

2. postponement of customization and cost – holding interloop buffers at upstream links delays customization and transportation expense until absolutely necessary.
3. preventing constraint starvation – unlinked PFB loops prevent shutdown of the constraint loop in the event of downstream outages.
4. identifying the constraint – while the structures examined do explicitly identify the constraint, the pipeline could operate with only the constraint loop identified. In this case, the constraint loop would operate as an unlinked basic CONWIP loop.
5. simpler configurations – loops can involve fewer organizations, relying on less complex relationships in the chain. As supply chain management is already complex enough, the least complex control method is preferred. Further, smaller loops minimize unnecessary information exchange and decrease the size of the information feedback loop.
6. benefits of a pull system – the CONWIP approach incorporates the advantages of pull production, providing better inventory control. This may ultimately counter the impacts of more buffer locations by keeping smaller amounts of inventory at more locations. With better control of WIT offered by the pull aspect of CONWIP, the overall WIT could still be lower than that observed with TOC, even with more buffers.
7. subdividing the system – in theory, the system should have only one constraint. However, as recognized by the factory physics approach, it is often

difficult to explicitly identify the constraint in a production line. The situation is further complicated by near constraints and floating bottlenecks. TOC, on the other hand, does not explicitly address these situations beyond the existence of two parallel operations which are both capacity constrained resources (as in Figure 3.11). The problem of constraint identification becomes even more complex at the supply chain level. While it is possible to at least identify the system's constraint loop, other loops may operate as near constraints. In these cases, it may be preferred to operate the system as if there were multiple constraints, identifying primary and secondary (or more) constraints as shown in Figures 3.10 and 3.13. Strictly speaking, TOC does not recognize near bottlenecks or floating bottlenecks. Thus the CONWIP model offers a more robust approach to a practical implementation issue that organizations in the chain may well encounter.

The application of the CONWIP concepts at the supply chain offers more strategies for addressing the concerns involved with strategically placing inventory in the supply chain. With its focus on controlling material flow through inventory levels in the system, the CONWIP approach relies on the actual state of the system to trigger releases. This approach is also feasible at the supply chain level, using WIT as the control parameter for material flow at the chain level. The implementation concerns and benefits when applying CONWIP to the chain are summarized in Tables 3.4 and 3.5 respectively (pages 81 and 82).

Table 3.4

POSSIBLE IMPLEMENTATION ISSUES IN APPLYING CONSTRAINT-BASED METHODS AT THE SUPPLY CHAIN LEVEL

Issue…	**Consideration in applying…**	
	TOC	**CONWIP**
Methods for cost distribution and inventory location determination	Yes	Yes
Establishing actual mechanism for determining buffer size	Yes	Yes
Differentiating between organizational and chain level inventory	Yes	Yes
Addressing the increased complexity of the chain environment	Yes	Yes
Achieving JIT information	Yes	Yes
Specifically identifying the constraint	Yes	Yes
Sequencing across several pipelines	Yes	
Exploding WIT	Yes	
Complexity and difficulty of establishing a release mechanism across several organizations		Yes
Difficulty of coordinating capacity/resource management at the organizational level without a “best guess” schedule		Yes
Maintaining supply chain inventory at lower levels if additional interloop buffers are used		Yes

Table 3.5

BENEFITS OF APPLYING CONSTRAINT-BASED METHODS AT THE SUPPLY CHAIN LEVEL

Benefit…	**Realized when applying…**	
	TOC	**CONWIP**
Information directed to control points for greater responsiveness to change	Yes	Yes
Reduced inventory levels and cost	Yes	Yes
Improved overall chain cycle time for better responsiveness	Yes	Yes
Reduced demand distortion	Yes	Yes
Increased chain stability	Yes	Yes
Enhanced customer service	Yes	Yes
Defined information flow to reduce unnecessary information exchange	Yes	Yes
Postponement of customization and cost		Yes
Constraint need not be specifically identified, only the constraint loop		Yes
Simpler configurations involving fewer organizations using smaller loops		Yes
Incorporates benefits of pull		Yes
Robust approach to near constraints and floating bottleneck through subdividing the system		Yes

CHAPTER IV

SUMMARY

The development of Supply Chain Management has occurred gradually over the latter half of the last century, gaining momentum and accelerating as the end of the century drew closer. In this century, SCM will continue to evolve at a seemingly ever-increasing rate in response to the continual changes in the business environment. More and more organizations will turn toward the supply chain as they exhaust opportunities for breakthrough improvement within the four walls of their organization. Manufacturers in particular can benefit from this increased focus on the chain since they are typically located further upstream in the chain and are more impacted by the Bullwhip effect, though the gains realized by manufacturers will vary by the type of supply chain. By effectively using tools already common at the production line level, organizations in the chain can tailor production control principles currently in use to address important supply chain considerations. In doing so, the focus on inventory in the system remains a key element. The Theory of Constraints and the factory physics principles behind the Constant WIP concepts focus on the system constraint with the aim of controlling inventory. Each can be extrapolated to focus on a system whose boundaries span the entire supply chain. But in doing so, it is important to understand the impact of the production line counterparts in the chain environment. It is important to specifically identify the inventory held for supply chain considerations so that these concerns are considered in the proper context, while other inventory considerations can be addressed at the organization level.

Conclusions and Contributions

Understanding that the production control principles used commonly at the line level apply almost directly to the chain level is the fundamental basis for examining the application of constraint-based methods to supply chain management. Since the supply chain is so much more complex than the production line, it is absolutely necessary to carefully analyze the specific structure and capabilities of each chain individually. There is no "silver bullet" that can address the wide variety of possible scenarios. However, the basic principles of TOC and CONWIP can be applied to the supply chain in a manner that effectively addresses key concerns in the chain environment, and manufacturers in particular can realize the additional benefits described. The application of V-A-T Analysis to the chain effectively identifies control points in the chain structure. Using these control points, both TOC and CONWIP ensure that assembly and constraint operations are continuously fed. The difference in focus of the two methods carries forward from the production line level to the supply chain. TOC's strength lies mainly in its scheduling methodology, with unique benefits and interesting possibilities in its application at the chain level. The CONWIP principles, on the other hand, effectively incorporate pull principles to provide an effective, more flexible and more robust schedule execution mechanism. With this seemingly synergistic relationship, it seems logical that the components of each could be "mixed and matched" using Drum-Buffer-

Rope scheduling with CONWIP execution to maximize gains in managing the supply chain.

One area in which constraint-based production control methods can be directly applied is supply chain simulation. While simulation is already well established and accepted in manufacturing [80, 81], it is more recently emerging as a comprehensive tool for evaluating both the operational and strategic elements of the supply chain [63]. The impact of time dependencies affects the entire chain and requires the use of simulation in analyzing the supply chain [82]. Simulation is already in use in a variety of settings, driven by organizations' needs to do one or more of the following:

- optimize the whole manufacturing network –the ability of the supply chain to meet the challenges of the market place depend more and more on the dynamics of the chain and not on isolated organizational changes [83]. Supply chain simulations that focus on the factory level capture the highest level of these interactions between supply chain entities [84]. However, implied in this approach is a supply chain reference model. The reference models in use today are widely varied, and there is no standard reference model that adequately represents the supply chain [85].
- control amplification of production dynamics up the supply chain – as noted earlier, system dynamics are a primary driver of inventory in the supply chain. This also drives the need for organizations to optimize individual pipelines within the chain to control or dampen the amplification of system dynamics up the

supply chain. Organizations must control the schedule instabilities within the chain and the inventory fluctuations that result [61].

- evaluate the impact of pull/push systems – while the main focus is on pull systems, the CONWIP pull/push interface is modeled in the same manner. The Theory of Constraints drum-buffer-rope is modeled in a manner similar to the traditional push manufacturing systems (e.g., MRP) [85]. These simulations allow organizations in the supply chain to evaluate the impacts of these various strategies in individual pipelines.
- determine the degree of vertical integration [61] – simulations track a number of statistics that can be used in determining the most robust supply chain configuration. The overall performance of the supply chain, in terms of cost and operational performance, can be gauged by a number of measures which include inventory investment, response and lead times, and customer service [87]. These measures, along with other similar measures, are important tools to evaluate the impact of operational control over supply chain entities [88] versus dynamic alignment in the chain.

Simulation models need a certain degree of complexity to “capture the key cause-and-effect relationships in the system” [86, p. 144]. The extension of constraint-based approaches from the production line to the supply chain could identify the significant interactions in the system. In lieu of a comprehensive reference model for the supply chain, these interactions would form the basis of the model, and drive the level of complexity.

Directions for Future Research

The discussion herein has focused on admittedly simple scenarios for the sole purpose of examining the applicability of the basic principles. As discussed, the supply chain presents a significantly more complex and intricate environment, so an obvious area for future research is the development of case studies which detail the application of these principles and analyze the performance of constraint-based methods in the chain environment. There are also many areas which directly impact the supply chain objectives discussed, including:

1. supply chain layout considerations
2. pipeline design
3. the impact of control policies (order quantities, reorder points and safety stocks) in a chain employing constraint-based control methods
4. effective control mechanisms for serial assembly operations in the supply chain
5. effectively blending the TOC and CONWIP concepts for enhanced chain performance, and comparing the performance of this system against others based only on the TOC or CONWIP approach.

While some of these topics have been addressed to varying degrees in the literature, it would be both interesting and beneficial to research the impacts of these areas in a chain where constraint-based methods form the basis of the overall system control. This would be particularly interesting in a chain that blends the concepts of TOC and CONWIP to optimize the chain's performance.

REFERENCES CITED

[1] Hopp, W. J. and Spearman, M. L. (2000) *Factory Physics*. Irwin Mcgraw-Hill, Boston, MA.

[2] Cox, J. F. and Spencer, M. S. (1998) *The Constraints Management Handbook*. St. Lucie Press, Boca Raton, FL.

[3] Lockamy, A. and Draman, R. H. (1998) A Constraint-based methodology for effective supply chain management. *Strategic Management of the manufacturing value chain: Proceedings of the International Conference of the Manufacturing Value-Chain, August '98*, 343-352.

[4] Keebler, J. S., Manrodt, K. B., Durtsche, D. A. and Ledyard, D. M. (1999) *Keeping Score*. Council of Logistics Management, Oak Brook, IL.

[5] Harwick, T. (1997) Optimal decision-making for the supply chain. *APICS Online*, **7**(1), accessed through http://www.apics.org/magazine/jan97/harwick.htm on 3/8/00.

[6] Evans, G. N., Towill, D. R. and Naim, M. M. (1995) Business process re-engineering the supply chain. *Production Planning & Control*, **6**(3), 227-237.

[7] Bendiner, J. (1998) Understanding supply chain optimization: From "what if" to what's best. *APICS Online*, **8**(1), accessed through http://www.apics.org/magazine/jan98/bendiner.htm on 3/8/00.

[8] Inger, R., Braithwaite, A. and Christopher, M. (1995) Creating a manufacturing environment that is in harmony with the market – the 'how' of supply chain management. *Production Planning & Control*, **6**(3), 246-257.

[9] Fliedner, G. (1997) Agility: The Next Competitive Weapon. *APICS Online*, **7**(1), accessed through http://www.apics.org/magazine/jan97/agility.htm on 3/8/00.

[10] Tompkins, J. A. (1997) Facilities planning: a vision for the 21st century. *IIE Solutions*, **29**(8), 18-19.

[11] Burk, V. A., Elsenbrook, T. and Webb, G. (1999) Major changes loom as industry approaches the internet frontier. *The Oil and Gas Journal*, **97**(50), 144.

[12] Enslow, B. and Schulte, R. (1998) Building a 'Zero-Latency Enterprise'. *Gartner Group Commentary*, 10 August 1998, accessed through http://gartner6.gartnerweb.com:80/gg/purchase/0/00/716/53/doc/00071653/ on 2/8/00.

[13] Copacino, W. C. (1997) *Supply Chain Management*. St. Lucie Press, Boca Raton, Fl.

[14] Jones, C. and Andren, E. (1997) Manufacturing Applications Strategies Scenario. *Gartner Group Strategic Analysis Report*, 13 February 1997, accessed through http://gartner11.gartnerweb.com:80/gg/purchase/0/00/329/38/doc/00032938 on 2/8/00.

[15] Dilger, K. A. (1997) Demand-chain systems, enterprise solutions unite in quest to provide better service. *Manufacturing Systems Issues in Supply Chain Management Supplement*, 2A-10A.

[16] Harland, C. (1995) The dynamics of customer dissatisfaction in supply chains. *Production Planning & Control*, **6**(3), 209-217.

[17] Donovan, M. (1996) Is manufacturing a weak link in your supply chain? *Industrial Management*, **38**(6), 1,3.

[18] Gormley, T. and Cameron, B. (1998) Progress toward utopia. *Manufacturing Systems*, **16**(5), 24.

[19] Bhattacharya, A. K., Coleman, J. L. and Brace, G. (1995) Re-positioning the supplier: an SME perspective. *Production Planning & Control*, **6**(3), 218-226.

[20] Hicks, D. A. (1996) Enterprise solutions: back on the supply chain gang. *IIE Solutions*, **28**(1), 25-28.

[21] Johnson, M. E. (1998) Giving 'Em What They Want. *Management Review*, **87**(10), 62-67.

[22] Trunick, P. A. (1998) Is Your Supply Chain Playing By The Rules? *Transportation & Distribution*, **39**(9), 51-54.

[23] Lane, C. (1996) CMMS takes a proactive approach. *IIE Solutions*, August, 2000.

[24] Bowman, R. J. (1997) 12 Best practices that are changing your job. *Distribution*, **96**(7), 26-30.

[25] Fulcher, J. (1996) A source of wealth. *Manufacturing Systems*, **14**(8), 13.

[26] Mabert, V. A. and Venkataramanan, M. A. (1998) Special Research Focus on Supply Chain Linkages: Challenges for Design Management in the 21st Century. *Decision Sciences*, **29**(3), 537-552.

[27] Baljko, J. L. (1999) SCM pundits: We need to talk. *Electronic Buyers News*, October 04, 56,58.

[28] Blackwell, R. D. (1997) *From Mind to Market*. HarperCollins Publishers, Inc., New York, NY.

[29] Parker, K. (1997) A Question of Collaboration. *Manufacturing Systems Hot Issues for Hot Times Supplement*, July, 9-12.

[30] Hill, S. (1998) A whole new outlook. *Manufacturing Systems*, **16**(9), 70-80.

[31] Stahl, R. A. (1997) Don’t Automate Inventory Tracking, Eliminate it. *APICS Online*, **7**(4), accessed through http://www.apics.org/magazine/apr97/stahl.htm on 3/9/00.

[32] Cameron, B. and Gormley, T. (1998) Commerce Communities. *Manufacturing Systems*, **16**(9), 24.

[33] Cameron, B. and McCullough, S. (1999) Train Leaving the Station. *Manufacturing Systems*, **17**(9), 20.

[34] Fulcher, J. (1998) Door-To-Door Service. *Manufacturing Systems*, **16**(2), 96-102.

[35] Dzlina, D. (1999) Collaboration Economics. *Folio*, **28**(14), 69-71.

[36] Dullin, E. (1998) Enterprise and Plant-Centric Scheduling. *IIE Solutions*, **30**(2), 16-20.

[37] Pearson, T. and Womeldorff, T. (1999) Predictive process management. *Manufacturing Systems*, **17**(11), 81-82, 86+.

[38] Stein, T. (1997) Orders From Chaos. *Information Week*, 636, 44-60, 50+.

[39] Hill, S. (1997) The Correct Time, Please. *Manufacturing Systems Issues in Supply Chain Management Supplement*, August, 12A-18A.

[40] Hitchcock Publishing Company (1997) Fulfilling the potential of global supply-chain technology. *Manufacturing Systems Hot Issues for Hot Times Supplement*, July, 10-11.

[41] Institute of Industrial Engineers (1999) Internet as a supply chain tool. *IIE Solutions*, **31**(8), 9.

[42] Sherman, R. J. (1997) First, establish demand. *Manufacturing Systems*, **15**(8), 68-72.

[43] Lummus, R. R., Duclos, L. K. and Vokurka, R. J. (1998) Improving supply chain performance by eliminating demand distortion: a simulation study of the Bullwhip Effect. Accessed through http://www.sbaer.uca.edu/docs/proceedingsII/98dsi1187.htm on 3/9/00.

[44] Harrington, L. (1999) If your partner's a gorilla… *Industry Week*, **248**(7), 28-37.

[45] Layden, J. (1998) Thoughts on supply-chain management. *Manufacturing Systems*, **16**(3), 80-88.

[46] Gupta, S. (1997) Supply chain management in complex manufacturing. *IIE Solutions*, **29**(3), 18-23.

[47] Enslow, B. (1998) Managing Variability to Improve Supply Chain Performance. *Gartner Group Research Note*, 14 July 1998, accessed through http://gartner11.gartnerweb.com:80/gg/purchase/0/00/709/66/doc/00070966/ on 2/8/00.

[48] Gupta, S. (1997) Beat the drum (buffer, rope). *Manufacturing Systems*, **15**(9), 86-89.

[49] Foster, T. (1996) Supply chain black holes. *Distribution*, **95**(11), 63.

[50] Harrington, L. (1996) Untapped savings abound. *Industry Week*, **245**(14), 53-58.

[51] Cooke, J. A. (1998) Panning for gold. *Logistics Management & Distribution Report*, **37**(11), 59-60, 62.

[52] Journal of Commerce (1997) New study on supply-chain rewards. *Traffic World*, April 28, 55.

[53] American Management Association (1999) Top performers save a lot. *Management Review*, December, 7.

[54] Dilger, K. A. (1998) Fill the gaps. *Manufacturing Systems*, **16**(3), 14, 18.

[55] Mcgraw-Hill Companies, Inc. (1999) Samsung: The making of a superstar. *Business Week*, December 20, 136.

[56] Bartholomew, D. (1999) What's really driving Apple's recovery. *Industry Week*, March 15.

[57] Andel, T. (1999) Harness the power to own your customer. *Material Handling Engineering*, **54**(6), SCF 13-16.

[58] Richardson, H. L. (1999) Bring global sources to your doorstep. *Transportation & Distribution*, **40**(2), SCF 20+.

[59] Crain Communications Inc. (1998) Chain link: new supplier group seeks to improve tier management. *Automotive News*, **71**(5770), 27.

[60] Swaminathan, J. M., Smith, S. F. and Sadeh, N. M. (1998) Modeling supply chain dynamics: a multiagent approach. *Decision Sciences*, **29**(3), 607-632.

[61] Bhaskaran, S. (1998) Simulation analysis of a manufacturing supply chain. *Decision Sciences*, **29**(3), 633-657.

[62] Bogle, D. (ed.) (2000) State of the art research in flexibility, operability and dynamics. *TWG3/D Bogle/R&D SoA Review/Rev 1/2000-05-25*. Accessed through http://www.chemeng.ucl.ac.uk/CAPENET/documents/fod/ on 11/9/00.

[63] Ganeshan, R. and Harrison, T. P. (1995) An introduction to supply chain management. Accessed through http://silmaril.smeal.psu.edu/misc/supply_chain_intro.html on 11/9/00.

[64] Goldratt, E. M. and Cox, J. (1986) *The Goal*. North River Press, Inc., Croton-on-Hudson, NY.

[65] Faulkner and Gray Inc. (1996) Getting to know manufacturing. *Accounting Technology*, **12**(4), 24.

[66] Pagel, D. (1999) Managing for optimal performance through effective coordination of the supply chain. *Production & Inventory Management Journal*, **40**(1), 66-70.

[67] Farley, G. A. (1997) Discovering supply chain management A roundtable discussion. *APICS Online*, **7**(1), accessed through http://www.apics.org/magazine/jan97/discover.htm on 3/8/00.

[68] Thomas, J. (1998) Beware of supply chains without management. *Logistics Management & Distribution Report*, **37**(10), 119.

[69] Thru-Put Technologies (1998) What color is your supply chain? Accessed through http://www.thru-put.com/technology/supply.html on 3/8/00.

[70] Andel, T. (1998) Get in shape for the millennium. *Transportation & Distribution*, **39**(2), SCF 4-8.

[71] Greenfield, D. (1996) Supply chain dominates APICS '96 Conference. *Intelligent Manufacturing*, **2**(11), accessed through http://www.lionhrtpub.com/IM/IMsubs/IN-11-96/apics.html on 3/8/00.

[72] Holt, J. R. TOC in supply chain management. Accessed through http://www.vancouver.wsu.edu/fac/holt/em530/supchain.htm on 3/8/00.

[73] Enslow, B. and Mesher, A. (1996) Zero Inventory: Worshipping false idols? *Gartner Group Research Note*, 23 July 1996, accessed through http://gartner6.gartnerweb.com/gg/purchase/0/00/303/85/doc/00030385/ on 2/8/00.

[74] Brander, A. (1995) *Forecasting and Customer Service Management*, Helbing & Lichtenhahn Verlag AG, Basel.

[75] Strader, T. J., Lin, F. and Shaw, M. J. (1998) Simulation of order fulfillment in divergent assembly supply chains. *Journal of Artificial Societies and Social Simulation*, **1**(2).

[76] Bedworth, B.D. and Bailey, J.E. (1987) *Integrated Production Control Systems: Management, Analysis, Design.* Wiley, New York, NY.

[77] Spearman, M.L. (2000) *ERP 2000 Conference,* April 6-7, 2000.

[78] Smith, J.J. (1994) TOC and MRPII: From Theory to Results, accessed through http://www.rogo.com/cac/JJSmith.html on 3/8/00.

[79] Simchi-Levi, D., Kaminsky, P. and Simchi-Levi, E. (1999) *Designing and Managing the Supply Chain: Concepts, Strategies and Cases.* Irwin McGraw-Hill, Boston, MA.

[80] Wyland, B., Buxton, K., and Fuqua, B. (2000) Simulating the supply chain. *IIE Solutions*, **32**(1), 37-38.

[81] Pimentel, E. F. (1999) Getting more from old techniques – discrete event simulation has the potential to do far more than it is ever used for. *Manufacturing Engineer*, **78**(3), 128-129.

[82] Behlau, T., Strothotte, C., Ziems, D., Schurholz, A., and Schmitz, M. Modeling and simulation of supply chains. Accessed through http://ifsl.mb.uni-magdeburg.de/~time/istanbul.htm on 11/9/00.

[83] Sadeh, N., Smith, S. F. and Swaminathan. Supply-chain modeling and analysis. Accessed through http://www.cs.cmu.edu/afs/cs/project/ozone/www/supply-chain.html on 11/9/00.

[84] Umeda, S. and Jones, A. Virtual supply chain management: a re-engineering approach using discrete event simulation. Accessed through http://www.mel.nist.gov/msidlibrary/doc/caracas.html on 11/9/00.

[85] Karmarkar, U. (2000) An ERP Reference Model. *ERP 2000 Conference*, April 6-7, 2000.

[86] Harrell, C., Ghosh, B. K., Bowden R. (2000) *Simulation Using Promodel*. McGraw-Hill, Boston, MA.

[87] Castle, D. C. and Lee, H. L. Probability based supply chain model simulates business enterprise system from supplier through final distribution. Accessed through http://ucs.orst.edu/~castle/stanford.htm on 11/9/00.

[88] Strader, T. J., Lin, F. and Shaw, M. J. (1998) Simulation of order fulfillment in divergent assembly supply chains. *Journal of Artificial Societies and Social Simulation*, **1**(2).