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Comparison of DRP and TOC financial performance within a multi-product, multi-echelon physical distribution environment

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This paper propositioned and tested whether a heuristic based on Theory of Constraints logic could improve system financial performance beyond traditional supply chain methods in a multi-product, multi-echelon physical distribution environment exhibiting seasonality and partial lost sales. A review of the literature was conducted about current distribution management and Theory of Constraints techniques. Next, field research was conducted with a major US manufacturer in order to capture the structure of its multi-product, multi-echelon physical distribution system. The field research facilitated the development of a baseline computer simulation of a fully distributed inventory system with orders planned by Distribution Resource Planning. That model served as the basis for development of comparative multi-echelon distribution models, one employing partial centralization of inventory with orders planned by Distribution Resource Planning, the other two models employing a Theory of Constraints-based heuristic for buffering and inventory replenishment. Simulation results show the Theory of Constraints-based systems are more effective on a financial basis when considering inventory carrying costs, retail-level transhipment and obsolescence expenses than either the existing distributed inventory system or the partially centralized system when orders are based on Distribution Resource Planning logic.

1. Introduction

The lessons learned by those who have implemented Theory of Constraints (TOC) in the manufacturing environment have not been fully exploited in the planning and control of supply chains. In determining the cause for the lack of crossover between manufacturing and supply chain management, Perez (1997) listed overcoming type casting of TOC as a 'manufacturing only' technique, the impossibility of controlling the movement of the constraint to a position outside of the logistic functions' control, and lack of extrapolation of TOC concepts and practices to deal with issues in the supply chain environment as major deterrents. However, Goldratt (1994) states that the basic logic of designing and placing buffers to protect the throughput of a manufacturing system can be used, with minor modifications, in the distribution environment. According to Goldratt, application of TOC to the distribution environment should result in reduction of inventory investment, leadtime and transportation costs while simultaneously increasing forecast accuracy and customer service levels.

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This work, primarily motivated by the apparent lack of formal research, explores whether application of TOC techniques can improve the financial performance of distribution systems beyond that which can be obtained through the current state-of-the-art supply chain management practice: Distribution Resource Planning (DRP). This research began with extensive field research in order to capture the structure of an existing distribution system exhibiting demand uncertainty, seasonality and partial lost sales. The field research facilitated the development of a decentralized inventory simulation model using DRP for inventory management. The Baseline model was then modified to reflect partial centralization of inventory using DRP for inventory management and two models representing the application of a TOC-based heuristic for buffering and inventory replenishment. The first TOC-based model, TOC-Customer Service, was developed to determine what levels of customer service and financial performance could be obtained by a TOC system maintaining inventory levels similar to those in the baseline DRP system. The second TOC-based model, TOC-Inventory Reduction, was developed to determine the extent to which application of a TOC-based heuristic could reduce inventory and its related costs while maintaining customer service levels comparable with the current DRP system. Financial measures of system performance during simulation of the four models were captured, allowing for comparison of the TOC-based heuristic and DRP.

2. Literature review

During the 1970s, DRP was developed to address deficiencies that had become apparent in the order point approach to inventory management. Based on the dependent demand logic of Material Requirements Planning (MRP), DRP controls the flow of goods between manufacturing, distribution centres and other stocking locations in a time-phased manner (Martin 1985, Tinsley and Ormsby 1988, Andel 1997), and has become an effective method for inventory control in the multi-product, multi-echelon physical distribution environment. Whybark (1975) was the first to discuss the application of MRP logic for inventory planning and control in the distribution environment. Theory was applied to practice in the same year as Whybark's publication, when Abbott Laboratories began to deploy the first DRP system. Andre Martin, who was Director of Materials Management for Abbott at the time, wrote the seminal work on this subject, *Distribution Resource Planning*, which explained the logic and the benefits of DRP (Martin 1990).

The basic logic of DRP is that full visibility of inventory levels and demand at each node in the supply chain allow manufacturers to make and ship only what is needed to meet current demand. This in turn reduces inventory investment, safety stock requirements and transportation costs while improving forecasts, customer service, flexibility and utilization of manufacturing resources (Vollmann *et al.* 1988, Martin 1990, Masters *et al.* 1992, Copacino 1997). These benefits arise because of the integration of demand forecasts into production scheduling and balancing the needs of the stocking locations with the capabilities of both the plant and suppliers (Ross 1988, Greene 1989, Masters *et al.* 1992). This level of integration breaks down the barriers between production, distribution and sales, and allows synchronization of production and transportation, resulting in less unallocated finished goods inventory (Sussams 1992). There have been numerous reports of the benefits companies have received through DRP implementation in the literature (Forger 1986, Horne 1989, Krepchin 1989, Hammel and Rock 1993, Davis 1994, Frasier-

Sleyman 1994). DRP is currently deemed a best practice for inventory management for complex distribution systems exhibiting multiple products and multiple echelons.

There are three fundamental differences between the probabilistic (order point) and time-phased (DRP) approaches that result in the improved performance of DRP systems (Maskell 1988). The first difference is that DRP approaches the distribution network from a global perspective while the order point approach attempts to maximize the system by ensuring local optimums at each stocking location. This deficiency of order point techniques is exasperated when companies implement them node-by-node rather than systematically without consideration of the effects of the local optimal inventory decisions on other locations in the supply chain (Blackburn and Millen 1982). The second difference between probabilistic and the time-phased approaches is that DRP is proactive in that it attempts to predict when inventory will fall to dangerous levels and places orders before the time period shortages are expected to occur. In contrast, order point techniques place new orders only after inventory has reached some predetermined level or after some predetermined period has elapsed. The third difference between the probabilistic and time-phased approaches is that DRP is an integrated approach, taking advantage of information technology in order to provide full visibility of inventory levels at all stocking locations. Order point techniques do not convey actual consumer demand information back up the supply chain, nor do they allow for visibility of inventory levels at all stocking locations.

Similar to DRP, the TOC began its development in the 1970s with the introduction of Optimal Production Technology scheduling and control computer software (Lockamy and Spencer 1998). Although TOC began as a production philosophy, it has evolved into three interrelated areas: logistics/production, problem solving/thinking tools and performance measurement (Spencer and Cox 1995). During its evolution, TOC has been shown to be applicable in a variety of areas: project management (Pittman 1993, Goldratt 1997), transfer pricing and make-or-buy decisions (Cox *et al.* 1997), retailing (Gardiner 1993), scheduling training (Ronen *et al.* 1994), supply chain management (Goldratt 1994) and a wide variety of production environments (Koziol 1988, Lambrecht and Segaert 1990, Raban and Nagel 1991). A review of the literature reveals that manufacturing systems using TOC techniques exceed the performance of systems using MRP, Lean Manufacturing, Agile Manufacturing and Just-in-Time techniques (Aggarwal 1985, Johnson 1986, Lambrecht and Segaert 1990, Ramsay *et al.* 1990, Fogarty *et al.* 1991, Cook 1994, Holt 1999). The results of these studies indicate that systems using TOC techniques produce significantly greater numbers of product while reducing inventory investment and decreasing the standard deviation of cycle time.

Given these findings, there is cause to suspect that implementation of TOC-based logic could capture similar benefits in the area of distribution planning. Eliyahu Goldratt, the 'founding father' of TOC, has spoken directly to this point. He states in *It's Not Luck* (1994: 40–46) that the basic logic of designing and placing buffers to protect the throughput of a manufacturing system can be used, with minor modifications, in the physical distribution environment. According to Goldratt, the application of this system to distribution systems should result in reduction of inventory investment, lead-time and transportation costs while simultaneously increasing forecast accuracy and customer service levels.

Furthermore, there is case evidence in the literature that TOC-based methods can be used to improve distribution outcomes. Proctor and Gamble (P&G) pioneered the application of TOC to the distribution environment. P&G self-reports a US$600 million reduction in inventory and elimination of many capital improvement expenditures due to more efficient scheduling of existing facilities. Binney and Smith, makers of Crayola crayons, have used TOC logic in redesigning their distribution channels, resulting in a significant reduction in inventory while simultaneously improving customer service levels (Gardiner *et al.* 1994). Warren Featherbone, manufacturer of children's clothing, has used TOC to decrease finished goods inventory, increase customer service levels and decrease lead-times (Whalen 1991).

Perhaps the best-known implementation of TOC in the distribution environment is General Motors' Cadillac Division's aborted introduction of Custom Xpress Delivery (CXD). A survey of Cadillac owners showed that 71% of customers step into a showroom with the express desire to purchase a particular model and that 92.4% purchase a vehicle with every option they originally wanted (Evanoff 1998). In order to provide customers with the exact vehicle they wish to purchase, more than 25% of sales required the dealer to special-order a vehicle or originate a dealer trade (Adler 1997). Armed with the knowledge that the industry's order-to-delivery time averaged between 36 and 44 days (Miller 1999) and that 32% of dealers said it took 61-90 days to receive special-order vehicles (which are already sold or for which the dealer had taken a down payment) (Anon. 1999), GM decided that it could no longer do business as usual. In order to improve its customer service level, the company introduced a radically new distribution system in 1996 based on TOC logic and designed by Goldratt—CXD.

CXD was tested by the Cadillac division in Florida and extended to other GM divisions nationwide in 1997. General Motors hailed CXD as a means for improving both dealer and corporate profitability. The basic premise of CXD was that cars would be stocked at regional holding centres in the most popular combinations of colours and options (Evanoff 1998). Dealers were promised delivery of these popularly equipped vehicles within 24 hours. Special-order vehicles, those not stocked at the holding centre, would be delivered within 3 weeks (Anon. 1998). GM expected vehicles to be positioned at the holding centres for approximately 10 days before being transported to a dealership for delivery to a specific customer, a significant improvement over the traditional practice of holding 60 days' inventory on dealer lots. In order to offset the cost of holding vehicles back in the distribution chain, GM instituted a $225 charge added onto the normal transportation fee.

As designed, CXD allowed dealerships to reduce costs through centralization of inventory, inventory reduction and freight consolidation while improving customer satisfaction through increased product variety, availability and reduction of lead-time for special-order products. Ancillary benefits from the system included: less vehicle damage due to increased space on the dealer lot, reduction of dealer trades and increased responsiveness to the market due to increased forecast accuracy (Mateja 1996, Anon. 1997). Responsiveness to market demand was improved due to a reduction in the number of special-order vehicles. As such, the assembly plant was able to fill special orders much more quickly, usually within the stated 3-week lead-time (Evanoff 1998).

However, several major shortcomings were found and the TOC system was suspended by a majority of GM divisions. The first problem that negatively affected CXD was that the nationwide rollout was limited to the Blazer and Jimmy lines. As the distribution system did not include all vehicles or a substantial percentage of dealer volume, dealers did not have an impetus to change the way they managed inventory (Anon. 1998). Thus, dealers either handled CXD orders as they would normal inventory, reducing the possible benefits, or had to run two separate ordering systems, increasing costs. The second major shortcoming was that CXD failed to forecast changes in demand. As such, rapid changes in demand had the ability to drain the inventory in the buffer leaving dealerships without inventory to draw from. This scenario played out in 1998, when a pre-holiday sales spike drained the inventory from the system (Council 1998). Owing to an apparent lack of training and lack of dealer trust in the system, GM was forced to suspend CXD for all non-Cadillac divisions in mid-1998 (Anon. 1998, Harris 1998).

GM has not completely abandoned CXD. The Cadillac division and its dealers continue to make changes to the system in an attempt to improve its usability and reliability. Several recommendations to improve usability are changes to the computer software that accompanied CXD. These include: availability screening to allow dealers to check what models are currently available at the holding centre, a 'balance-to-go' feature that would allow dealers to track their allocation, and 'reservation tagging' that would allow dealers to reserve vehicles that are not currently available at the holding centre (Anon. 1998). GM is also trying to improve the robustness of the physical system in order to decrease the likelihood of inventory unavailability. Pleased with the development of CXD, GM has reportedly initiated discussions with several railroads to create 11 regional distribution centres, each capable of holding 10 000-15 000 vehicles, in order to facilitate the re-introduction of the system (Miller 1999).

Therefore, this review of the relevant literature suggests that there is sufficient cause to conduct formal research regarding the extension of TOC-based production/logistics and measurement techniques to distribution planning in that such research could likely reveal specific beneficial methods.

3. Synopsis of relevant TOC-based concepts

As the literature review reveals sufficient cause to conduct formal research, the authors at this point proposition that there is a TOC-based heuristic that will yield improvements in financial performance in a multi-product, multi-echelon physical distribution environment. Based on Goldratt's statements and an overall understanding of TOC techniques, the authors conclude that the topics of 'drum–buffer–rope' (DBR) releasing/scheduling method, buffer management and V-A-T analysis are of special interest toward the development of TOC-based distribution planning. Those concepts are reviewed from the literature below.

The basic scheduling technique used in TOC is Drum–Buffer–Rope (DBR), which has been well-defined in the literature (Goldratt and Fox 1986, Lambrecht and Decaluwe 1988, Schragenheim and Ronen 1990, Schragenheim and Ronen 1991, Goldratt and Cox 1992, Gardiner *et al.* 1993, Umble and Srikanth 1995). The drum is the constraint, the system component with the least capacity, which, in turn defines the throughput of the entire system. Stated another way, a constraint is anything that constrains the system from achieving higher performance relative to its goal (Umble and Srikanth 1995, Blackstone 1998). Buffers such as material queues, additional capacity and time allowances are strategically positioned to ensure the constraint is never idled, thereby insuring maximum output relative to the system's capacity. The drum, in conjunction with the rope, controls the pace of the system by controlling the release of materials into the system. The rope is a signal by the constraint to the gating operation that allows additional inventory to move into the production system. By controlling the release of materials, all processes are forced to work at the rate of the constraint, preventing work-in-process inventory from accumulating.

Application of DBR logic necessitates management strategically buffer the system to protect against variability at the constraint and at other control points. The purpose of buffering is to protect the ability of the system to produce the schedule (Schragenheim and Ronen 1991). In traditional manufacturing settings, buffers are often synonymous with work-in-process or finished goods inventory. However, TOC makes extensive use of time and capacity buffers. Time buffers offset the release of material by a protective margin to protect the system from internal disruptions (Umble and Srikanth 1995). Capacity buffers exist in a TOC system to the extent that non-constrained resources have excess capacity. Determination of the initial buffer size is still somewhat a matter of contention within the TOC community; Blackstone (1998) states one should just 'choose a reasonable initial buffer size and get on with it', noting that buffer management should be employed to increase or decrease the size of the buffer to reflect changes in the operating environment.

A compendium of rules has been accumulated to effect TOC buffer management. These rules allow buffer management to serve three purposes (Schragenheim and Ronen 1990, 1991). First, buffer management allows management to identify possible problems in the manufacturing system. Control of the system is achieved through comparison of actual versus planned buffer levels at set times during the manufacturing schedule. In this way, managers can spot problems with schedule attainment before the point at which it would become critical, and, through quick feedback to the problem work centre, reduce unnecessary expediting. Beyond identification of problems, buffer management can be used to focus improvement efforts on those processes that have the greatest negative impact on schedule performance, simplifying the management of continuous improvement efforts. Second, buffer management allows managers to assess the impact of changes made to the system as they are implemented. Finally, buffer management allows managers to monitor the trade-off between protection of the constraint and lead-time.

As shown in figure 1, the total amount of planned protection time allotted to each buffer is broken into three regions (Cox and Blackstone 1990, Schragenheim and Ronen 1991). Materials entering the buffer proceed from region 3 to region 1 as time passes. Thus, the contents of the buffer are in a constant state of progression through the buffer. Region 1, as it is closest to the demand point, is the most important region and all material in this region should be present. Holes, or missing material, in this region present the very real possibility of starving the constraint, causing deviation from the schedule or missing due dates to the customer; therefore, immediate identification and expediting of missing material is necessary. Region 2 represents intermediate protection for the constraint. As such, not all of the planned material in this region should be present. Missing material in this region is not generally expedited; however, its absence and the cause of the disruption are investigated and documented for the focus of continuous improvement efforts. Use of the Pareto Principle allows for focused improvement to the system based on the frequency and degree of cost associated with the underlying cause of each hole in the buffer (Goldratt and Fox 1986, Cox and Blackstone 1990, Schragenheim and Ronen 1991, Umble and Srikanth 1995). Material in region 3 of the buffer represents distant protection of the constraint, as such, very little of the material should be

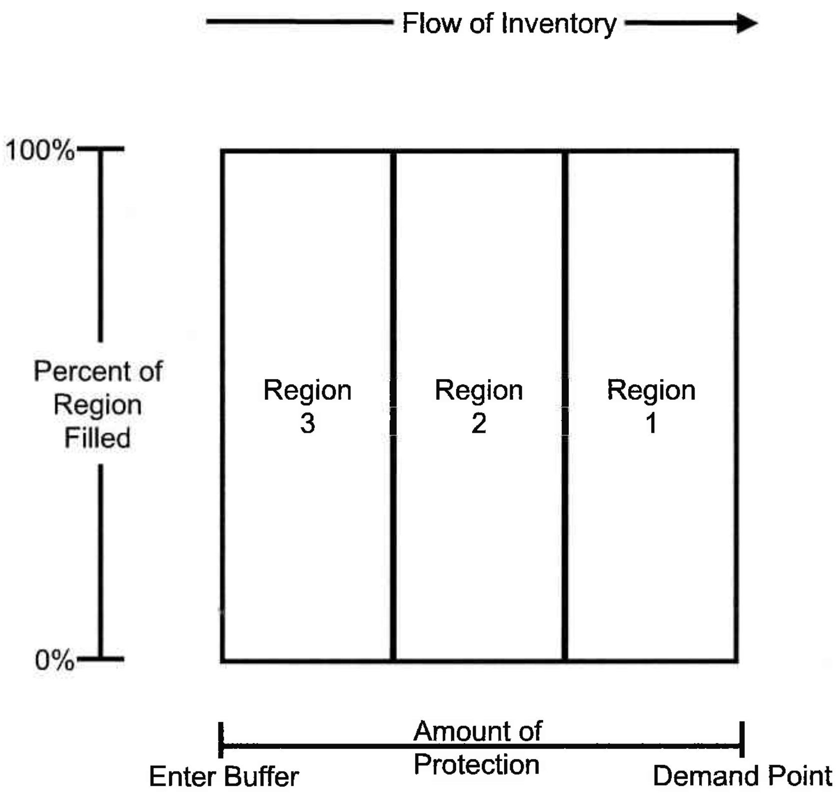

Figure 1. TIme buffer.

present and holes in this region are not a cause for concern. In order to prevent holes from penetrating region 1 of the buffer undetected, buffers must be checked frequently.

Buffers are deemed to be of the correct size if 90% of all parts are completed with no expediting (Goldratt 1990, Gardiner *et al.* 1993). This allows for sufficient protection of the system's constraint while necessitating expediting of orders less than 10% of the time. As stated above, buffer size is allowed to change based on changes in the environment. Frequent expediting indicates that the buffer is too small and should be enlarged. Less frequent expediting would indicate that the buffer is too large and should be reduced in size. By comparing the actual versus planned buffer protection, management is assisted in determining the correct trade-off between protection and lead-time.

TOC takes a systems' approach to planning and control. Rather than planning each individual process as a series of cascading links, TOC uses a management by exception perspective to planning and control (Gardiner *et al.* 1993). Specific action plans, work schedules and inventory allocations are planned for only a few locations within the system while the vast majority of points work on an 'as needed' basis. Strategic buffering of the system is accomplished by means of V-A-T analysis (Cox and Blackstone 1990, Umble 1992, Umble and Srikanth 1995). V-A-T analysis looks at the logical product flows and the processes necessary for production in order to determine the critical processes or 'control points' that must be buffered or scheduled. By controlling actions at these control points, the entire system is managed effectively (Cox and Blackstone 1990). V-A-T analysis essentially attempts to classify

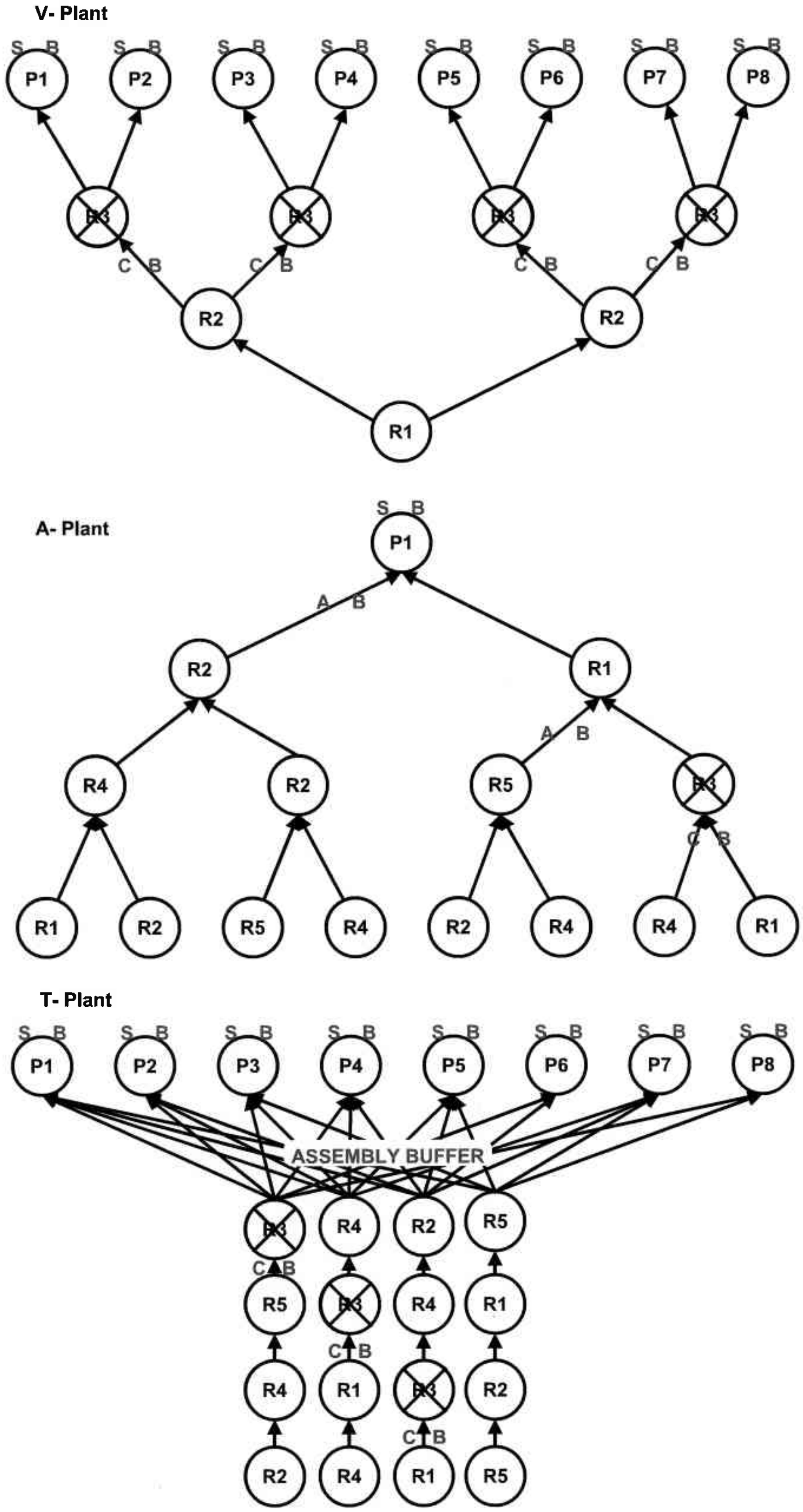

Figure 2. Strategic buffering of the logical flows. Adapted from Umble and Srikanth (1995).

the 'shape' of product flow, as each shape typically possesses its own unique control points. The major types of product flow that have currently been identified in the TOC literature are V-flow, A-flow and T-flow.

The V-flow is dominated by diverging product flows along a fixed routing. The number of raw materials entering the system is relatively small; however, the number of end items produced is comparatively large. The A-flow is dominated by converging product flows in a jumbled flow environment. The number of raw materials, relative to the number of end items, is quite large. The T-flow is characterized by a relatively small number of common components being assembled into a plethora of unique end items. The proper buffering strategy for each type of flow is shown in figure 2. Constraint buffers (CB) are placed directly in front of constrained resources (R with X through the resource) to protect the constraint from variability upstream in the system. Assembly buffers (AB) are placed on non-constraint lines where they converge with constrained lines to speed the flow of materials through the system. Shipping buffers (SB) are parts buffers maintained at the system exit points in order to protect delivery dates of the various products (P). By strategically placing inventory at the appropriate control points, the total amount of inventory in the system is reduced while providing adequate protection for system throughput.

4. Field research

In order to reach conclusions about distribution system financial performance under DRP and TOC, it was decided that a mixture of methodologies was most appropriate for this study. According to McGrath (1982), 'strict' methodologies such as pure mathematical modelling offer a higher degree of precision but lack a degree of realism, while methodologies such as field research and case studies offer a higher degree of realism at the expense of precision. Including both methods in the research captures the strengths of each. Moore (1988) specifically advises a combination of research methodologies, including case and nomothetic methods, toward the design of distribution networks. Accordingly, this research began with extensive field research within and about a major US company in order to capture a realistic distribution environment that could be modelled and tested for improvement through TOC-based logic.

The company is one of the less than a dozen major corporations in its industry. As with many other industries, this industry experienced rapid consolidation during the 1990s. In 1999, the industry sold 16.9 million units at revenue of $400 billion. Nimble competitors are found in both Europe and along the Pacific Rim. The industry operates over 22 000 retail outlets in the USA. Internet-based retailing activity continues to rise as well. Inventory represents a major expense both for the company under study and the industry at large. Excess inventory is extremely common and usually results in manufacturer-sponsored rebate programmes to decrease system-wide inventory investment. Therefore, an improved distribution system would generate significant cost reductions for the company and its industry.

The company is a major global durable goods manufacturer with its historical roots and world-wide headquarters in the USA. It maintains a manufacturing or sales presence in over 200 nations and territories around the globe and employs over 300 000 people in over 600 facilities world-wide. The company currently markets over 75 different core models, which disaggregate via customization and options into a myriad of stock keeping units (SKUs). Through various contract agreements, it operates thousands of retail outlets throughout the world. It also holds a degree of ownership in many suppliers. Therefore, it possesses the requisite influence to manipulate its entire supply chain and distribution system toward improvement, another reason why this company is especially appropriate for this research topic. Most of the field research focused upon one of the company's local sales systems operated in a medium-sized metropolitan area of the USA.

Extensive field research was conducted about the company and its local sales system. Much of the field research took the form of on-site individual interviews. The company also granted access to a certain amount of historical data. The field research data were supplemented with publicly available information. The primary result of the field research effort was the accumulation of sufficient information to develop an accurate simulation of the physical distribution system in place between the manufacturing facility and the local sales network.

5. TOC distribution planning heuristic

Broadly stated, TOC-based distribution planning can be accomplished through strategic buffering and scheduling at specific control points determined by V-A-T analysis of the distribution system, modification of the performance measurement system and modification of inventory ordering policies. Similar to DRP's use of a Bill of Distribution, the first step in developing a TOC-based distribution system is identification of the inventory stocking locations and mapping the flow of inventory and information through the system. During this process, resources used by the system should be identified, the per cent of resource capacity used calculated and significant policies about order policies, information flows and system performance measures should be identified. Evaluation of the system current state allows for explicit identification of the distribution system's constraint.

Explicit identification of the constraint has three major impacts on the system. The first is that explicit identification of the constraint allows implementation of a modified DBR finite scheduling system for inventory control throughout the system. The second impact is that explicit identification of the system constraint allows system administrators to focus on the processes or policies that will allow the system to increase throughput to the customer thus increasing profits now and into the future. The third impact is that explicit identification of the system constraint allows a change to the measurement system in order to focus on system throughput rather than local optimums. Discussion of the proposed measurement system will follow below.

The current inventory flows in the distribution system are shown in figure 3. To ensure the validity of the system current state analysis, distribution managers were asked during the field research phase to participate actively in the gathering of relevant data and the defining of variables to be included in the decentralized DRP model that simulates the current system in use. Those data and variables as provided were then used to develop an initial Rummler–Brache flowchart of the system (Rummler and Brache 1990). Next, management was asked to verify that the flowchart accurately reflects the operating environment. Finally, iterative adjustments were made to the flowchart until it was adequately aligned with management perception of the actual system. Analysis of the system current state based on field research revealed that the manufacturing and distribution systems' capacity is more than sufficient to handle current market demand. As such, it is likely that the system is market constrained and that this market constraint may be exasperated by the existence of policy constraints concerning the demand management and product

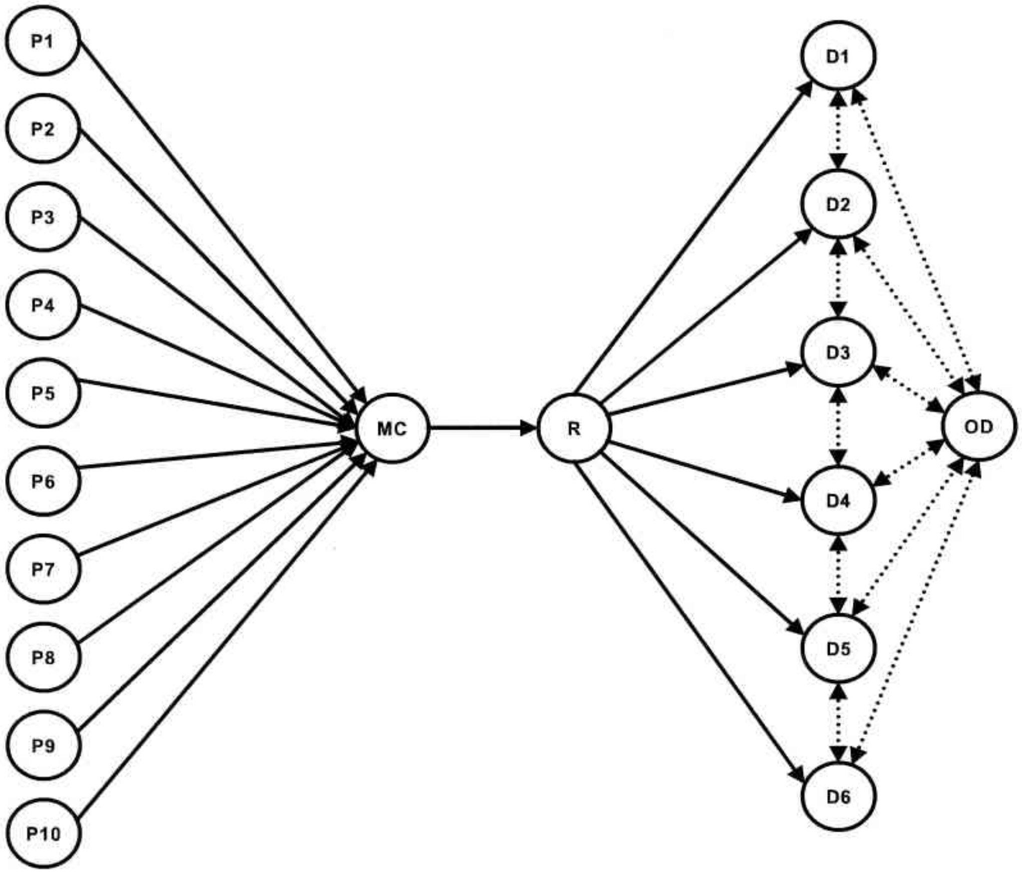

Figure 3. Current distribution system.

positioning strategies employed by the manufacturer. Having identified the constraint as the market, a rope mechanism and buffers can be developed and placed based on V-A-T analysis of the product flows.

Traditionally, the rope provides a direct link from manufacturing to purchasing, with the accompanying measurement system used to link manufacturing to marketing (Wahlers and Cox 1994). Adding a second rope from the market to an internal resource constraint ensures that a line of communication is open from marketing/ sales to manufacturing, increasing the effectiveness of scheduling. The second rope acts as both a queue limiter, allowing only a certain inventory investment maintaining small lead times and high inventory turnover, and as a signal for production. As a signal for production, the rope from the market is allowed to control the production mix at the manufacturing facility thus integrating the system from marketing to purchasing, as the original rope from the constraint to the gating operation controls the release of materials and replenishment of those materials by purchasing. This integrated system would base all purchasing and production decisions on replenishing units sold to the consumer or those units that can be expected to sell within the reduced planning horizon.

The proposed rope mechanism from the market to manufacturing is a modification of the production authorization card (PAC) system used for control and coordination of material and information flows in multiple cell manufacturing systems (Buzacott and Shanthikumar 1992). In the PAC system, control and coordination of information and material movement between cells is achieved by using a number of different kanbans. The adaptation of the PAC system to fit the distribution environment resulted in a two-stage roping process. The first stage, using order tags, helps production planners determine capacity requirements and clearly to communicate expected adjustments to the buffer size. The second stage of the rope process, using requisition tags and cancellation notices, signals production of a specific product for which there is current demand.

Upon determining the proper rope mechanism to be used by the TOC-heuristic, ordering policies within the distribution system must be addressed. Under the TOC-heuristic, retail locations purchase only those items that have been purchased by customers or those items that can reasonably be expected to sell during the replenishment cycle. This requires that retail and manufacturing locations use lot-for-lot replenishment ordering policies based on either daily or the smallest economically feasible order period. This should facilitate improved access to customer demand data, leading to lower inventory cost (through increases in inventory turnover and consolidation of freight), lower lead-time, lower variability of demand at the manufacturing location (bullwhip), higher due date performance and increased customer satisfaction (through increased item availability and variety). The effect is to increase the velocity of purchased goods into the system, through the system and from the system to customers into a smooth, near continuous stream. An additional benefit of this type of ordering policy is that the cash cycle time from the purchase of raw materials to sale of final product is dramatically reduced.

After determining the constraint, rope mechanism and ordering policies for use by the TOC-heuristic, specific control points and inventory stocking points within the system were identified based on V-A-T analysis. All processes that do not require specific work schedules complete their assigned tasks on a first-in-first-out work only when there is work available basis. V-A-T analysis of the system under study finds evidence of V-flow from the second distribution centre to the retail locations, sitting atop an A-flow routing system from the multiple points of manufacture to the first distribution centre. The proper buffering strategy in a manufacturing environment exhibiting a V-flow is to place buffers at the constraint and between assembly and the source of demand. The proper buffer strategy in a manufacturing environment exhibiting an A-flow is to place buffers at the constraint, at points where non-constraint lines converge with constraint lines, and between assembly and the source of demand. Buffers were located accordingly, with some modification to accommodate the particular circumstance of the company's product and industry. Figure 4 shows the product flows that resulted from reengineering of the distribution system according to the TOC-heuristic as explained above. Buffer management is then employed and the system is run according to normal BDR policies except as noted above. However, buffer management must be redesigned proactively to consider feedback from sales forecasts, lead-time requirements and seasonality effects so as to reduce the possibility of stockouts. This is necessary, as seasonality effect is significant for the products under study; the field research revealed more than 70% of sales occurs between February and July.

Strategic buffering disconnects production facilities from the uncertainties of demand at the retail locations. Strategic buffering also allows for consideration and utilization of postponement strategies within the distribution network, allowing the buffer to act as an assembly centre, capable of customizing standard products for

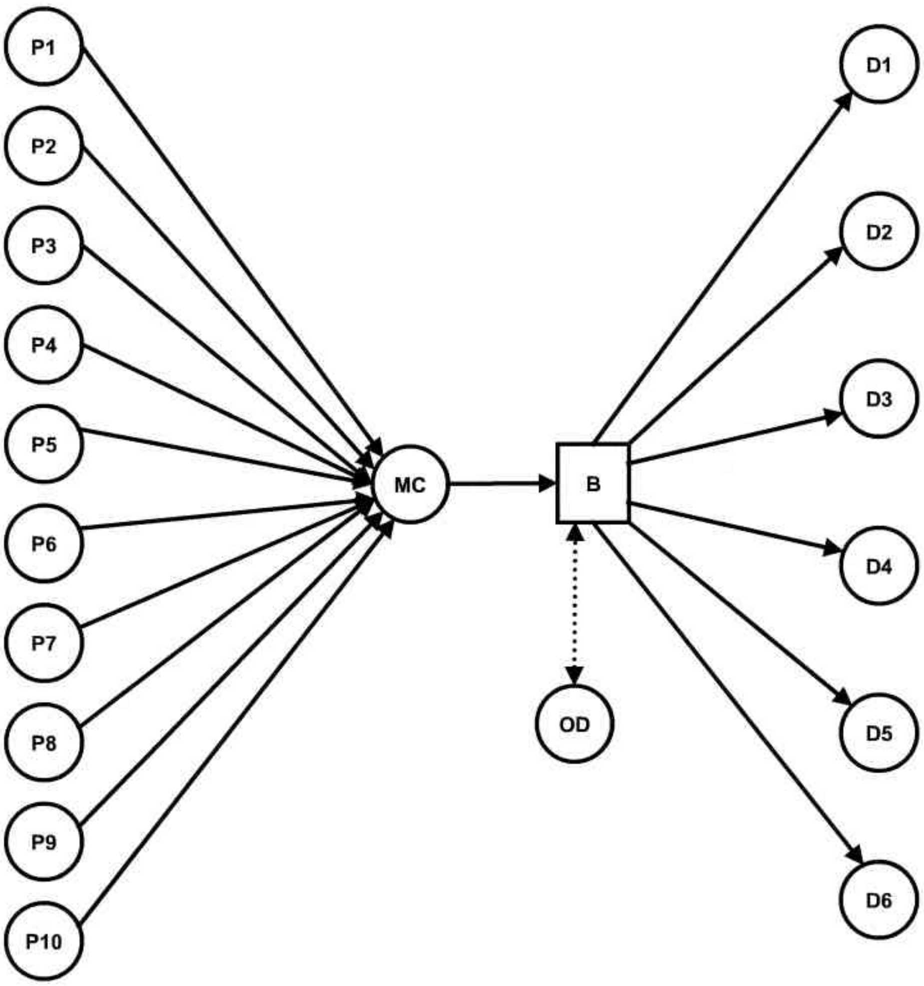

Figure 4. Proposed distribution system.

specific customer orders. Each of the three types of postponement strategies (form, time, place) can be applied to the distribution system currently under study. In addition to reducing the probability of misallocation of inventory and manufacturing capacity, the use of postponement in the system under design results in a reduction of the complexity of the overall system. As reducing the number of SKUs and the degree of speculation decreases the complexity of managing distribution systems.

The retail network sold 111 SKUs, for 503 products, during the sales year under study. Examination of the product configurations as a per cent of sales reveals findings similar to those reported by Daugherty and Pittman (1995), a limited number of distinct products produce a majority of sales. The top 10 product configurations, approximately 9% of sold combinations, produced 46.72% of total sales, while the bottom 80%, sales of five or less, produced just 32% of total sales. Six components were chosen for postponement due to ease of installation or assembly; none require extensive capital investment for either equipment or redesign of the existing product. Using this strategy, the total number of SKUs sold is reduced to by more than 50% to 54 distinct configurations. This is achieved by reducing the number of optional components that must be managed to 13. The top 10 SKUs under this strategy account for almost 77% of all products sold. The total component inventory investment required for implementation of this strategy is estimated to be approximately half the invoice price of a single product.

5. Performance measurement system

Physical distribution is the boundary-spanning activity between the manufacturing and marketing departments. As such, a comprehensive measurement system is necessary to assist the logistics function to balance conflicting departmental goals, measurement systems and resulting behaviour (Christopher 1992, Bowersox *et al.* 1993). A typical problem in supply chain management is that the measurement system attempts to optimize the performance of the individual processes, which are seen as cascading links within a system. In such a situation, the goal of each process and the measurements used to control performance is focused on servicing the needs of the next downstream link in the system rather than the end-user/consumer. As each link attempts to maximize its performance in accordance with its measurement system, dysfunctional behaviour may result.

Blackstone (1998) states the second prerequisite for implementation of a TOC system, after identification of the constraint, is the explicit acknowledgement of a goal and establishment of a performance measurement system to measure and support attainment of that goal. Application of TOC logic to supply chain measurement should allow identification of those processes that are optimizing their individual performance at the expense of the system's overall performance (Knill 1998). The TOC measurement system presented here is consistent with the concept presented by Goldratt (1990) and modified by Alber and Walker (1998) for developing integrated measures of supply chain performance. At the top management/global level, net profit, return on investment and cash flows are used in order to determine whether the organization is achieving its goals. At the middle management and stocking location level, throughput, inventory and operating expense are used in order to align intermediate objectives with the organization's goals. At the local level, throughput dollar days, inventory dollar days and local operating expense (LOE) are used to control the actions of each process.

Several of the measures have slightly changed definitions in order to be applicable in the distribution environment. In many traditional physical distribution environments, channel members count inventory shipped to the next downstream stocking location as sold. Alber and Walker (1998) recommend using a modified definition of Throughput in order to prevent misallocation of inventory shipments as sales. Therefore, for the purpose of this study, Throughput will be defined as the sales price (Manufacturer's Suggested Retail Price, or MSRP) minus the invoice price of finished goods sold to the consumer at the end of the supply chain. Inventory may exist at every stocking location and is defined as the money spent on material and labour throughout the supply chain for product that will be sold (Invoice Price). Operating Expense is the money spent throughout the supply chain for everything else (Alber and Walker 1998). It will be computed as the sum of the normal destination charge, cost of rebates applied to units sold after the end of the model year, the increase in warranty expense due to inventory held in excess of 90 days and inventory carrying costs. Operating expense will include LOE, the total of all expenses controllable at the process/department level, including the cost of transhipment of inventory between dealerships.

Net Profit (NP) will be used as an absolute measure of goal attainment and will be calculated as MSRP minus invoice minus operating expense. Since the goal is to make money now and in the future, NP allows a quick reference point with regard to obtaining that goal. However, NP alone does not allow management a reference point as to how well they are investing the stockholder's investment in the company. For that reason, Return on Investment (ROI) is used as a relative measure of goal attainment, allowing managers at the corporate level to track the relative efficiency of investment. ROI will be calculated by dividing NP by the average inventory present at the retail or central buffer location. Cash Flow (CF) is a measure of corporate survivability, the ability to adapt to changes in the market environment. CF will be calculated as Throughput minus Operating Expense minus any change in inventory. These measures will be used in order to determine the effectiveness of both the TOC and DRP systems in reducing the total cost of distribution.

6. Development process of the simulation models

Four simulation models were developed using ProModel, a popular simulation software application. First, a single decentralized DRP model (Baseline) was developed in order to simulate the current DRP system in use by the durable goods manufacturer. The Baseline model simulates the order and distribution system between a single manufacturing location and a local sales system comprised of six retail outlets. Based on field research, the simulation allows for seasonality of demand and partial lost sales due to inventory stockouts. In an effort to reduce the complexity of the system, a single product line containing more than 100 product variations and annual sales of approximately 500 units was modelled. Average system inventory for the Baseline model was set at approximately 78 units, with each retail location carrying 13 units of inventory. DRP order logic was based on a seasonally adjusted forecast, with a lot size of 1 and orders uniformly distributed throughout the month long order period in weekly time buckets.

After insuring model validity and reliability, the Baseline model was modified to reflect partial centralization of inventory using DRP for inventory management and two models representing the application of a TOC-based heuristic for buffering and inventory replenishment. This was accomplished by modifying the simulation design to allow a centralized warehouse at the second distribution centre location. The first of the three simulations, DRP-Central, applies traditional DRP logic to inventory management at the central warehouse and retail locations. Under the DRP-Central design, the centralized warehouse capacity offers sufficient space to facilitate warehousing any units in excess of nine units per retail location or approximately 40% of the total local system inventory.

In the other two simulations, TOC logic was employed in order to test the proposition of improved financial outcomes under TOC-based logic. In these two models, the centralized warehouse functions as the point of TOC buffering; reflected by the reduction in inventory holding to two units at each retail location, while all other local inventory is held at the central warehouse and distributed only upon the occurrence of demand. Taking advantage of the centralization of inventory, the central warehouse not only acts as a second-echelon distribution centre, but also has the ability to final-assemble-to-order based on first-echelon local sales system demand. This ability is expected to generate lower inventory levels throughout the supply chain, a lower number of stockouts as well as lower customer-order-to-fulfilment time.

The first TOC application, TOC-Customer Service (TOC-CS), maintains current inventory levels in order to test the heuristic's ability to maximize customer satisfaction. By holding inventory levels constant, this buffering concept incurs higher inventory holding costs and a greater possibility of problems associated with excess warranty expense, but should be able to offset these greater costs with increased revenues. The total number of distinct product combinations held within the buffer at any given point will be 10 for the non-seasonal period and 15 for the seasonal period. A total of between 65 and 130 products, approximately 60 days' supply, are expected to be within the system based on an initial buffer size of 100 units. The variation in inventory holding should be seen as a function of buffer adjustments due to seasonality.

The second TOC application, TOC-Inventory Reduction (TOC-IR), was developed to test the heuristic's ability to maintain current customer service levels while reducing inventory levels. The total number of distinct product combinations held within the buffer is constrained to 15 for the seasonal period and 10 for the non-seasonal period. Based on an initial buffer size of 56 vehicles, the total number of products expected within the local system is between 36 and 70, or approximately 30–40 days of inventory on a seasonally adjusted basis. It should be noted that while the size of the buffer differs for the two TOC-based systems, their operation and control is the same.

Buffer management in the simulation model is handled at the end of each monthly planning cycle. At the end of each month, the contents of the buffer are compared with the expected level of inventory by means of a subroutine. If the inventory content of the buffer is less than one-third of the planned buffer, the buffer size is increased by 30%. If the inventory content of the buffer exceeds two-thirds of the planned buffer, buffer size is adjusted down by 5%. After adjusting the buffer size, new buffer control points are calculated and the process is resumed. Field research indicated the manufacturer's preference for the system to respond quickly to a lack of inventory to reduce the probability of stockouts and dissatisfied customers defecting to competitors. Hence, the buffer management technique allows large increases to the buffer size while slowly bleeding inventory from the system in an effort to seek a point of equilibrium. The time between buffer adjustments reflects the system lead-time (approximately 21–27 days), or the time between when an adjustment would take place and when the resulting change to inventory levels would become apparent at the buffer location.

In order to insure that the planned buffer in each simulation does not adjust to a similar size, a minimum buffer size was inserted into both models by means of an 'If ... Then ...' logic statement. The resulting statement requires that the planned buffer in the TOC-CS system never adjust to less than 65 units of inventory during the non-seasonal period and not less than 80 units during the seasonal period. The minimum size of the planned buffer reflects the manufacture's desire for the amount of inventory in the local system to be equal to 60 days of inventory. In the TOC-IR system, the planned buffer minimum size was established at a size of 30 units. This reflects the desire to test the heuristic's ability to maintain customer service levels at the present level while decreasing inventory levels. Preplanned maximum buffer size limitations were not used for either system during this study. Although artificial caps could be used to limit inventory holdings, as this is an exploratory study, it was unclear where the maximum level of inventory holding should be set.

Each simulation was run for a minimum of 10 years after reaching equilibrium; data for analyses were drawn from post-equilibrium status. Each simulation was replicated a minimum of 30 times for 10 years.

7. Product entities within the simulation

The entities that transverse the simulation models represent approximately 6000 SKUs within the durable goods manufacturer's product line. All 6000 SKUs fall from a single core model that forms the basis for six major subtypes. Those subtypes further disaggregate into final SKUs based upon varying colours, trim levels, power levels, options, etc. Some of the content of these final SKUs can be defined at a final-assembly-to-order process, while other content must be defined at the manufacturing process. In order to decrease variance due to individual SKU price, each product was assigned a standard cost of $22 500 and a standard price of $25 500. These 6000 SKUs represent approximately 0.6% of the manufacturer's total 1998 sales for all retail locations and 6.0% of 1998 sales in the local sales system under study.

8. Cost modelling within the simulation

Five major cost functions were modelled within the simulations that are believed to be those costs that would primarily differentiate financial performance between the four systems modelled.

- *Inventory carrying cost:* defined on the basis of information discovered during the field research as well as from other publicly available sources, this is a function of the standard manufacturing cost of each unit as defined within this study and the amount of time the unit remains in inventory. Inventory holding costs will accrue at a rate of 8.5% of the invoice cost per year.
- *Point-of-sale absorption*: represents the amount paid to retailers by the manufacturer to underwrite inventory expenses incurred at the retail level. It varies to a maximum of 3% of the price paid by the retailer and is a function of the amount of time a unit has been in inventory. A maximum of 3% of the invoice cost will be paid to the retailer, with the rate decreasing to zero after 90 days.
- *Retail transhipment*: represents the cost of transhipment of inventory between retail locations. Transhipments result when inventory is mismatched with demand. Such transhipments are common practice and a common cost in the industry under study. Within the simulation models, this cost is carried at a fixed amount per unit transhipped, that amount set based upon the information collected during the field research and from other publicly available materials. The cost of transhipment will be $30 per occurrence per unit.
- *New product introduction expense*: obsolescence costs associated with new product introduction, which occurs on a fixed periodic basis, are high and frequently encountered in the industry under study. The primary relevant expenses are discounts and promotions offered in order to create demand for product made obsolete by new product introduction. The cost of the relevant rebates will be $2000/unit if the unit is held past the introduction of new products.
- *Excess warranty expense*: during field research, it was discovered that units inventoried over 90 days typically generate much higher warranty claims. Therefore, within the simulation models, units inventoried over 90 days

generate a fixed amount of cost to account for this phenomenon properly. The cost for excess warranty expense will be $500/unit held past 90 days.

The authors recognize the limitation of this cost model in that it does not truly capture or model all costs. In a more general sense, researchers have been warned that all cost models are so limited in nature and that they must consider carefully any attempt to formulate exact cost; i.e. 'costs are sometimes elusive; difficult to estimate' (Deming 1986). The results of the field research indicate that this model does capture much of significant system costs expected to differentiate distribution systems and therefore is adequate toward the aim of this research.

9. Data collection and analysis

Again, the primary proposition of this study is that there is a TOC-based heuristic that will reduce global costs in a multi-product, multi-echelon physical distribution environment. As this research is exploratory rather than theory building in nature, a rigorous statistical testing of that proposition is not appropriate. Therefore, conclusions will be drawn on the basis of a straight economic comparison of the multi-echelon DRP and TOC system simulation outcomes with regards to throughput, inventory, operating expense, net profit, return on investment and cash flow.

The TOC-CS system was successful in fulfilling its intended purpose as it was able to produce higher levels of customer service with an inventory investment similar to that in the DRP models. Using the modified buffer management techniques described above, the TOC-CS system averaged 72.38 units of inventory during the simulation runs (table 1). The average inventory age was 46 days with a standard deviation of 1.77 days. As shown in table 2, this resulted in an average inventory carrying cost of $1.36 million and obsolescence expense due to new product introduction of $1.79 million. Excess warranty expense averaged $328 000 for each 10-year period. These results compare favourably with either DRP system. The Baseline model averaged 86.44 units of inventory, holding each 61 days on average. The resulting inventory carrying costs were $1.63 million, obsolescence costs of $2.12 million and excess warranty expense of $632 034. The DRP-Central system averaged

	Baseline	DRP-Central	TOC-CS	TOC-IR
Customers served	151 951	146 785	169 366	151 644
Customers lost	61 273	67 255	43 205	61 338
Overall fill rate (%)	71.26	68.58	79.67	71.20
Average local inventory (units)	86.44	71.29	72.38	43.12
Average inventory age at time of sale	61.33	52.15	46.127	30.645
Average number of units shipped from buffer per 10 years	n.a.	1572.4	5488.73	4809.9
Per cent of sales requiring transhipment (%)	51.16	50.24	0.00	0.00
Per cent of sales incurring rebate (%)	21.04	19.45	15.91	10.96
Per cent of sales incurring excess warranty expense (%)	24.99	20.22	11.63	4.99

n.a., Not available

Table 1. Aggregate sales breakdown.

		Inventory carrying costs	Point of sale absorption	Retail transhipment expense	New product introduction expense	Excess warranty expense	Total cost of distribution
Baseline	Average	1 625 857	1 930 135	77 584	2 127 586	632 034	6 394 713
	SD	55 916	46 689	2045	56 103	28 731	150 999
	Maximum	1 820 391	2 060 416	82 320	2 246 000	709 000	6 916 567
	Minimum	1 550 939	1 871 718	73 980	2 028 000	586 500	6 178 448
	Per unit						1263
DRP-Central	Average	1 336 289	1 778 448	55 106	1 900 267	494 133	5 564 343
	SD	52 402	47 757	1669	108 287	29 947	201 746
	Maximum	1 450 419	1 867 957	59 800	2 122 000	557 000	5 957 049
	Minimum	1 241 945	1 653 003	52 050	1 708 000	440 000	5 160 176
	Per unit						1137
TOC-CS	Average	1 362 733	2 246 062	n.a.	1 793 533	328 000	5 730 328
	SD	34 465	84 879	n.a.	50 544	43 408	115,360
	Maximum	1 442 744	2 471 604	n.a.	1 866 000	404 500	6 089 848
	Minimum	1 275 339	2 086 636	n.a.	1 700 000	239 000	5 532 198
	Per unit						1016
TOC-IR	Average	811 404	1 466 401	n.a.	1 106 333	126 117	3 510 255
	SD	119 228	174 864	n.a.	157 912	41 153	482 451
	Maximum	1 096 669	1 833 873	n.a.	1 488 000	226 000	4 568 543
	Minimum	617 056	1 150 312	n.a.	836 000	66 000	2 682 368
	Per unit						693

n.a. Not available.

Table 2. Cost analysis.

71.29 units of inventory with an average age of 52 days. Average carrying costs were \$1.34 million, obsolescence expense averaged \$1.9 million and excess warranty expense of \$494 133.

The aggregate cost performance of the TOC-CS model is not significantly better than either the DRP-Central or the TOC-IR models, and is only marginally better than the Baseline model. In fact, the total cost of distribution performance in the DRP-Central model is actually better on a nominal basis than that produced by the TOC-CS model (table 2). Much of this additional cost is attributed to the point of sale absorption expense, which is significantly higher than any of the other models tested. The increased cost of distribution for the TOC-CS system was offset by its ability to fill customer orders from units in stock at a significantly higher rate than the other models, resulting in the sale of an additional 17 000 units over the course of the simulation runs. This resulted in a lower cost of distribution than both of the DRP models when compared on a per unit basis; \$1016/unit compared with \$1263 and \$1137 for the baseline and DRP-Central models, respectively.

Analysis of the data obtained from the simulations reveals a clear cost advantage for the TOC-IR system over all other systems. The purpose of the TOC-IR system was to explore whether a system using the TOC-heuristic could substantially reduce the costs associated with inventory while maintaining customer service levels comparable with the current DRP system. In this regard, the TOC-IR system was a success. As shown in table 1, the TOC-IR model produces fill rates similar to both DRP systems while holding less than half the inventory investment (43.12 units) of the Baseline model. Average inventory age for this system was 30.6 days, approxi-

		Revenue from sales	Invoice cost	Throughput	Operating expense	Inventory	Net profit	Return on investment	Cash flow
Baseline	Average	129 158 350	113 963 250	15 195 100	6 394 713	1 947 735	8 800 387	4.5227	8 809 816
	SD	2 957 837	2 609 856	347 981	150 999	63 930	288 028	0.2040	303 719
	Maximum	135 762 000	119 790 000	15 972 000	6 916 567	2 172 422	9 288 406	4.9127	9 261 501
	Minimum	122 757 000	108 315 000	14 442 000	6 178 448	1 838 023	8 122 785	4.1239	8 107 210
	Per unit	25 500	22 500	3 000	1 263	87	1 737		
DRP-Central	Average	124 767 250	110 088 750	14 678 500	5 564 343	1 605 307	9 114 157	5.6904	9 112 557
	SD	2 487 237	2 194 621	292 616	201 746	73 014	268 182	0.3360	300 097
	Maximum	129 795 000	114 525 000	15 270 000	5 957 049	1 749 177	9 843 851	6.4361	10 009 983
	Minimum	120 283 500	106 132 500	14 151 000	5 160 176	1 468 912	8 674 844	5.1235	8 565 011
	Per unit	25 500	22 500	3 000	1 137	71	1 863		
TOC-CS	Average	143 935 600	127 002 000	16 933 600	5 730 328	1 627 332	11 203 272	6.8923	11 202 467
	SD	3 279 418	2 893 604	385 814	115 360	45 141	407 359	0.3748	437 478
	Maximum	151 699 500	133 852 500	17 847 000	6 089 848	1 718 737	12 202 164	7.7814	12 200 446
	Minimum	138 082 500	121 837 500	16 245 000	5 532 198	1 527 090	10 450 854	6.2785	10 422 623
	Per unit	25 500	22 500	3 000	1 016	72	1 984		
TOC-IR	Average	128 897 400	113 733 000	15 164 400	3 510 255	964 697	11 654 145	12.3443	11 652 096
	SD	5 614 908	4 954 330	660 577	482 451	147 286	429 006	1.8678	490 302
	Maximum	138 694 500	122 377 500	16 317 000	4 568 543	1 307 735	12 521 959	15.9020	12 658 900
	Minimum	118 294 500	104 377 500	13 917 000	2 682 368	750 672	10 988 563	8.6787	11 001 773
	Per unit	25 500	22 500	3 000	693	43	2 307		

Table 3. System profitability.

mately 50% less than the baseline system and 33–42% less than either the TOC-CS or DRP-Central. Inventory carrying, excess warranty and obsolescence expenses fell accordingly, to \$811 404, \$126 117 and \$1.1 million, respectively. The total cost of distribution (table 2) for the TOC-IR system averaged \$3.51 million for each of the simulation runs, an average cost of \$693/unit. This is substantially less than the total and per unit cost of distribution for the baseline (\$6.39 million), DRP-Central (\$5.56 million) and TOC-CS (5.73 million) models. At no point did the maximum total cost of distribution for the TOC-IR model exceed the minimum total cost for any of the other models. Additionally, significant differences exist between the TOC-IR model and all other models for the expenses of inventory carrying, transhipment, new product introduction and excess warranty.

As shown in table 3, the results obtained from the simulations show a clear profit advantage for both the TOC-CS and TOC-IR distribution systems over either version of the DRP system. Owing to the additional sales discussed above, the TOC-CS model was able to produce throughput at the rate of \$16.9 million per simulation run while the TOC-IR model was capable of \$15.2 million. By comparison, the Baseline model was able to produce throughput at the rate of \$15.2 million and the DRP-Central model produced an average of \$14.7 million. The average profit obtained for each of the 30 runs was \$11.20 million and \$11.65 million for TOC-CS and TOC-IR, respectively, while profit from the DRP systems was \$9.1 million (Central) and \$8.8 million (Baseline). At no point does the average profit produced by either of the TOC systems fail to exceed the maximum profit obtained by either of the DRP systems. Additionally, the ROI obtained by the TOC-IR model (12.34%) is an order of magnitude greater than either of the DRP models, while the ROI of the TOC-CS model (6.89%) is marginally greater than that of the DRP-Central (5.69) and significantly greater than the Baseline (4.52%) models. Analysis of Cash Flow reveals similar results with the TOC-IR model leading (\$11.65 million), followed by the TOC-CS (\$11.2 million), DRP-Central (\$9.1 million) and Baseline (\$8.8 million) models.

10. Summary, conclusions and implications

The primary conclusion of this study is that in this specific multi-product, multi-echelon physical distribution case, there exists a TOC-based solution that will provide superior global financial performance as compared with a traditional DRP-based solution. The study developed and validated a current system state for the case through field research, simulated both DRP- and TOC-based solutions for that system state, collected simulated financial measurements from the simulation trials then compared the two sets of simulated financial results. Tables 1–3 clearly indicate the superior financial performance of the TOC-based solution.

This research contributes to, and expands on, the body of production knowledge not only in its demonstration that TOC-based distribution can provide superior financial performance in the distribution environment, but also in that it is among the first to transfer application of TOC knowledge into the area of distribution. Such transfer should inspire those academics who actively pursue study within specific subareas of the TOC body of knowledge to consider and research how their interests may also transfer into the area of distribution. The work should also interest distribution researchers who primarily follow traditional streams of research such as DRP, in that they may now wish to consider how they might modify their existing theoretical models to incorporate some of the benefits that TOC-based approaches might offer.

The work also contributes through its investigation of the multi-product, multi-echelon distribution environment. Much of the existing literature investigates less complex single-product and/or single echelon distribution environments. While such distribution environments are less complex to analyse, their study sacrifices a degree of realism. Discussions within this research study attempt to address model incorporation of various multi-product and/or multi-echelon factors—the management of a high number of SKUs, the measurement of global financial performance over multiple echelons, SKUs that derive from parent products in other echelons, product costs that can be affected by alteration of location of production processes over the various echelons, inventory costs that are dependent upon echelon—these are discussions that may well interest distribution researchers, who, as they contribute to this less-researched area, are faced with relatively undeveloped consideration of such issues in their own modelling and research. Accordingly, such discussion might well be of interest, whether that research seeks to incorporate TOC-based approaches or not.

This study should also be of interest to distribution practitioners. The TOC techniques are, as a whole, more accessible to, and comprehensible by, practitioners than many traditional, more theoretical techniques. Accordingly, practitioners are more empowered to implement TOC techniques. Distribution practitioners, especially those with previous background and/or experience with TOC methods, should be able to develop implementations for improvement of current distribution systems based upon the overall perspective represented in this study.

While this study offers a number of opportunities for future research, the most applicable recommendation, given the heuristic and pragmatic nature of TOC methods, would be for future researchers to develop additional TOC-based distribution cases toward establishing a higher degree of generalizablity, as well as toward the gathering of additional evidence of the incremental performance that can be garnered from the application of TOC techniques within the distribution environment.

References

ADLER, A. L., 1997, The right car at the right time: industry finds new ways to give buyers just what they want, when they want it. *Detroit Free Press.*

AGGARWAL, S. C., 1985, MRP, JIT, OPT, FMS? *Harvard Business Review,* **63**, 8–16.

ALBER, K. L. and WALKER, W. T., 1998, *Supply Chain Management: Principles and Techniques for the Practitioner* (Falls Church: APICS).

ANDEL, T., 1997, Are you ready for efficient consumer response? *Transportation and Distribution,* **38**, 39–46.

ANON., 1997, Cadillac sets new standard with national rollout of Custom Xpress Delivery. *PR Newswire.*

ANON., 1998, GM sidetracks Xpress delivery; 24-hour response to dealers put on hold. *San Diego Union-Tribune,* NC-2.

ANON., 1999, Order disorder: the gap between what customers want and what factories build remains huge, and each year vast incentives are needed to move unwanted iron. It's a multibillion-dollar knot automakers can't seem to untie. *Automotive News.*

BLACKBURN, J. D. and MILLEN, R. A., 1982, The impact of a rolling schedule in a multi-level M. R. P. system. *Journal of Operations Management,* **2**, 125–135.

BLACKSTONE, J. H., 1998, *Theory of Constraints Based Planning and Control* (Athens: University of Georgia), p. 28.

BOWERSOX, D. J., CARTER, P. L. and MONCZKA, R. M., 1993, Materials logistics management. *International Journal of Physical Distribution and Logistics Management,* **23**, 46–51.

BUZACOTT, J. A. and SHANTHIKUMAR, J. G., 1992, A general approach for coordinating production in multi-cell manufacturing systems. *Production and Operations Management,* **1**, 34–52.

CHRISTOPHER, M., 1992, *Logistics: The Strategic Issues* (London: Chapman & Hall).

COOK, D. P., 1994, A simulation comparison of traditional, JIT, and TOC manufacturing systems in a flow shop with bottlenecks. *Production and Inventory Management Journal,* **35**, 73–78.

COPACINO, W. C., 1997, *Supply Chain Management: The Basics and Beyond* (Boca Raton: St Lucie).

COUNCIL, C. D., 1998, Cadillac dealers getting impatient with Custom Xpress Delivery. *Ward's Dealer Business,* **32**, 9.

COX, J. F. and BLACKSTONE, J. H., 1990, *A Framework for Organizing and Managing to Improve Your Manufacturing Performance* (Athens: University of Georgia).

COX, J. F., HOWE, W. G. and BOYD, L. H., 1997, Transfer pricing effects on locally measured organizations. *Industrial Management,* **39**, 20–29.

DAUGHERTY, P. J. and PITTMAN, P. H., 1995, Utilization of time-based strategies: creating distribution flexibility/responsiveness. *International Journal of Operations and Production Management,* **15**, 54–60.

DAVIS, D., 1994, Tough customers. *Manufacturing Systems,* 16–27.

DEMING, W. E., 1986, *Out of the Crisis* (Boston, MA: MIT CAES).

EVANOFF, T., 1998, Cadillac cuts its delivery times sharply: depots can accelerate custom orders. *Detroit Free Press.*

FOGARTY, D. W., BLACKSTONE, J. H. and HOFFMAN, T. R., 1991, *Production and Inventory Management* (Cincinnati, OH: South-Western).

FORGER, G., 1986, How Lotus cut inventory and increased productivity. *Modern Materials Handling,* **41**, 70–71.

FRASIER-SLEYMAN, K., 1994, Forecasting and the continuous replenishment craze of the 1990s. *Journal of Business Forecasting,* **13**, 3–8.

GARDINER, S. C., 1993, Measures of product attractiveness and the theory of constraints. *International Journal of Retail and Distribution Management,* **21**, 37–40.

GARDINER, S. C., BLACKSTONE, J. H. and GARDINER, L. R., 1993, Drum–buffer–rope and buffer management study and practices. *International Journal of Operations and Production Management,* **13**, 68–78.

GARDINER, S. C., BLACKSTONE, J. H. and GARDINER, L. R., 1994, The evolution of the theory of constraints. *Industrial Management,* **36**, 13–16.

GOLDRATT, E. M., 1990, *The Hay*stack Syndrome: Sifting Information Out of the Data Ocean (Great Barrington, MA: North River).

GOLDRATT, E. M., 1994, *It's Not Luck* (Great Barrington, MA: North River).

GOLDRATT, E. M., 1997, *Critical Chain* (Great Barrington, MA: North River).

GOLDRATT, E. M. and COX, J., 1992, *The Goal* (Croton-on-Hudson, NY: North River).

GOLDRATT, E. M. and FOX, R. E., 1986, *The Race* (Croton-on-Hudson, NY: North River).

GREENE, A. H., 1989, Plant-wide systems: a wider view of distribution. *Production and Inventory Management Review and APICS News,* **9**, 32–33.

HAMMEL, T. R. and ROCK, K. L., 1993, Tightening the supply chain. *Production and Inventory Management Journal,* **34**, 63–70.

HARRIS, D., 1998, GM suspends 24-hour delivery test. *Automotive News,* **72**, 41.

HOLT, J. R., 1999, *Candid Comparison of Operational Management Approaches* (Vancouver: Washington State University), pp. 1–11.

HORNE, R., 1989, Charting a course for integrated logistics. *Transportation and Distribution,* **30**, 45–51.

JOHNSON, A., 1986, MRP? MRP II? OPT? CIM? FMS? JIT? Is any system letter-perfect? *Management Review,* **75**, 22–27.

KNILL, B., 1998, Does TOC fit SCF? *Transportation and Distribution,* **39**(8), SCF2.

Koziol, D. S., 1988, How the Constraint Theory improved a job-shop operation. *Management Accounting,* **69**, 44–49.

Krepchin, I. P., 1989, PC-based MRP, DRP help Lipton cut inventories. *Modern Materials Handling,* **44**, 86–88.

Lambrecht, M. R. and Decaluwe, L., 1988, JIT and constraint theory: the issue of bottleneck management. *Production and Inventory Management Journal,* **29**, 61–65.

Lambrecht, M. R. and Segaert, A., 1990, Buffer stock allocation in serial and assembly type of production lines. *International Journal of Operations and Production Management,* **10**, 47–61.

Lockamy, A. I. and Spencer, M. S., 1998, Performance measurement in a theory of constraints environment. *International Journal of Production Research,* **36**, 2045–2060.

Martin, A. J., 1985, DRP (Distribution Resource Planning)—can you afford not to have it? *Material Handling Engineering,* **40**, 131–139.

Martin, A. J., 1990, *DRP: Distribution Resource Planning* (Essex Junction: Oliver Wright).

Maskell, B. H., 1988, Distribution Resource Planning—Part 1: An introduction. *Manufacturing Systems,* **6**, 60–64.

Masters, J. M., Allenby, G. M., LaLonde, B. J. and Maltz, A., 1992, On the adoption of DRP. *Journal of Business Logistics,* **13**, 47–67.

Mateja, J., 1996, The right car, right away. *Chicago Tribune,* Sec. 4, p. 5.

McGrath, J., 1982, Dilemmatics: the study of research choices and dilemmas. In Judgement Calls in Research (Beverly Hills, CA: Sage), pp. 69–80.

Miller, J., 1999, GM wants railroads to expand fast orders. *Automotive News.*

Moore, R. I., 1988, *Distribution Inventory Control: a Systems Approach* (Athens: Department of Management, University of Georgia), p. 427.

Perez, J. L., 1997, TOC for world class global supply chain management. *Computers and Industrial Engineering,* **33**, 289–293.

Pittman, P. H., 1993, *Project Management: a Systems Approach Based on the Theory of Constraints to Developing a More Effective Methodology for the Planning and Control of Projects* (Athens: Department of Management, University of Georgia), p. 219.

Raban, S. and Nagel, R. N., 1991, Constraint-based control of flexible flow lines. *International journal of Production Research,* **29**, 1941–1951.

Ramsay, M. L., Brown, S. and Tabibzadeh, K., 1990, Push, pull and squeeze shopfloor control with computer simulation. *Industrial Engineering,* **22**, 39–45.

Ronen, B., Gur, R. and Pass, S., 1994, Focused management in military organizations: an avenue for future industrial engineering. *Computers and Industrial Engineering,* **27**, 543–544.

Ross, D., 1988, Distribution Resource Planning: integrating the information flow. *Industrial Management,* **12**, S7–S9.

Rummler, G. A. and Brache, A. P., 1990, *Improving Performance: How to Manage the White Space on the Organization Chart* (San Francisco: Jossey-Bass).

Schragenheim, E. and Ronen, B., 1990, Drum–buffer–rope shopfloor control. *Production and Inventory Management Journal,* **31**, 18–22.

Schragenheim, E. and Ronen, B., 1991, Buffer management: a diagnostic tool for production control. *Production and Inventory Management Journal,* **32**, 74–79.

Spencer, M. S. and Cox, J. F., 1995, Optimum production technology (OPT) and the theory of constraints (TOC): analysis and genealogy. *International Journal of Production Research,* **33**, 1495–1504.

Sussams, J. E., 1992, *Logistics Modelling* (London: Pitman).

Tinsley, D. B. and Ormsby, J. G., 1988, Improving marketing with DRP. *Industrial Marketing Management,* **17**, 347–354.

Umble, M. M., 1992, Analyzing manufacturing problems using V-A-T analysis. *Production and Inventory Control Journal,* **35**, 55–60.

Umble, M. and Srikanth, M. L., 1995, *Synchronous Manufacturing: Principles for World Class Excellence* (Wallingford, UK: Spectrum).

Vollmann, T. E., Berry, W. L. and Whybark, D. C., 1988, *Manufacturing Planning and Control Systems* (Homewood, UK: Richard D. Irwin).

Wahlers, J. L. and Cox, J. F., III, 1994, Competitive factors and performance measurement: applying the theory of constraints to meet customer needs. *International Journal of Production Economics,* **37**, 229–240.

Whalen, G., 1991, *Crisis vs. Opportunity*. Quick Response 91 (Pittsburgh, PA: Automatic Identification Manufacturers).

Whybark, D. C., 1975, *MRP: A Profitable Concept for Distribution.* Fifth Annual Transportation and Logistics Educators Conference, Columbus, OH, Ohio State University, Transportation and Logistics Fund.