Local TOC measures for supply chain collaboration

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ABSTRACT

Although the role of performance measures ensuring effective collaboration among supply chain (SC) links has recently been widely recognized, the literature suggesting practical solutions is sparse. This paper demonstrates that theory of constraints (TOC)-based local measures, known as *throughput and inventory dollar-days* (T/IDD), induce SC links to do what is good for the SC network and thereby play an important role in making each link function as a synergistic whole. We model a SC network of a well-known TOC case study using discrete event simulation and discuss a set of scenarios. The scenarios explain how these measures - without sharing sensitive financial data - allow members of a SC network to monitor both the *effectiveness* and *efficiency* of SC members and systematically lead them to create win-win solutions following TOC-based planning and control concepts. We conclude this paper with discussion on the limitations of the proposed research and provide directions for future research.

1. Introduction

The concept of supply chain (SC) management has risen to prominence in the past two decades because of its well documented economic, managerial, strategic, and operational benefits (Carter and Narasimhan 1996; Erengüç *et al.* 1999; Carter et al. 2000). Lambert and Cooper (2000) emphasized that businesses are no longer competing as sole entities but rather as supply chains. The quest for competitive advantage began with individual companies focusing on the agility of their internal SCs (i.e., the coordination of key functional areas within the company). At the onset of the 21st century, the companies are striving to achieve inter-company optimization and synchronization by reconfiguring as SC networks (Poirier and Reiter, 1996; Cooper *et al.* 1997; Greis and Kasarda 1997). Consequently, the need for valid measures of effectiveness (the extent to which customer requirements are met) and efficiency (the extent to which resources are utilized) of the SC members as well as the entire network has been recognized (Neely et al., 1995; Shepherd and Günter 2006; Gunasekaran and Kobu, 2007; Gupta and Andersen, 2011).

Supply chain is essentially a series of (globally) linked suppliers and customers; every customer is in turn a supplier to the next downstream firm, adding value until a finished product reaches the ultimate end user. From operations perspective, SC management is about managing the flow of goods among physically distributed operations and SC network is about balancing the network of plants, warehouses, distribution centers and transportation centers. The structure of the SC networks can be different for different firms, even within the same industry (Fisher 1997;), can be used for strategic purposes to differentiate one type of supply chain from another (Anderson and Lee 2000, Yan and Shaw 2002; Flynn and Flynn, 2005). Importantly, SC network involves vital flows of information and money besides complex flows of products and its members often are captured into a conflict, constantly feeling pressure to compete as well as cooperate (Nagarajan and Sosic, 2008; Netessine, 2009).

The main objective of SC network management is to coordinate and synchronize the links (autonomous or semi-autonomous business entities) towards a common goal of delivering goods to the end customer in the fastest and most predictable fashion, and thereby, ensure that earned profits are equitably shared and costs are fairly distributed among the links (Anderson and Lee, 2000, Narayanan and Raman, 2004). Uncoordinated demand creation and unsynchronized supply activities across the links can lead to problems such as delayed new product introductions, excessive pipeline inventory, constant shortages and backorders, frequent order cancellations and returns, and chronic over-capacity problems (Min 1999; Flynn and Flynn 2005).

Supply chain management explicitly recognizes the interdependence among the various links as well as inherent difficulties in making each link function as a synergistic whole (Walker 2000). In reality, two types of SC networks may exist: non-cooperative and cooperative. A non-cooperative SC is one where each firm attempts to optimize its individual performance, knowing that all of the others will do the same. In a cooperative SC, the members coordinate and agree to work towards the general welfare of the supply chain (Covington 1996; Holt, 1999). The need for cooperative supply chains has given rise to the field of SC collaboration (Holweg et al. 2005; Kampstra et al. 2006; Stank et al. 2011). Collaboration and coordination in SC networks and the central role of SC performance measures in preventing organizational silos have been recognized as the most pressing and least researched problems (SCMR and CSC 2004; Netessine, 2009).

An inherent dilemma faced by companies striving for collaboration can be described as follows (Simatupang *et al.* 2004): on one hand companies feel pressure to base decisions on their SC-wide measures, but on the other hand they feel pressure to base decisions on link-centric measures. Although basing their decisions on SC-wide measures is necessary to enlarge the total profits generated by the entire SC network, each individual company has responsibilities of being profitable on their own which makes it necessary to base decisions on link-centric measures. Towards a solution to this conflict, Simatupang *et al.* (2004) conceptualizes TOC-based replenishment solution (Goldratt, 1994, 2000; Kendall 2004) and a pair of measures, known as **t**hroughput and **i**nventory **d**ollar-**d**ays (T/IDD), as necessary conditions to enhance SC collaboration. They cautioned that TOC based solution approaches are non-conventional and should be adopted after extensive experimental learning. Among other research directions, they suggested "the evaluation of the self-enforcing" collaborative properties of T/IDD measures (p. 27). Conceptually speaking, TDD measures the *effectiveness* of SC members in fulfilling the customer requirements i.e., market demand whereas IDD measures the *efficiency* of SC members in terms of its resource utilization e.g., not building excessive inventory.

Our paper expands on their conceptual work and addresses the research question i.e., w*hat is the role of the local TOC measures, throughput and inventory dollar-days, in promoting SC collaboration?* Using a discrete-event simulation model of a relatively complex SC network where SC members employ T/IDD measures, we demonstrate how SC members in their attempt to improve T/IDDD measures arrive at win/win solutions leading to higher profits for the SC members as well as for the network as a whole. More specifically, the paper is organized as follows: In the second section, we briefly review SC literature with emphasis on TOC and its measures. In the third section, we introduce a SC network based on a well-known TOC case study termed as the ADF SC network. In the forth section, we explain the development, validation and verification of proposed simulation model emphasizing T/IDD measurement computations by each SC member. In the fifth section, we present a set of scenarios describing how T/IDD measures help members to identify the SC constraint and encourage actions/decisions consistent with the TOC-based drum-buffer-rope scheduling system, and thereby, leading towards a strengthened SC network. Finally, we conclude our paper with directions for further research in the areas of real-world implementations e.g., the role Goldratt's evaporating clouds might play in ensuring successful TOC implementation.

2. Literature review

2.1 From conventional perspective

The performance measures play an important role in monitoring performance, managing process, improving communications, diagnosing problems, and evaluating opportunities for SC members. Consequently, attempts have been made to optimize SC performance by employing measures which are profit related (Li and O'Brien 1999), responsiveness or lead-time related (Li and O'Brien 1999), service quality related (Shin et. al. 2000; Humphreys et al. 2001; Stanley and Wisner 2001), and cost saving related (Shin et al. 2000; Viswanathan and Piplani, 2001). Van Hoek (1998) argue that the existing literature often encourage local optimization and lack a balanced approach to integrating financial and nonfinancial measures. Moreover, the dearth of useful frameworks to manage SC performance is widely acknowledged by the academicians as well as practitioners (Chan and Qi, 2003; Shepherd and Günter 2006; Gunasekaran and Kobu, 2007). Towards the development of an effective performance management system, Tompkins (1998) proposed a concept of Supply Chain Synthesis as "a continuous improvement process, ensuring customer satisfaction from original raw material provider to the ultimate finished product consumer. It is like a good marriage, where the partners care more about the state of their union than their own immediate needs… There has to be the same affection and passion for channel success."

2.2. From conceptual TOC perspective

The theory of constraints, a computer scheduling software evolved into a management philosophy, has recently been put forth to address external supply chain design and planning related issues (see Appendix I). Conceptually speaking, policies and programs to manage a SC network from TOC perspective should reflect an awareness of and focus on throughput at three levels: the *mindset* of the SC members, the *measures* that drive the members as well as the network as a whole, and the *methods* employed to manage the SC constraints (Srikanth and Robertson, 1998; Boyd and Gupta, 2004). Thus, successful SC collaboration requires senior management across the SC members to address all the three dimensions of TOC (3Ms) – mindset, measures and methods. That is, each member should adhere to peculiar *mindset* focused on making (rather than saving) money, employ *measures* rewarding global optima and implement *methodology* of identifying and managing the high leverage points. Senior management should embrace the term "throughput chain" over supply chain by recognizing that the ultimate goal is to expand the overall market expansion of the throughput chain rather than cost minimization at each link. Such TOC mindset views SC members' profitability as a necessary condition to effect collaboration. Senior management of the SC members should adhere to a parsimonious set of three global measures– throughput, inventory and operating expenses (Simatupang et al., 2004; Kamstra et al., 2006) to induce each member to align its optimal operating point relative to the SC network. These measures make it abundantly clear that no SC member earns their share of profit merely by shipping a part or component to the next link unless the finished product is bought by the end customer. Simatupang et al. (2004) envisions senior management of the SC members negotiating their share of the total throughput for the supply chain, revealing sensitive financial information on inventory and operating expenses, and creating executive level positions focused on SC wide decisions and collaborations.

Finally, the SC members should implement the five-focusing steps (FFS), and specifically Drum-Buffer-Rope (DBR) scheduling methodology for the entire throughput chain. The primary constraint SC member in the throughput chain must be identified and exploited while the remaining members subordinate in a way to exploit the constraint. In other words, SC inventory should be strategically located in front of the system constraint, known as the constraint buffer, in front of the assembly point, known as the assembly buffer and in the end of the supply chain, known as shipping buffer. The sizes of these buffers should be managed to the desired days of supply targets. The SC members who are not the constraint points, should be able to drive their inventory out of their subsystem (Stein, 1997, Pérez, 1997; Walker, 2000).

2.3 From practical TOC perspective

From real-world applications perspective, the most common and successful applications of TOC concepts has been in the production-distribution environment where the inventory levels at regional warehouses and retail outlets are quickly replenished as the end customer draws the finished products. Such collaborative replenishment policy exploits the fact that cumulative forecast at plant level are more accurate and heuristically determines the reasonable replenishment and emergency inventory levels. Goldratt (1994) using an illustrative case study, first argued that the basic logic of designing and placing buffers to protect the throughput can be extended to the distribution environment and postulated that such application would result in significant increase in customer serve levels and forecast accuracy while simultaneous reduction of inventory investment, lead-time, and transportation costs.

Covington (1996) further provides an evidence of how TOC concepts can be applied to bring together managers from SC member companies to cooperate and improve the overall SC performance. Gupta (1997) explains how a SC member can employ TOC approach to exploit constraint resources along the SC network. Cox (1999) states that many companies are investing millions of dollars linking departments, divisions, and trading partners via technologies, such as enterprise resource planning systems, and will be disappointed because as long as links in a supply chain do not have two fundamental conditions i.e., the right goal for the chain and the right measures to the satisfaction of all links in the chain, the chain will ultimately fail. Walker (2000) points out that many trading partners in a supply chain are having problems accepting and internalizing the TOC cliché: "A supply chain is only as strong as its weakest partner." Watson and Polito (2003) pointed out that application of TOC-based planning and control to manage SC network is still in its early stage and demonstrated its application to the distribution environment. They simulated a multi-product, multi-echelon physical distribution environment after extensive field research and demonstrated that their proposed TOC-based heuristic for buffering and replenishing the inventory is more effective on financial basis compare to the state-of-the art SC management practice termed as distribution resource planning. Additionally, there have been a number of attempts made to further enhance TOC replenishment system (e.g., Yuan et al., 2003; Belvedere and Grando, 2005; Wu et al., 2010). However, not much attention has been given to TOC local measures – the main focus of this paper.

2.4. From Local TOC measures perspective

Goldratt (1990) originally introduced “throughput dollar-days” and “inventory dollar-days” measures to ‘judge the impact of the local area being measured has on the end result’ (p. 145) in the context of an internal supply chain – a complex manufacturing environment. However, literature in the refereed journals about these measures is sparse. Schragenheim et al., (2009) postulated that successful DBR implementations make these TOC measures redundant. Recently, Gupta and Andersen (2011) provided supporting evidence that indeed T/IDD measures, if used properly, can lead to successful DBR like implementation in non-TOC environment and encouraged further research on the role of these measures in the context of SC network.

Goldratt *et al.* (2000) revived these measures in production-distribution environment and Simatupang et al. (2004) further conceptualizes the role these measures, yet the role of these measure in the context of complex SC networks is not well-understood. Thus, the main purpose of this paper is to demonstrate that how these measures *ensure proper coordination and cooperation among the SC members without revealing their financially sensitive information*. Using a simulation model of the ADF SC network, we show that these measures when employed by SC members lead entire network on a continuous improvement path by assisting in identification of constraint firms and implementation of DBR-like system across the SC network. Importantly, these measures fulfill the need for transparency, mutual trust, and open communication among SC members by using only readily available information e.g., selling price of the end product and raw material costs.

In summary, this paper is a contribution towards building theory and developing normative models for successful SC management for which the need has been widely recognized (Lamert et al., 1998; Lambert and Cooper, 2000; Min and Zhou, 2002; Gunasekaran, 2004).

3. A Case Study: The ADF Supply Chain Network

Goldratt (1993, p. 29) originally introduced this case study to demonstrate TOC approach to managing complex production environments. Since then, it has been widely used by many others with slight modifications (see e.g., Patterson 1996; Gupta et al. 2010; Srikanth 2010; Olsen and Patterson 2011). Figure 1 presents its modification as SC network consisting of five independent firms (SCG, SCW, SCC, SCB and SCM), each consisting of its own value chain and adding value to three end products (FGA, FGD and FGF). Such conceptualization is discussed in Mason et al.

(2006) where a relatively complex relationship is assumed among the firms processing the supply of raw materials/components and moving products from one firm to other firms downstream after adding value. No single firm has control over the entire supply chain as inter-firm relationship (rather than ownership) is assumed, and hence no member has the power to optimize the supply chain. (Note: such conceptualization is markedly more complex than a typical production-distribution relationship assumed in contemporary SC management literature discussed later). Such depiction demands the creation and dissemination of a flow of information among network members to ensure an efficient and effective product transition resulting in win/win for all network members.

Figure 1 shows how raw materials RMA, RMC, RME and RMF worth \$30/unit, \$35/unit and \$30/unit and \$65/unit are processed and value is added (in terms of processing time) by the subsequent SC members and finally three finished products (FGA, FGD and FGF) are produced and sold at \$180, \$240 and \$180. 1 also clearly shows the supply chain for each of the three products as well as specific components produced by each supply chain firm. We note this representation of the supply chain network can easily be extended to represent more complex relationships among network members. We use the notation SC**Xyza** where the third digit **X** identifies the SC member, forth digit **y** identifies product and the last two digits za points to a cell in Excel table (in Figure 1) depicting the value added in terms of processing time investment. For example, SC**Gaa3** refers to SC member SCG processing a part for finished product FGA for 19 minutes.

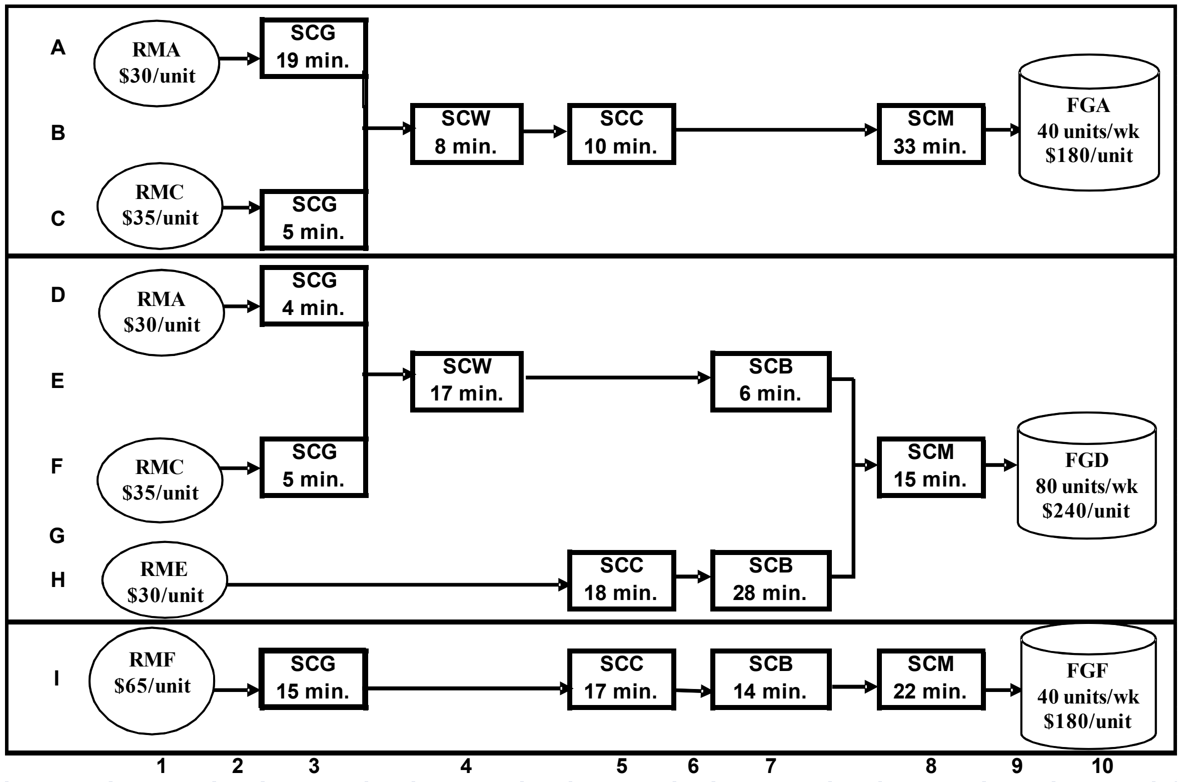

Figure 1 – The ADF supply chain network

Table 1 further shows weekly throughput, operating expenses, and net profit for each firm as well as for the overall ADF SC network. We acknowledge that determining the percentage of the throughput for each member company could be an important problem in itself worth investigating. For this paper, we assume that the group of companies worked backwards insuring each one in the chain has an adequate profit and determined up front the percentage of the throughput each company would get. This concept, explained in Covington (1996) and Simatupang et al. (2006), ties everyone in the chain to the market conditions and makes them act like partners.

< Table1 – Financials of the ADF supply chain network>

Table 1 shows the respective throughput, operating expenses and net profit for each member assuming that there is a weekly demand of 40FGA-80FGD-40FGF. It also shows throughput for each product and how we have allocated throughput and operating expenses across SC members as well as to the individual parts/components produced by the specific members (based on the value added in terms of processing times spent by a specific supply chain member for a specific part/component). For example, **Table 1** shows how $115/unit of throughput (i.e., selling price of $180 minus truly variable costs $65 consisting of raw material costs) charged to an end customer for product FGA is shared by members. Over the period of time, if the supply chain is managed properly and weekly demands are met, the SC network as a whole and its members are expected to realize potential profits shown in Table 1.

Table 1also shows available capacity and processing times estimates assumed for each SC member for this network and computes utilization by analyzing capacity requirements at each SC member. For example, the table shows SCW and SCB SC members have capacity of 480 minutes each on daily basis where as the other three SC members have 960 minutes each. The table also shows that the SC network as a whole will not be able to produce the required weekly product-mix 40FGA-80FGD-40FGF because the SCB member does not have enough capacity i.e., it is a constraint.

Of course, this is very sensitive financial information and is not readily available because members may not want to reveal this information (we assumed this is the case). We note that Table 1 is developed using Microsoft Excel which (based on a given input in terms of number of units produced and sold of each product) can predict the impact on financial performance of the members as well as the whole SC. We use this table primarily to verify and validate the simulation model as well as to analyze various scenarios proposed in a later section.

<Figure 2 – T/IDD values for members SCB>

As mentioned earlier, *Throughput-dollar-days* is a measure of effectiveness at responding to demand. When a SC member does deliver a product on time as agreed upon, it is potentially jeopardizing the sale of a finished good to the end customer. TDD is calculated based on the final selling price of an item and the number of days past the due date an order is (Goldratt, 1990).[1]

For example, if member SCM of the ADF network (shown in Figure 1) receives a batch (40 units) of components used to make product FGF (with selling price of $180) from the member SCB a total of 1 days late, then the TDD value of SC**Bfi7** will be 7,200 ($180 x 1 x 40) and thereby, will keep track of the effectiveness of its supplier SCB over a period of time. This is how TDD value will be calculated for each SC member for each part it produces. As a result of how TDD is calculated, the lateness penalty will stay with the order all the way to the final shipping date. (This is not correct in our model. I have a "Finished by" date for each company in the model. Thus the lateness caused by the first company, can in some instances be corrected by the second company. For the constraint however, the lateness will eventually hit the customer, if nothing is done. Need to be inserted as per your earlier note). This is meant as a way of expediting late orders, but more important is the pattern of TDD values along the supply chain network. A pattern of high and continuously increasing TDD value occurring at a specific supply chain member indicates that either the SC member itself or the upstream supply chain member is a constraint and some actions should be taken to improve the supply chain performance.

Inventory-dollar-days, on the other hand, is a measure of efficiency of a SC member for a period of time. IDD value is calculated based on the final selling price of an item and how long an order has been in inventory. Whether the order is sitting in receiving or getting processed is not important.

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1 In this paper, the final selling price is used because that is what the lateness will cost the entire supply chain if the order is not delivered. (Note: Although some researchers (e.g., Schregnheim ?, Kendall?) have suggested SC throughput instead of final selling price, we used final selling price as originally proposed by Goldratt (1990) for a variety of reasons such as unwillingness on the part of SC members to share sensitive financial data e.g., throughput value. More importantly, we observed that the results and conclusions in this paper do not differ even if we used throughput to calculate TDD.

For example, in Figure 1, suppose member SCB has a batch of I5 component (40 units) to be processed into finished good FGF and the product has been in inventory for 3 days, it would result in a $21,600 ($180 x 3 x 40) IDD penalty. Some inventory is expected, so zero IDD is not the goal. The goal is to minimize this number. IDD value measures how efficient a specific SC member is at moving the product down the supply chain. If IDD value is increasing over the period, the SC member's efficiency is getting worse whereas decreasing IDD value is a sign of being efficient (Or a sign that you are emptying your stock, with the risk of depleting it, because your supplier is a constraint – an email comment from Soeren). It is especially important to watch for growing IDD or large fluctuations in IDD over the period of time. These will indicate a capacity problem.

A SC member with high IDD value (indicating delay in converting inventory into a finished product) and high TDD value (indicating an increase in penalty for missing the delivery dates) is the weakest link in the supply chain. For example, Figure below shows the computations of T/IDD values for a SC member, SCB, over a period of four weeks when weekly material is released for 40A-80D-40F. We note that the T/IDD values grow exponentially if corrective actions are not taken. Brief discussion of each graph to be added. **Note: Similar to our IJPR paper, we should show a graph of T/IDD values for a constraint SC member so that the reader can get a feel of how these measures will be (used in the subsequent scenarios).**

We note that further verification can be made due to the fact that the SC members downstream will also have high TDD value because they will also be late in delivering the product. Hence, the supply chain as a whole, should be taking initiatives to fully utilize the constraint member's capacity as well as to subordinate other SC members' activities. In the following section, we show how such efforts undertaken to reduce TDD and IDD measures across supply chain members corresponds to DBR-like implementation and thereby result in increasing Net profits for the supply chain as a whole as well as individual members (measured in terms of throughput, inventory and operating expenses).

4. Simulation model

In today's complex business environment, need for a simulation-based tool has been widely recognized for designing robust supply chains and for analyzing business dynamics among trading partners (Tezi and Cavalieri, 2004; Zee and Vorst, 2005). A number of simulation models capable of mimicking several key business processes across supply chains have been proposed in the literature for professional as well as educational purposes. For example, Bagchi et al. (1998) described a commercially available IBM SC Simulator which can help members make strategic business decisions (e.g., site location, replenishment, manufacturing, transportation policies, stocking and service levels) about the design and operation of its supply chains. Ingalls and Kasales (1999) described an ARENA-based discrete-event simulation model termed as Compaq Supply Chain Analysis Tool, which allows for operational and financial performance analysis of various configurations of a supply chain. Archibald et al. (1999) discussed an application of a simulation tool the IBM Supply Chain Analyzer, which was used to analyze the manufacturing, distribution, transportation, and retail aspects of a hypothetical company's supply chain. A variety of simulation games have been proposed to further our understanding of emerging production/distribution environments (Chang et al., 2009; Yuh-wen et al., 2010).

We developed a simulation model of the ADF SC network shown in Figure 1 using a combination of Visual Basic for Applications (VBA) and Microsoft Excel. We selected this platform mainly for its simplicity and flexibility in allowing managers to analyze different scenarios by setting user-defined set of input parameters tabulated in Table 2. The simulation model allows users to demonstrate and discuss SC performance improvements by primarily observing T/IDD values for each SC link and guide uses to take set of actions consistent with the five-focusing steps like continuous improvement process for the SC network.

More specifically, the model provides an opportunity to log events that occur during execution, such as idling resources, available materials, beginning and ending of processing, etc. and thereby, provide way to evaluate if the simulation is executed as intended. Additionally, the model employs commonly known interface of Excel to define various input parameters e.g., it allows the user to employ statistical distributions of choice to create variability. The model let users export results to a separate Excel file and provide detailed information about each SC member as well as summarized results for the entire ADF SC network in the forms of charts and tables. (Note: Although we refrain from providing the details of the coded simulation program in this paper, the complete excel file can be obtained from the authors upon request for further research).

4.1 Verification and validation of the model

In order to verify the behavior of the model, it was checked extensively using a special verification scenario (Table 2, column *verification) (Please verify if this column is correct)*. In this scenario, we assumed perfect conditions i.e., there is no variation and uncertainty in the entire SC network and additionally, there is no capacity constraint on any of the SC members, all work for 24 hours a day (480 minutes/5 days a week? I thought so). To verify the behavior of our model, we made machine 1 breaks down the first 6 days and machine 2 break down for one minute less than machine 1 at company SCG (Table 2, column verification shows no machine break down?. We also made the processing time and setup time for SCGaa3 different (in what sense?) the first day from all other days, to ensure that our model would behave accordingly when variation is imposed on it.

Under such conditions, we expected our simulation model to be able to produce all the products (i.e., 40FGA-80FGD-40FGF per week) (WHY? and show that the ideal financial performance (as discussed in the Introduction and shown in Table 1) is realized. Because of the breakdown at SCG the first 6 days all orders from week 1 would be 1 day late, we expected SCG to have a TDD value of 60.00 (equal to two times the selling price of FGA or FGD (SCG carries out two processes for these products) and one time the selling price of FGF times the batch-size of that product. The IDD value will increase rapidly for SCG the first week, but after the companies all have recovered from this initial clot of stock, IDD values should only occur occasionally when a company receives a batch so late that it cannot complete it within the same day. The verification scenario turned out the expected result.

Upon completion of the development, verification and validation phase of the simulation model, we constructed one scenario with a runtime of 24 weeks, split into different time periods with various events taking place in between the time periods. Further, in a real world manufacturing environment, a great deal of variation occurs at different stages during the manufacturing. Set up times are incurred when a company switches to produce a different part, processing times fluctuate, machines break down and/or don't have enough capacity to meet the demand etc. These mentioned sources of variation were fed to the model as shown in Error: Reference source not found. Each segment of the scenario was run 12 times using different seed values of the random number generator to reflect the stochastic nature of the model.

Table – Parameters for simulated scenarios

	Verification*	**Base Run**	**Exploit**	**Subordinate#**	**Daily Release**
General settings					
Warm-up (weeks)	0	2	2	2	2
Runtime (weeks)	3	12	12	12	12
Product priority	FIFO	FIFO	FGF;FGD;FGA	FGF;FGD;FGA	FGF;FGD;FGA
Quoted lead-time	4 weeks	4 weeks	4 weeks	4 weeks	2 weeks
Demand (FGA/FGD/FGF)	40/80/40	40/80/40	40/80/40	40/80/40	8/16/8
Capacity (minutes per day)					
SCG	2880	960	960	960	960
SCW	2880	480	480	480	480
SCC	2880	960	960	960	960
SCB	2880	480	480	480	480
SCM	2880	960	960	960	960
Setup time (minutes per process)					
SCG	0	N(120;120*0.1)	N(120;120*0.1)	N(120;120*0.1)	N(60;60*0.1)
SCW	0	0	0	0	0
SCC	0	N(60;60*0.1)	N(60;60*0.1)	N(60;60*0.1)	N(30;30*0.1)
SCB	0	N(15;15*0.1)	0	0	0
SCM	0	N(30;30*0.1)	N(30;30*0.1)	N(30;30*0.1)	N(15;15*0.1)
Risk of breakdown during processing					
SCG	0	0,1%	0,1%	0,1%	0,1%
SCW	0	0,1%	0,1%	0,1%	0,1%
SCC	0	0,1%	0,1%	0,1%	0,1%
SCB	0	0,1%	0%	0%	0%
SCM	0	0,1%	0,1%	0,1%	0,1%
Length of breakdown, when it occurs					
SCG	0	N(200;200*0.1)	N(200;200*0.1)	N(200;200*0.1)	N(200;200*0.1)
SCW	0	N(170;170*0.1	N(170;170*0.1	N(170;170*0.1	N(170;170*0.1

		)	)	)	)
SCC	0	N(150;150*0.1)	N(150;150*0.1)	N(150;150*0.1)	N(150;150*0.1)
SCB	0	N(20;20*0.1)	0	0	0
SCM	0	N(100;100*0.1)	N(100;100*0.1)	N(100;100*0.1)	N(100;100*0.1)
Processing time variation (where X is the time required for a specific process)					
SCG	X	N(X;X*0.25)	N(X;X*0.25)	N(X;X*0.25)	N(X;X*0.25)
SCW	X	N(X;X*0.25)	N(X;X*0.25)	N(X;X*0.25)	N(X;X*0.25)
SCC	X	N(X;X*0.25)	N(X;X*0.25)	N(X;X*0.25)	N(X;X*0.25)
SCB	X	N(X;X*0.25)	N(X;X*0.05)	N(X;X*0.05)	N(X;X*0.05)
SCM	X	N(X;X*0.25)	N(X;X*0.25)	N(X;X*0.25)	N(X;X*0.25)

* Several special events were imposed in the verification scenario, to probe the model
# SCB has had process times reduced by increasing process times at other companies

5. Experimental results – analysis and discussion

This section outlines the story behind the scenario built in the previous section and illustrates how the T/IDD measures may aid the collaborative efforts of the companies in the SC Network. The ADF SC N arises in response to an identified business opportunity in a collaborative effort between the five companies: SCG, SCW, SCC, SCB and SCM. In the configuration illustrated in **Figure X**, the companies are able to produce three products FGA, FGD and FGF on a make-to-order basis. A constant weekly demand of 40/80/40 for these products respectively has been established. The data in **Figure X** about processing times are known only to the individual companies and are fraught with uncertainty as this business opportunity is new to all companies. Financial data in **Table X** is the result of a negotiation process among the members, thus only the value of raw materials and the final selling price is known to all members.

Several of the companies have long setup times, potentially lengthy breakdowns, and some degree of variation in process time. Since the lead time of 4 weeks is deemed appropriate for the market the SC members negotiate one week of lead time for each process. As some processes are produced in parallel, each product has a lead time of 4 weeks to the customer. This background information and the parameters in **Table X** lay the foundation for analysis and discussion in the subsequent headings in this section.

The Base Run: Identify the ADF Network constraint

The utilization rates in **Table X** indicated that even under conditions with no variability and no setups the SC member SCB does not have enough capacity to produce all the components needed to meet the weekly demand for 80FGD-40FGF. However, SCB accepted to make an attempt giving that the expected load was fraught with uncertainty. Figure X is a dashboard available to all SCN members, with TDD and IDD values arranged by product and process.

At the beginning of the collaboration the 4 weeks of customer lead time includes a substantial lead time buffer, because all members of the supply chain, except SCB, do not need a full week to produce all components. Thus for the majority of the period, there is no indication in TDD that any company is unable to keep its promises. While TDD looks fine, IDD reveals a severe problem arising. Only product FGA has a stable IDD with small fluctuations, both FGD and FGF has an upward trending IDD value, which is caused by SCB. Figure X is the TDD and IDD values solely for company SCB. By day 15 it should be clear at least to SCB that stock is accumulating in a systematic way. The upward trending IDD value at SCB is clear through all seedings of the simulation, in this particular seeding the TDD value also indicates a problem at the end of the period, though no delays to customers as SCM is able to catch up with the delay.

An average of the financial results for the first 6 weeks of collaboration is shown in Table X. All companies are profitable in the period, but as expected from the IDD values, SCB has a substantially higher inventory than the other companies. These results indicate the short term nature of the profits obtained by SCG, SCW and SCC, as their profits are based on a demand, which cannot be fulfilled by the entire SCN.

Company	Parts	Throughput/unit			Financials				
		FGA	FGD	FGF	Units	T	OE	NP	I
SCG	aa3	25.71			240.00	6,170.40			
	ac3	6.76			240.00	1,622.40			
	dd3		6.24		480.00	2,995.20			
	df3		7.80		480.00	3,744.00			
	fi3			22.12	240.00	5,308.80			
							12,375.00	7,465.80	0.00
SCW	ab4	10.82			240.00	2,596.80			
	de4		26.51		413.33	10,957.47			
							6,445.32	7,108.95	5,269.33
SCC	ab5	27.06			230.00	6,223.80			
	dh5		28.06		480.00	13,468.80			
	fi5			39.81	200.00	7,962.00			
							16,757.88	10,896.72	4,567.70
SCB	de7		9.35		333.33	3,116.67			
	dh7		43.66		273.33	11,933.73			
	fi7			20.64	133.33	2,752.00			
							12,375.00	5,427.40	28,905.07
SCM	ab11	44.65			203.33	9,078.83			
	df11		23.38		253.33	5,922.93			
	fi11			32.43	123.33	3,999.70			
							18,046.80	954.67	16,311.43

Based solely on the IDD values from the third week and onwards, the members of the ADF SCN are expected to make an effort to improve the effectiveness and the efficiency of the supply chain.

Choking the release

Knowing what link is constraining the supply chain network from making more money, allow the members to focus their efforts on making sure that they are making as much use of the constraint as possible. This step is particularly aimed at internal improvements at SCB, but there are also decisions of concern for other members of the SCN. In the simulation model it is assumed that the following actions are taken so that they are all ready to be effectuated at the start of week 7.

Action 1.1: Whenever a constraint is used to process more than one product, it needs to be determined which products should have priority over the others. The TDD and IDD values increase for product FGD and FGF, because SCB does not have enough time to produce the full demand on both of them. Dividing the total throughput of a product with the amount of processing-time SCB must complete on it, we arrive at a throughput pr. constraint unit (T/CU). For FGD and FGF this number is: \$145 / (28 + 6) = 4.26 and \$115 / 14 = 8.21, which means that the ADF supply chain network will receive the most throughput when SCB spends its time on FGF. But looking at SCB as a single company the T/CU calculation looks different: \$53.01/(26 + 8) = 1.56 and 20.64/14 = 1.47. If SCB were to optimize as a company the decision would be to prioritize FGD over FGF, yet we assume because the difference for SCB is small, while it is large for the SCN, that SCB will reach an agreement with the other companies to prioritize FGF over FGD. To do that SCM is asked not to accept any orders for FGD, until the current inventory is used.

Action 1.2: Starvation at the constraint should be avoided to the degree possible. Members upstream from SCB must arrange their work to prevent idle time at SCB. The key here is to avoid producing

FGA when it is possible to produce FGF or FGD. Thus all companies are instructed to prioritize FGF over FGD, which in turn has higher priority than FGA.

Action 1.3: Reducing the time spent setting up to produce different products, will free up capacity at SCB. It is assumed that through a setup reduction program it is possible for SCB to move all setup-time from being done with the machines stopped to being done parallel with production.

Action 1.4: A similar source of extra productive capacity can be realized if SCB can minimize the number of breakdowns or the length of them. Thus it is also assumed that SCB is capable of entirely removing any disruptive breakdowns and further free up capacity for production.

Action 1.5: The last action taken by SCB is to reduce the variability in the processing times so that the standard deviation of the processing time is 5% of the mean instead of 25% of the mean.

These five actions have been placed at the beginning of week 7 as shown in Table X. This period will the second period will then be a 4 week extension of the first period. Figure X is a dashboard from the beginning to week 10.

The effect of the actions taken are evident in the way TDD and IDD develops in from the start of week 7 to the end of week 10. Because FGF has the highest priority in all companies, the excess inventory at SCB is rapidly decreasing. Further the IDD for FGD increases as this product has lost priority over FGF. Where FGA had a very stable IDD in the first period, disruptions are now more easily transferred to FGA, thus around day 42 an event at SCM causes inventory to build up. TDD values are also affected by the actions. The high priority at FGF ensures that only a small disruption to customers takes place, yet the TDD value at SCM for FGD is damaged by the lower priority this product has at SCB.

The average financial results for the 4 week period are shown in Table X. In this period SCG, SCW and SCC is affected by the fact that SCB reduces its inventory. SCW has a slight loss while SCG and SCW have a slight profit. Profits are improved at SCB despite that the period is two weeks shorter and the inventory has been reduced greatly. Profits for SCM also improve significantly, but the inventory grows as FGD has lower priority and is dependent upon two components from SCB.

Company	Parts	Throughput pr. unit			Financial results				
		FGA	FGD	FGF	Units	T	OE	NP	I
SCG	aa3	25,71			160,00	4.113,60			
	ac3	6,76			160,00	1.081,60			
	dd3		6,24		0,00	0,00			
	df3		7,80		0,00	0,00			
	fi3			22,12	160,00	3.539,20			
							8.250,00	484,40	0,00
SCW	ab4	10,82			156,67	1.695,13			
	de4		26,51		66,67	1.767,33			
							4.296,88	-834,41	324,90
SCC	ab5	27,06			153,33	4.149,20			
	dh5		28,06		0,00	0,00			
	fi5			39,81	200,00	7.962,00			
							11.171,92	939,28	1.443,87
SCB	de7		9,35		146,67	1.371,33			
	dh7		43,66		186,67	8.149,87			
	fi7			20,64	243,33	5.022,40			
							8.250,00	6.293,60	2.961,70

SCM	ab11	44,65			156,67	6.995,17			
	df11		23,38		173,33	4.052,53			
	fi11			32,43	246,67	7.999,40			
							12.031,20	7.015,90	13.660,63

At this point the IDD values at SCB are showing a decreasing trend, which indicates that the demands placed on it is coming under control. Yet there is still the unfulfilled demand for FGD to consider. It is of interest to every company in the supply chain to fulfill this demand if possible.

Offloading SCB

In the previous scenarios it has been clear that SCB is the only company incapable of satisfying the market demand. The other companies have varying degrees of excess capacity. Any way in which the companies can help SCB produce the full demand - without using their full excess capacity - will help the supply chain reach higher profits.

Action 2.1: Offloading work from SCB to other companies will both increase TDD and IDD. Given that another company e.g. SCM has the capability to take over some of the processing currently done by SCB, time would be free up at SCB to turn out more products.

At the beginning of week 11 this action was done by moving 8 minutes of processing time from SCB to SCM on product FGD and 6 minutes from SCB to SCG on product FGF. By doing this SCB is now loaded to 100% when the full market demand of 80FGD and 40FGF is released. By this token we expected that IDD would become relatively stable at a lower level across all products, the reason being that material would no longer pile up in front of SCB. However, variability at other processes may cause spikes in IDD that will later decrease again as the company recovers from the variability. The graphs from the beginning to the end of week 16 can be seen in figure X.

Now that the constraint has been offloaded the financial performance improves, to the point where the average weekly profit will be equal to the maximum weekly profit calculated for the supply chain.

Improving the flow of materials

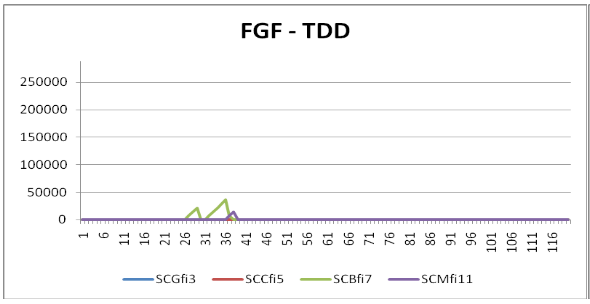
Now that the ADF SCN produces the full customer demand, the graphs promote a different kind of behavior. For the individual companies, which periodically see their TDD going up, internal- or collaborative improvements will focus on removing the causes of these spikes. Removing the spikes in TDD will automatically help stabilizing the IDD value even further, since a delay in one company will result in a buildup of inventory there as well. When TDD is flat at zero and IDD is stabilized, the collaborative efforts of the companies are again needed to reach a stable level of IDD at a lower level.

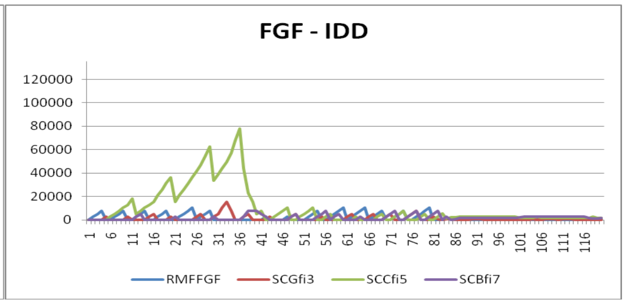
Action 3.1: With a focused effort it is possible for SCG, SCC and SCM to cut their setup-times in half. Faster setups allows for smaller batches and thus a lower IDD value.

Action 3.2: With preventive maintenance and other efforts aimed at improving the reliability of machines, SCG, SCC, SCW and SCM reduces the likelihood of breakdowns significantly. This action further frees up capacity which improves the flow.

Action 3.3: On the basis of these two actions the members of the ADF SCN commits to daily batches instead of weekly batches. Thus instead of a constant weekly demand of 40/80/40 a constant daily demand of 8/16/8 is assumed onwards.

In essence IDD measures the flow of materials as the penalty incurred becomes higher, the longer a specific material stays with one company. Reducing processing times, adding capacity and reducing batch sizes are all valid means to increase the material flow of the supply chain. In our model we assume that SCG, SCW, SCC and SCM are all able to improve their operations to the point where breakdown occurs less frequently and setup times are cut in half. Such an improvement provides enough capacity to cope with the more frequent setups, which in turn allows for smaller batches. Figure X shows only the progression of TDD and IDD with these actions implemented.





The dashboard reveals that the changes have no effect on TDD, while IDD rapidly approaches a lower level of stability. With the simple assumptions included in the model, the financial result of cutting batch sizes only amounts to a decrease in money tied up in inventory and a one-time profit equal to the weekly throughput times the difference in leadtime measured in weeks. Other studies that have focused on the benefit of information sharing across the supply chain, have also found cost improvements as a result of a better flow of products (Cachon and Fisher, 2000). Besides the positive effect on cash flow, profits and operating expenses, cutting batch sizes allows for improvements in customer quoted lead time. In this example the quoted leadtime can be reduced from 4 weeks to 2 weeks, in which a one week protective time buffer is included. A shorter lead time could be a key component to increase market share, by providing superior service to customers.

Benefits of using TDD and IDD

It is a benefit that the whole supply chain knows where something is wrong, and can monitor whether actions of other members jeopardizes their long term profits.

The measures provide a continuous push towards better effectiveness and efficiency, and they will point out where there is a need for action.

If the measures are used both on a network basis and in the individual companies, the measurement system is the same both places, which enables supply chain partners to better understand each other's internal systems.

The measures do not require disclosure of any sensitive financial data.

Limitations

Explain why the LOE measure has not received as much attention in the paper as TDD and IDD.

Explain how the results are believed to be the same, if the case used was a make-to-stock chain.

Explain that there are still some obstacles to overcome before the measures are completely practical.

The model is a simplification as all simulation models are.

Conclusion

Concluding remarks

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Appendix II: 3Ms of TO: Mindset, Measurements and Methodology (based on Boyd and Gupta, 2004)
(Please advise if there is a need for this appendix)

Methodology as a dimension of the theory of constraints

The theory of constraint states every business system has at least one constraint (or at most very few) in its way to continuously improve financial performance. A constraint is defined as anything that limits the system from achieving higher performance relative to its goal. Goldratt and Cox list five focusing steps: (i) Identify the system constraint(s), (ii) decide how to exploit the system's constraint(s), (iii) subordinate everything else to the above decision, (iv) elevate the system's constraint(s), and (v) go back to step 1 without allowing inertia to cause a new system constraint.

As an improvement process, the five focusing steps are targeted to identify, manage, and eliminate constraints (Goldratt and Cox 1984). They focus process improvement where it will have the maximum impact on the system at any point in time i.e., on the constraint whether is market demand or capacity of a specific resource. Inherent in this process are the concepts of V-A-T process structure analysis, drum-buffer-rope, and buffer management (Goldratt and Cox 1984), which are used to develop the constraint's schedule and manage buffer inventories within an organization. The major assumption made is that the organizational constraint is production function. However, if the constraint is market demand for the product, the management team employs thinking process tools such as current reality trees and evaporating clouds to create irrefutable customer offerings.

Measurements as a dimension of the theory of constraints

One of the major obstacles in the way of continuously improving financial performance of an organization is its performance measurement system. Goldratt and Cox (1984) argued that cost-accounting based measures commonly used in organizations encourage attention on local improvements in functional areas (particularly focusing too much on cutting costs and improving departmental efficiencies) with little consideration of the impact on the performance of the whole system. TOC proposes an approach, commonly referred to as throughput accounting, based on a new set of measures, throughput (T) i.e., money coming in, inventory (I) i.e., money stuck inside, and operational expense (OE) i.e., money going out. These measures embody a view of costs that rejects not only cost allocations but also the concept of product cost. Importantly, increasing throughput by selling more products is given much higher priority over reducing operating expenses. They also go beyond direct costing by claiming that direct labor is generally more accurately viewed as a fixed cost than a variable cost and therefore should not be allocated to products. Goldratt and Fox (1986) proposed various linkages between these new measures and financial measures (net profit i.e. T- OE, return-on-investment i.e., T/I, and cash flow i.e., NP $\pm$ ΔI) for assessing a firm's ability to attain the goal. Thus, if throughput increases, then net profit, return-on-investment and cash flow will increase. Some researchers have begun to consider performance measurement systems based on TOC concepts. Lockamy and Cox (1994) proposed such a performance measurement system for aligning an organization's functional performance measures, including the operations function, with the firm's goal of making money. Lockamy and Spencer (1998) reviewed the TOC-related performance measurement literature and examined the use of performance measures in a manufacturing company with the purpose of generating propositions and possible validation in the future.

Cont.

Mindset as a dimension of the theory of constraints

Finally, the ultimate obstacle is its organizational mindset, which is a measure of the underlying attitudes, assumptions and beliefs of management. In TOC, organization's primary emphasis should be on making money instead of saving money because most costs are fixed (Goldratt, 1990a). Goldratt (1994) further clarifies that although the ultimate goal of a for-profit organization is to make money, the significance of necessary conditions such as quality products, customer satisfaction, employee security and equitable pay should not be underestimated. These necessary conditions have long been established as the core concepts of total quality management in empirical research (Powell, 1995; Flynn et al., 1995). The TOC proponents argue that customer and employee satisfaction should be viewed as necessary conditions that must be met before attempting to improve profitability, and that they must be expressly stated to ensure that management policies and practices are consistent with them (Cox and Spencer, 1998). In this view, customer satisfaction and employee satisfaction are threshold conditions rather than goals in the sense of something to be continually strived.