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Capturing the Process Efficiency and Congestion of Supply Chains

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Abstract— **This paper examines the performance of supply chain in stages keeping the essence of processes that knits the stages of supply chain. By focusing on the process as the unit of analysis, the management of inter-organizational relations in a way which is generally known as network, on performance is analyzed. In order to enhance and extend the variation of date envelopment analysis (DEA) methodology, this paper serves to supplement the DEA literature in its application to supply chain retail sector. In addition an examination of input congestion is carried out indicates that a managerial inefficiency exist in the different process cycles of supply chains. However, presence of congestion indicates the inability to dispose of unwanted inputs costlessly. Using the DEA variation of the supply chains are partitioned into three levels/stratums namely 'best-in-class', 'average' and 'laggard'. Substantial performance inefficiency is uncovered in the four process cycle dimensions. Relatively down-stream process cycles of the supply chain exhibit better performance than the up-stream process cycles. Our innovative approach identifies areas for improved supply chain performance over the four process cycles. The classification of supply chains serve as a guideline for best practices, and projects directly to the best class.**

Keywords: supply chain, DEA, congestion, process cycles

1 Introduction

A major sintered and fiction building product manufacturer achieved a $2 million saving in raw material cost by leveraging its purchase volume, obtaining a marginally lower unit price for an automobile type raw material, and changing suppliers. Six months later, a study of manufacturing efficiency found that the new supplier's material reduced finished products yield and increased product rework rates that translated into reduced customer in-stock levels. The over-all effect? About $4.5 million cost to the overall bottom line. In this case the action was in line with the performance measure that had been established for purchasing department, yet the company was worse off overall. By each player in the supply chain acting independently to meet its own performance measures, the result is duplicate inventories, ineffective promotions, excess handling and poor new product introduction practices that add significant cost to consumers and reduce the profitability of everyone involved in the chain. If you only manage your department from within the four-walls, you end up with a balloon effect that cripples your business.

Supply chain is a combined system which comprises planning, sourcing, making and development of processes with its constituent parts to include material suppliers, production facilities, distribution centers and customers linked together through the feed forward flow of material as well as feedback flow of information [14]. A company can identify its supply chain by first selecting a particular product group or product family. Then it should trace the flow of materials and information from the final customer backward through the distribution system, to the manufacturer and then to the suppliers and the source of raw material. The entire chain of activities and processes is known as the supply chain for that product group. An increasingly popular perspective today is to view the flow of materials from the point of conception to consumption as a system which involves strategic coordination of each echelon to be managed. This perspective is commonly referred to as supply chain management. To improve efficiency and effectiveness of a supply chain it is crucial to increase co-ordination both across firms and within firms which are members of the supply chain. A typical firm consist of separate departments which manages the different aspects of the supply chain. For instance, purchasing takes care of the suppliers and raw materials inventory, operations takes care of manufacturing and work-in-process inventory and marketing manages demand and finished goods inveontory. When these department lacks co-ordination, there are dramatic effects on supply chain within the firm as well as outside the firm as seen from the case mentioned at the outset where purchasing department acted independently to meet its own performance measures thus incurring an overall total cost. Thus measuring supply chain performance is the

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first step towards improvement.

Performance measurement plays an essential role in evaluating production because it can define not only the current state of the system but also its future. According to Dyson[11], performance measurement helps move the system in the desired direction through the effect exerted by the behavioral responses towards these performance measures that exist within the system. Mis-specified performance measures, however, will cause unintended consequences, with the system moving in the wrong direction [11]. The underlying assumption behind this claim is the role or presence of drivers such as effciency and effectiveness in the composition of performance. To put it in a simple way, effciency in Dyson's [11] claim is 'doing things right' and effectiveness is 'doing the right thing'. The combination of these two key drivers helps move the system in the right direction by doing the right thing. The definition of performance/performance management revolves around key concepts like efficiency and effectiveness. Let's take a simple example of two car manufacturing companies to distinguish the two concepts. Suppose one of the firms produces car for the market and it does it right without any slacks[1], with optimal utilization of resources relative to the other firm, we can label that firm as efficient however we cannot label it as effective. Effectiveness is the degree to which the outputs of a firm achieve the stated objectives of that service for example, the extent to which the firm is meeting the customer demand for a sedan or different car models. The efficient firm in the example may not be necessarily effective or an inefficient firm on the other hand may be effective and vice versa. Thus efficiency is the degree to which the observed use of resources to produce outputs of a given quality matches the optimal use of resources to produce outputs of a given quality. This can be assessed in terms of technical efficiency and allocative efficiency. Efficiency, by its description, is reactive. It cannot be pro-active. It has to be measurable but what happens in the future is not measurable. Efficiency has to be more historical[6]. The future strategy of a firm is formulated based on the efficiency results of past and present.

Supply chain falls in the domain of production management which includes series of activities such as product design, forecasting, organizing physical facilities, quality control, plant maintenance, materials management and the like. All these activities need to be organized and implemented that the firm should realize increased productivity. Productivity refers to the amount of goods and services produced with the resources used. Productivity is measured with the help of a formula which is as follows:

$$Productivity = \frac{Amount\ of\ goods\ produced}{Amount\ of\ resources\ used}$$

[1]The extra amount by which an input (output) can be reduced (increased) to attain technical efficiency after all inputs (outputs) have been reduced (increased) in equal proportions to reach the production frontier

Productivity and efficiency are closely related however there is a difference between the two concepts. The indices of productivity is an absolute concept, measured by the ratio of amount of output to amount of resources whereas the efficiency indices is a relative concept, measured by comparing the actual ratio of amount of output to amount of resources with optimal ratio of output to input.

The efficiency is determined by using a variation of frontier estimation especially data envelopment analysis (DEA) amidst multiple inputs and outputs. In particular, DEA methodology has proved to be powerful for benchmarking and identifying efficient frontiers especially for single producers or decision making units (DMU). Literature reviews, such as the excellent bibliography in Seiford [20], reveal that research examining the use of mathematical programming and associated statistical techniques to aid decision-making in supply chain benchmarking is lacking. Liang et al.[16] points out that traditionally most models (deterministic and stochastic) dealt with isolated parts of supply chain systems. Liang et al.[16] developed a Stackelberg co-operative model to evaluate the efficiency of SC members using DEA but their study was neither empirical nor showed any relationship of co-operation among members. An empirical study to evaluate the efficiency of whole supply chain was done by Reiner and Hoffman[18]. They tried to evaluate the processes in a supply chain using the performance measure of SCOR[2], however they considered various processes of a single supply chain instead of multiple chains. This leaves us with a literature gap and a question on how to measure the performance of supply chain considering each supply chain as meta-DMU. Research is required to find out how to measure the efficiency of a supply chain keeping an eye on key performance metrics that can cover all the interfaces in a supply chain. Usually the supply chain is evaluated in a sequential order:

$Suppliers \rightarrow Manufacturer \rightarrow Distributor \rightarrow Retailer \rightarrow Consumer$

Some researchers have tried to evaluate the chain in a serial order. Some of them tried to use a single performance measure e.g. (Cheung and Hausman[9]). Others like Chen and Zhu[7] provided two approaches in modeling efficiency as a two-stage process. Golany et. al.[15] provided an efficiency measurement framework for systems composed of two subsystems arranged in series that simultaneously compute the efficiency of the aggregate system and each subsystem. Zhu[22], on the other hand, presented a DEA-based supply chain model to define and measure the efficiency of a supply chain and that of its members. Fare and Grosskopf[13] and Castelli et al[4] introduced the network DEA model, in which the interior structure of production units can be explicitly modeled.

[2]Supply-Chain Operations Reference model. c.f. [19] for some of the more subtle details

However, a supply chain is a sequence of processes and flows that take place within and between different stages and combine to fill a customer need for a product. The objective of every supply chain is to maximize the overall value generated. The value a supply chain generates is the difference between what the final product is worth to the customer and the effort the supply chain expends in filling the customer's request. For most commercial supply chains, value will be strongly correlated with *supply chain profitability*. *Supply chain profitability* is the total profit shared across all the supply chain stages [8]. All the above mentioned studies evaluated supply chain in stages ignoring the essence of processes that knits the stages of supply chain. By focusing on the process as the unit of analysis, the management of inter-organizational relations in a way which is generally known as network, on performance is analyzed. In order to enhance and extend the variation of DEA methodology this paper serves to supplement the DEA literature in its application to supply chain retail sector. Using the DEA variation of [21] the supply chains are partitioned into three levels/stratums namely 'best-in-class', 'average' and 'laggard' [1]. In addition an examination of input congestion is carried out indicates that a managerial inefficiency [10] exist in 'average' and 'laggard' supply chains. By simply reconfiguring this excess resources it may be possible to increase output without reducing the inputs. Equipped with this knowledge, managers will be better able to determine when large reengineering projects are necessary versus minor adjustments to existing business processes. The supply chain process cycles and performance evaluation is discussed in Section 2 followed by our object-oriented DEA models and the resulting empirical findings in Section 3. Finally, Section 4 summarizes and concludes the paper.

2 Processes in Supply Chain

As already mentioned at the outset, a supply chain is a sequence of processes and flows that take place within and between different stages and combine to fill a customer need for a product with an objective to maximize the overall value of the supply chain. Previous studies evaluated supply chain in stages ignoring the essence of processes that knits the stages of supply chain. Therefore evaluating supply chain processes and subprocesses will help to effectively analyze supply chain as a whole. Davenport and Short (1990) define 'processas a set of logically related tasks performed to achieve a defined business outcome and suggest that processes can be divided into those that are operationally oriented (those related to the product and customer) and management oriented (those that deal with obtaining and coordinating resources). There are two different ways to view the processes performed in a supply chain.

- Cycle View: The processes of a supply chain are divided into a series of cycles, each performed at the interface between two successive stages of a supply chain
- Push/pull view: The processes in a supply chain are divided into two categories depending on whether they are executed in response to a customer order or in anticipation of customer orders.

A cycle view of the supply chain clearly defines the processes involved and the owners of each process. This view is very useful when considering operational decisions because it specifies the roles and responsibilities of each member of the supply chain and the desired outcome of each member of the supply chain and the desired outcome for each process. While the push/pull view of the supply chain categorizes processes based on whether they are initiated in response to a customer order (pull) or in anticipation of a customer order (push). This view is useful when considering the strategic decisions. A schematic representation of both the processes are shown in figure 1.

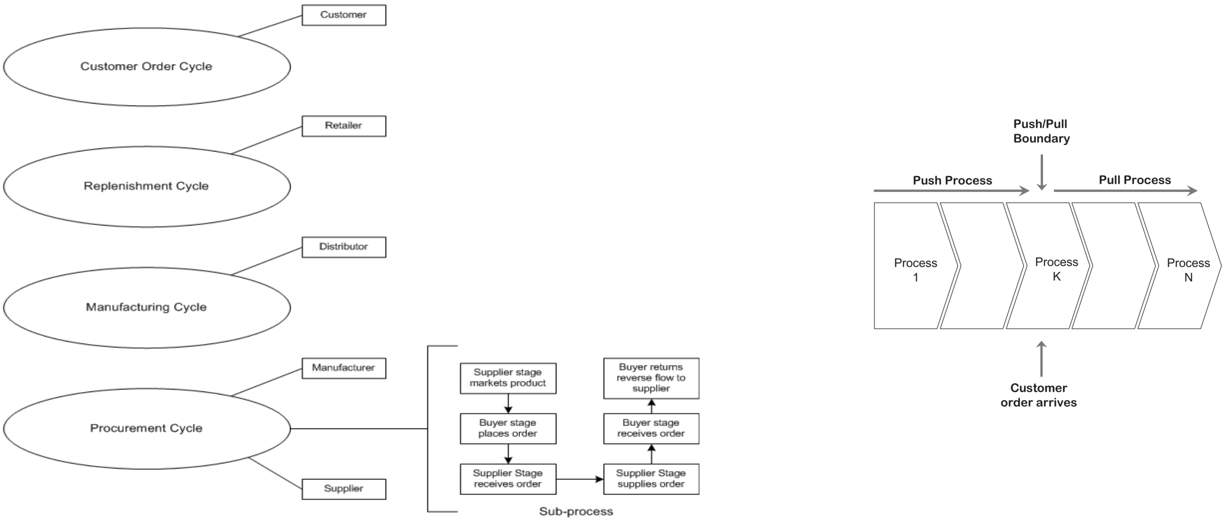
Let's consider the cycle view of supply chain processes. Given the five stages of a supply chain, all supply chain processes can be broken down into four process cycles as shown in figure 1(a). Each cycle occurs at the interface between two successive stages. The five stages thus result in four supply chain process cycles. Each cycle consist of sub-processes again shown in figure 1(b). These subprocesses may vary from industry to industry. We now describe the various supply chain cycles comprehensively in the subsequent sub-sections.

2.0.1 Customer Order Cycle

The *customer order cycle* [8] occurs at the customer/retailer interface and includes all processes directly invloved in receiving and filling the customer's order. Typically, the customer initiates this cycle at a retailer site and the cycle primarily involves filling customer demand. The retailer's interaction with the customer starts when the customer receives the order. The processes involved in the customer order cycle are shown in Figure 1(b) and include:

- Customer arrival
- Customer order entry
- Customer order fulfillment
- Customer order receiving

Customer arrival: The starting point for any supply chain is the arrival of a customer to a facility or a location where he or she has access to his or her choices



(a) Supply cycle view

(b) Push/pull view

Figure 1: Process views of a supply chain: There are two different ways to view the processes performed in a supply chain. Figure (a) Cycle view of supply chain processes (b) Push/pull view of supply chain processes. Cycle view is important when considering operational decisions and push/pull view for strategic decision.

and makes a decision regarding a purchase. Customer arrival can occur when the customer walks into a supermarket to make a purchase. The goal in this process of customer's arrival is to facilitate an appropriate product so that the customer's arrival turns into a customer order. At a retail super mall a customer order may involve managing customer flows and product displays. The objective of the customer arrival process is to maximize the conversion of customer arrivals to customer orders.

Customer order entry: The customer order entry refers to customers informing the retailer what products they want to purchase and the retailer allocating product to customer. At a super mall, order entry may take the form of customers loading all items that they intend to purchase into their carts.

Customer order fulfillment: During this process, the customer's order is filled and sent to the customer. At a super mall, the customer performs this process. In general, customer order fulfillment takes place from retailer inventory.

Customer order receiving: During this process, the customer receives the order and takes ownership. Records of this receipt may be updated and payment completed. At a super mall, receiving occurs at the checkout counter.

Given the five supply chain stages (supplier-manufacturer-distributor-retailer-customer), all supply chain processes are divided into four process cycles and the factors are expressed as inputs and outputs in each cycle. In the first cycle i.e. the *customer order cycle* in a retail setting, the customer walks into a supermarket to make purchase. The manager may group similar merchandise enabling customers to find desired items easily (a process layout). At the same time, the layout often leads customers along predetermined paths such as up and down aisles (a product layout). With this hybrid layout of the retail mart, the customer chooses his/her product and ends with customer receiving the product. Hence, in this cycle the inputs identified are - *technological functionality*, *sales order by FTE (Full-Time Employee)* and the outputs are - *order fulfillment cycle time*, *customer check-out time*. The data categories that are used for analysis in customer order process cycle are described in table 1.

Table 1: Inputs/outputs of customer order process cycle

Inputs	
Technological functionality	The functionality of the technology in place. This is measured in units of functionality where a higher number indicates more functionality.
Sales order by FTE	This indicator measures the number of customer orders that are processed by full time employees per day.
Outputs	
Order fulfillment cycle time	It is a continuous measurement defined as the amount of time from customer authorization of a sales order to the customer receipt of product
Cycle inventory	It represents the average order quantity amount on hand

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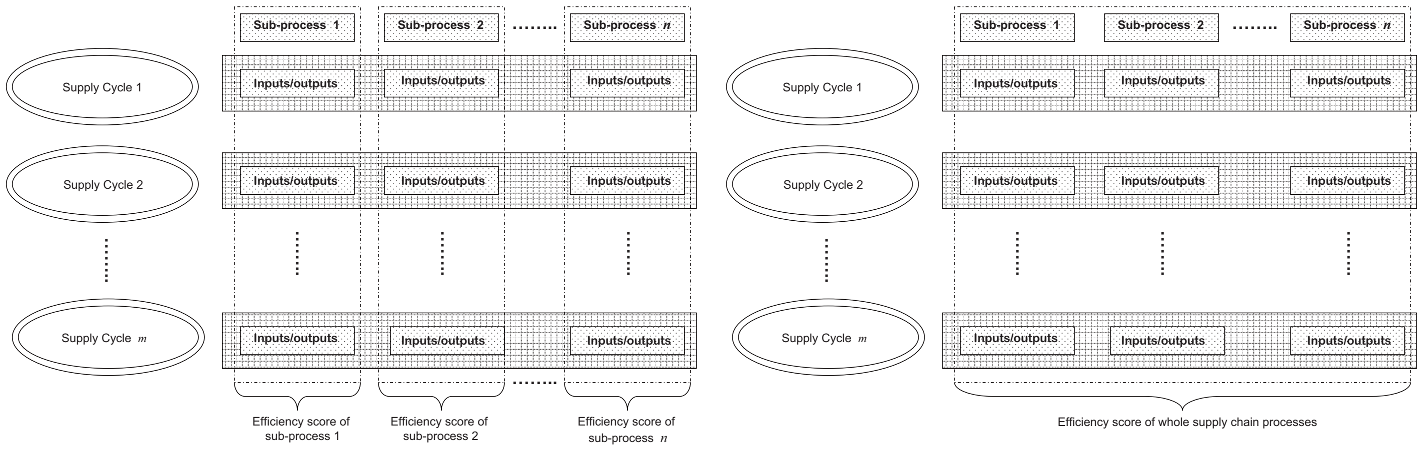

(a) Sub-process evaluation

(b) Meta-process evaluation

Figure 2: Figure (a) Sub-process evaluation in each supply chain process cycle (b) Schematic for evaluating the meta-process efficiency of supply chains

2.0.2 Replenishment Process Cycle

The *replenishment process cycle* [8] occurs at the retailer/distributor interface and includes all processes involved in replenishing retailer inventory. It is initiated when a retailer places an order to replenish inventories to meet future demand. A replenishment cycle may be triggered at a supermarket that is running out of stock of a particular product e.g. detergent. The replenishment cycle is similar to customer order process cycle except that the retailer is now the customer. The processes involved in the replenishment cycle include:

- Retail order trigger
- Retail order entry
- Retail order fulfillment
- Retail order receiving

Retail order trigger: As the retailer fills customer demand, inventory is depleted and must be replenished to meet future demand. A key activity the retailer performs during the replenishment cycle is to devise a replenishement or ordering policy that triggers and order from the previous stage. The objective when setting replenishment order triggers is to maximize profitability by ensuring economies of scale and balancing product availability and cost of holding inventory. The outcome of the retail order trigger process is the generation of a replenishment order that is ready to be passed on to the distributor or manufacturer.

Table 2: Inputs/outputs of replenishment process cycle

Inputs	
Technological functionality	The functionality of the technology in place. This is measured in units of functionality where a higher number indicates more functionality.
Sales order by FTE	This indicator measures the number of retail orders that are processed by full time employees per day.
Outputs	
Fill rate	The number of items ordered compared with items shipped. Fill rate can be calculated on a line item, SKU, case or value basis.
Inventory replenishment cycle time	Measure of the Manufacturing Cycle Time plus the time included to deploy the product to the appropriate distribution center.
Cycle inventory	It represents the average order quantity amount on hand

Retail order entry: This process is similar to customer order entry at the retailer. The only difference is that the retailer is now the customer placing the order that is conveyed to the distributor. The objective of the retail order entry process is that an order be entered accurately and conveyed quickly to all supply chain processes affected by the order.

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Retail order fulfillment: This process is similar to customer order fulfillment except that it takes place at the distributor. A key difference is the size of each order as the customer order tend to be much smaller than the replenishment orders.

Retail order receiving: Once the replenishment order arrives at a retailer, the retailer must receive it physically and update all inventory records. This process involves product flow from the distributor to the retailer as well as information updates at the retailer and the flow of funds form the retailer to the distributor.

In replenishment process cycle the inputs identified are - Technological functionality, sales order by FTE (Full-Time Employee) and the outputs identified are - fill rate, inventory lead time, and cycle inventory. The data categories that are used for analysis in replenishment process cycle are described in table 2.

2.0.3 Manufacturing Cycle

The *manufacturing cycle* [8] occurs at the distributor/manufacturer (or retailer/manufacturer) interface and includes all processes involved in replenishing retailer inventory. The manufacturing cycle is triggered by customer orders/replenishment orders/forecast of customer demand and current product availability in the manufacturer's finished goods warehouse. The processes involved in the manufacturing cycle are shown in figure 1(b) and include:

- Order arrival
- Production scheduling
- Manufacturing and shipping
- Receiving at distributor, retailer or customer

Order arrival: During this process, a finished-goods warehouse or distributor sets a replenishment order trigger based on the forecast of future demand and current product inventories. This process is similar to the retail order trigger process in the replenishment cycle.

Production scheduling: During the production scheduling process, orders are allocated to a production plan. Given the desired production quantities for each product, the manufacturer must decide on the precise production sequence. The demand for a finished good tends to be independent and relatively stable. However, firms typically make more than one product on the same facilities, so production is generally done in lots. The quantities and delivery items needed to make those end items are determined by the production schedule. More specifically, *materials requirement planning (MRP) explosion* and *capacity requirement planning (CRP)* are used. MRP explosion converts the requirements of various final products into a material requirements plan that specifies the replenishment schedules of all the sub assemblies, components and raw materials needed by the final product. Whereas, CRP is the process of determining what personnel and equipment capacities are needed to meet the production objective embodied in the master schedule and material requirement plan. Figure 3 describes MRP and CRP activities in schematic form. Forecasts and orders are combined in the production plan, which is formalized in the *master production schedule (MPS)*. The MPS, along with a *bill-of-material (BOM)* file and inventory status information, is used to formulate the MRP. The MRP determines what components are needed and when they should be ordered from and outside vendor/supplier or produced in-house. The CRP function translates the MRP decisions into hours of capacity (time) needed. If material, equipments and personnel are adequate, orders are released and the workload is assigned to the various work stations.

Manufacturing and shipping: During the manufacturing phase of the process, the manufacture produces to the production schedule. During the shipping phase of this

Table 3: Inputs/outputs of manufacturing process cycle

Inputs	
Bill-of-materials (BOM)	A record of all the components of an item, the parent-component relationships, and the usage quantities derived from engineering and process design
Usage quantity	The number of units of a component needed to make one unit of its immediate parent.
Independent demand ratio	For manufacturers that also supply replacement parts and consumables this metric helps to define the percentage mix of demand for an item from independent (outside sources) vs dependent (inside sources). The ratio is calculated by dividing the unit usage for customer orders by the total unit usage of the item from all sources (work orders, sales samples, destructive testing, inventory adjustments, etc.).
Outputs	
Finished product cycle time	Average time associated with finalizing activities, such as: package, stock, etc.
End item	The final product sold to a customer.

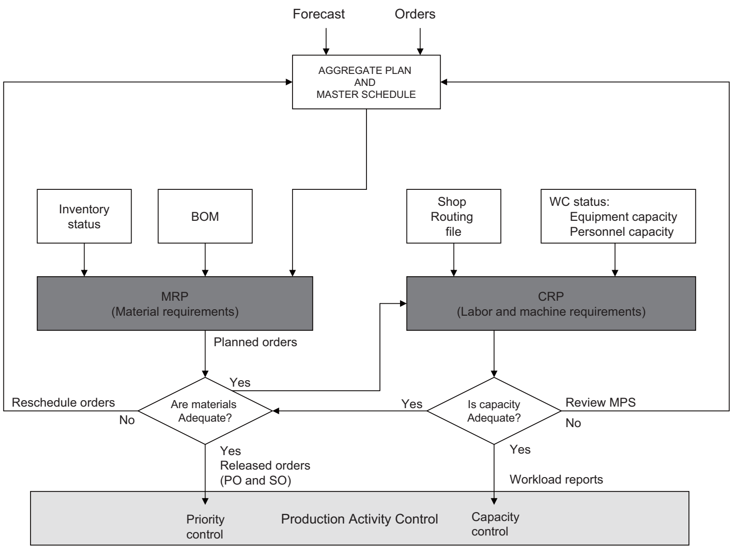

Figure 3: Material and capacity planning flowchart

process, the product is shipped to the customer, retailer, distributor, or finished-product warehouse.

Receiving: In this process, the product is received at the distributor, finished-goods warehouse, retailer, or customer and inventory records are updated. Other processes related to storage and fund transfer also take place.

In manufacturing process cycle the inputs identified are - bill-of-materials (BOM), usage quantity, Independent demand ratio, and the outputs identified are - Finished product cycle time, end item. The data categories that are used for analysis in replenishment process cycle are described in table 3.

2.0.4 Procurement Cycle

The *procurement cycle* [8] occurs at the manufacturer/supplier interface and includes all processes necessary to ensure that materials are available for manufacturing to occur according to schedule. During the procurement cycle, the manufacturer orders componenets from suppliers that replenish the component inventories. The relationship is quite similar to that between a distributor and manufacturer with one significant difference. Wheras retailer/distributor orders are triggered by uncertain customer demand, components orders can be determined precisely once the manufacturer has decided what the production schedule will be. In practice, there may be several tiers of suppliers, each producing a component for next tier. A similar cycle would then flow back from one stage to the next. The processes of procurement cycle are shown in figure 1(b). In procurement process cycle the inputs identified are - *Purchased item*, *Direct Material Cost*, and the outputs identified are - *On time ship rate*, *Delivery Schedule Adherence (DSA)*. The data categories that are used for analysis in replenishment process cycle are described in table 4.

The evaluation of efficiency of sub-processes is performed by inputs and outputs of each supply chain process cycle. After collecting data of inputs and outputs of processes, efficiency of each sub-process will be evaluated using DEA. Figure 2(a) shows the structure of evaluating efficiency of a supply chain sub-process which has m cycles (usually there will be four cycles but in some industry there may be less, e.g. Dell, Amazon etc.) with n sub-processes in each supply chain. Here we have shown just one sub-process of a single cycle however there will be many sub-processes in each supply cycle. Therefore at this stage, computations of efficiency are executed as many times as the number of sub-processes in the chain, as efficiency is evaluated at the process-level. In case of figure 2(a), there are n results of sub-process efficiency in each supply cycle.

2.0.5 Evaluating overall efficiency of a supply chain

Efficiency of a sub-process induced above is meaningful when a target process to be improved is determined by selecting a problematic process or an important process for increasing customer satisfaction. Since our goal is to evaluate the whole supply chain process, it is necessary to aggregate the sub-processes of each cycle to obtain a global process solution. Therefore, in this study, we will evaluate the overall efficiency of each supply chain

Table 4: Inputs/outputs of procurement process cycle

Inputs	
Purchased item	An item that has one or more parents, but no components because it comes from a supplier
Direct material cost	Sum of costs associated with acquisition of support material
Outputs	
On time ship rate	percent of orders where shipped on or before the requested ship date. On time ship rate can be calculated on a line item, SKU, case or value basis
Delivery schedule adherence (DSA)	Delivery Schedule adherence (DSA) is a business metric used to calculate the timeliness of deliveries from suppliers. Delivery schedule adherence is calculated by dividing the number of on time deliveries in a period by the total number of deliveries made. The result is then multiplied by 100 and expressed as a percentage

through a pure output DEA model suggested by Lovell and Pastor [17]. With the DEA model, the weights of each sub-process can be included in evaluating the overall efficiency of a supply chain. Unlike a simple aggregation of processes efficiency, it considers relative impacts of processes on supply chains efficiency (refer to Figure 3 for illustration). It will use efficiency scores of each process as values of output in order to assess the efficiency of a supply chain. In the case of Figure 2(b), each supply cycle will have the efficiency scores of n sub-processes and the whole supply chain has the overall efficiency of m supply cycles. Thus this aggregate efficiency of supply chain will be considered as single DMU. In a similar vein, different supply chains of a particular industry will be analyzed.

3 Measuring Process Efficiency and Congestion of each Process Cycle

There are some issues related to measuring the efficiency of a supply chain using DEA. The first is supply chain operations involve multiple inputs and outputs of different forms at different stages and second is that the performance evaluation and improvement actions should be coordinated across all levels of production in a supply network. In this paper, we evaluate supply chain stages in process cycles keeping the essence of processes that knits the stages of supply chain. By focusing on the process as the unit of analysis, the management of inter-organizational relations in a way which is generally known as network, on performance will be analyzed.

DEA models are classified with respect to the type of envelopment surface, the efficiency measurement and the orientation (input or output). There are two basic types of envelopment surfaces in DEA known as constant returns-to-scale (CRS) and variable returns-to-scale (VRS) surfaces. Each model makes implicit assumptions concerning returns-to-scale associated with each type of surface. Charnes et al.[5] introduced the CCR or CRS model that assumes that the increase of outputs is proportional to the increase of inputs at any scale of operation. Banker et al.[2] introduced the BCC or VRS model allowing the production technology to exhibit increasing returns-to-scale (IRS) and decreasing returns-to-scale (DRS) as well as CRS.

3.0.6 The BCC Model

The input-oriented BCC model evaluates the efficiency of $DMU_o(o = 1, ..., n)$ by solving the following envelopment form:
(BCC_o)
$min_{\theta_B,\lambda}\theta_B$
subject to $\theta_B x_o - X\lambda \geq 0$
$Y\lambda \geq y_o$
$e\lambda \geq 0,$
where θ_B is a scalar

The dual multiplier form of this linear program (BCC_o) is expressed as

$max_{v,u,u_o} z = uy_o - u_o$
subject to $vx_o = 1$
$-vX + uY - u_o e \leq 0$
$v \geq 0, u \geq 0,$ u_o free in sign,
where, v and u are vectors and z and u_o are scalars and the latter, being 'free in sign,' may be positive or negative or zero. The equivalent BCC fractional program is obtained from the dual program as:

$max \frac{uy_o - u_o}{vx_o}$
subject to $\frac{uy_j - u_o}{vx_j} \leq 1$ $(j = 1, ..., n)$
$v \geq 0, u \geq 0,$ u_o free.

The primal problem (BCC_o) is solved using two-phase procedure. In the first phase, we minimize θ_B and, in the

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second phase, we maximize the sum of the input excesses and output shortfalls, keeping $\theta_B = \theta_B^*$. An optimal solution for (BCC_o) is represented by $\theta_B^*, \lambda^*, s^{-*}, s^{+*}$, where s^{-*} and s^{+*} represent the maximal input excesses and output shortfalls, respectively.

BCC-Efficiency: If an optimal solution $\theta_B^*, \lambda^*, s^{-*}, s^{+*}$ obtained in this two phase process for (BCC_o) satisfies

$$\theta_B^* = 1$$

and has no slacks ($s^{-*} = 0$ and $s^{+*} = 0$), then the DMU_o is called BCC-efficient, otherwise it is BCC-inefficient.

Reference Set: For a BCC-inefficient DMU_o, we define its reference set, E_o, based on an optimal solution λ^* by $E_o = \left\{ j | \lambda_j^* \geq 0 \right\}$ $(j \in \{1, ..., n\})$

If there are multiple optimal solutions, we can choose any one to find that

$$\theta_B^* x_o = \sum_{j \in E_o} \lambda_j^* x_j + s^{-*}$$

$$y_o = \sum_{j \in E_o} \lambda_j^* y_j - s^{+*}$$

Thus the improvement path via the BCC projection,

$\hat{x}_o \Leftarrow \theta_B^* x_o - s^{-*}$
$\hat{y}_o \Leftarrow y_o + s^{+*}$

Figure 4 shows the efficiency results of the CCR and BCC model for 11 supply chain sub-processes of a particular product (e.g. detergent). First, the efficient supply chains, in each process cycle are: customer order cycle (1, 4, 7, 9, and 11) replenishment cycle (1, 2, 5, 6, 8, 11), manufacturing cycle (2, 4, 6) and procurement cycle (5, 6, 9). The same figure shows the efficiency results of RTS. The RTS efficiency score is calculated as the ratio of a CCR efficiency score to a BCC efficiency score. Figure 4 indicates that, customer order cycle, the BCC efficient but not scale-efficient process cycles were operating on an IRS frontier. For customer order cycle, five BCC-efficient retail chains were operating on IRS and four on DRS frontiers. Of the BCC-inefficient supply chains, 64% and 20% were in the IRS region in cycle 1 and cycle 2, respectively. As economists have long recognized, an IRS frontier firm would generally be in a more favorable position for expansion, compared to a firm operating in a CRS or DRS region. Note that the concept of RTS may be ambiguous unless a process cycle is on the BCC-efficient frontier, since we classified RTS for inefficient process cycles by their input oriented BCC projections. Thus, a different RTS classification may be obtained for a different orientation, since the input-oriented and the output-oriented BCC models can yield different projection points on the VRS frontier. Thus, it is necessary to explore the robustness of the RTS classification under the output oriented DEA method. Note that an IRS DMU (under the output-oriented DEA method) must be termed as IRS by the input oriented DEA method. Therefore, one only needs to check the CRS and DRS banks in the current study. Using the input-oriented approach, we discover that only two DRS supply chains in replenishment cycle (DMUs 2, 4, 6 and 9) and seven DRS (DMUs 1, 3, 4, 5, 6, 7, and 9) in the manufacturing cycle. These results indicate that (i) in general, the RTS classification under different process cycle is independent of the orientation of DEA model; and (ii) there are serious input deficiencies in manufacturing cycle3 at the current usage quantities derived from engineering and process design.

3.1 Input Congestion in Supply Chains

Congestion is said to occur when the output that is maximally possible can be increased by reducing one or more inputs without improving any other input or output. Conversely, congestion is said to occur when some of the outputs that are maximally possible are reduced by increasing one or more inputs without improving any other input or output. For example, excess inventory cluttering a factory floor in a way that interferes with production. By simply reconfiguring this excess inventory it may be possible to increase output without reducing inventory. This improvement represents the elimination of inefficiency that is caused by the way excess inventory is managed. There are many models dealing with congestion but we start with FGL (Fre, Grosskopf and Lovell 1985, 1994) because it has been the longest standing and most used approach to congestion in the DEA literature.

Fare, Grosskopf and Lovell (FGL) approach proceeds in two stages. The first stage uses an input oriented model as follows (Fare et al.[12]):

$$\theta^* = min\theta$$

subject to,

$$\theta x_{io} \geq \sum_{j=1}^{n} x_{ij} \lambda_j, i = 1, 2, ..., m \quad (1)$$

$$y_{ro} \leq \sum_{j=1}^{n} y_{rj} \lambda_j, r = 1, 2, ..., s$$

$$\lambda_j \geq 0, j = 1, 2, ..., n$$

where $j = 1, ..., n$ indexes the set of DMUs (Decision Making Units) which are of interest. Here is the observed

DMU ID	Customer Order Cycle			Replenishment Cycle			Manufacturing Cycle			Procurement Cycle		
	CCR	BCC	RTS	CCR	BCC	RTS	CCR	BCC	RTS	CCR	BCC	RTS
1	1.00	1.00	Constant	1.00	1.00	Constant	0.08	0.19	DRS	0.63	0.98	DRS
2	0.70	0.84	IRS	0.48	1.00	IRS	1.00	1.00	Constant	0.73	0.84	IRS
3	0.45	0.49	DRS	0.76	0.82	IRS	0.06	0.09	DRS	0.17	0.18	IRS
4	1.00	1.00	Constant	0.45	0.61	IRS	0.46	1.00	DRS	0.64	0.92	DRS
5	0.51	0.54	IRS	1.00	1.00	Constant	0.13	0.39	DRS	0.44	1.00	DRS
6	0.43	0.62	IRS	0.66	1.00	IRS	0.27	1.00	DRS	0.64	1.00	DRS
7	0.97	1.00	DRS	0.69	0.70	DRS	0.02	0.03	DRS	0.12	0.12	IRS
8	0.52	0.53	IRS	1.00	1.00	Constant	0.10	0.10	Constant	0.28	0.30	IRS
9	0.90	1.00	IRS	0.45	0.95	IRS	0.43	0.75	DRS	1.00	1.00	Constant
10	0.74	0.94	DRS	1.00	1.00	Constant	0.01	0.02	IRS	0.09	0.11	IRS
11	0.76	1.00	DRS	0.96	1.00	DRS	0.01	0.02	IRS	0.06	0.07	IRS

Figure 4: CCR, BCC and RTS results

DMU ID	Customer Order Cycle			Replenishment Cycle			Manufacturing Cycle			Procurement Cycle		
	θ^*	β^*	$\frac{\theta^*}{\beta^*}$	θ^*	β^*	$\frac{\theta^*}{\beta^*}$	θ^*	β^*	$\frac{\theta^*}{\beta^*}$	θ^*	β^*	$\frac{\theta^*}{\beta^*}$
1	1.00	1.00	1.00	1.00	1.00	1.00	0.19	0.19	1.00	0.98	0.98	1.00
2	0.84	0.84	1.00	0.98	1.00	0.98	1.00	1.00	1.00	0.79	0.84	0.94
3	0.45	0.49	0.91	0.80	0.82	0.97	0.06	0.09	0.66	0.17	0.18	0.94
4	1.00	1.00	1.00	0.61	0.61	1.00	0.87	1.00	0.87	0.92	0.92	1.00
5	0.51	0.51	1.00	1.00	1.00	1.00	0.31	0.39	0.79	0.66	1.00	0.66
6	0.60	0.62	0.96	0.66	1.00	0.66	0.77	1.00	0.77	1.00	1.00	1.00
7	0.97	1.00	0.97	0.69	0.70	0.98	0.02	0.03	0.66	0.12	0.12	1.00
8	0.52	0.53	0.98	1.00	1.00	1.00	0.10	0.10	1.00	0.28	0.30	0.93
9	1.00	1.00	1.00	0.95	0.95	1.00	0.75	0.75	1.00	1.00	1.00	1.00
10	0.74	0.74	1.00	1.00	1.00	1.00	0.02	0.02	1.00	0.10	0.11	0.90
11	0.76	0.76	1.00	0.96	1.00	0.96	0.02	0.02	1.00	0.07	0.07	1.00

Figure 5: Input efficiency and congestion

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amount of input $i = 1, ..., m$ used by DMU_j and y_{ro} is the observed amount of output $r = 1, ..., s$ produced by DMU_j. The $x_{io}$and y_{ro} represent the amounts of inputs $i = 1, ..., m$ and outputs $r = 1, ..., s$ associated with DMU_o where, DMU_o is the $DMU_j = DMU_o$ to be evaluated relative to all DMU_j (including itself). The objective is to minimize all of the inputs of DMU_o in the proportion θ^* where, because the $x_{io} = x_{ij}$ and $y_{ro} = y_{rj}$ for $DMU_j = DMU_o$ appear on both sides of the constraints, the optimal $\theta = \theta^*$ does not exceed unity and the nonnegativity of the λ_j, x_{ij}, and y_{ij} implies that the value of θ^* will not be negative under the optimization in (1). Hence,

$$0 \leq Min\theta = \theta^* \leq 1 \tag{2}$$

We now have the following definition of technical efficiency and inefficiency,
Technical efficiency is achieved by DMU_o if and only if $\theta^* = 1$
Technical inefficiency is present in the performance of DMU_o if and only if $0 \leq \theta^* < 1$
Next, FGL then go on to the following second stage model,

$$\beta^* = min\beta$$

subject to,

$$\beta x_{io} = \sum_{j=1}^{n} x_{ij}\lambda_j, i = 1, 2, ..., m \tag{3}$$

$$y_{ro} \leq \sum_{j=1}^{n} y_{rj}\lambda_j, r = 1, 2, ..., s$$

$$\lambda_j \geq 0, j = 1, 2, ..., n$$

Note that the first $i = 1, ..., m$ inequalities in (1) are replaced by equations in (3). Thus slack is not possible in the inputs. The fact that only the output can yield non-zero slack is then referred to as weak disposal by Fre et al.[12]. Hence, we have $0 = \theta^* \leq \beta_*$. FGL use this property to develop a measure of congestion,

$$0 \leq C(\theta^*, \beta_*) = \frac{\theta^*}{\beta_*} \leq 1 \tag{4}$$

Combining models (1) and (3) in a two-stage manner, FGL utilize this measure to identify congestion in terms of the following conditions,
(i) Congestion is identified as present in the performance of DMU_o if and only if

$$C(\theta^*, \beta_*) < 1 \tag{5}$$

(ii) Congestion is identified as not present in the performance of DMU_o if and only if $C(\theta^*, \beta_*) = 1$
In figure 5, we focus on the points for DMUs 3, 6, 7, and 8, of customer order cycle which are the only ones that satisfy the conditon for congestion specified in equation (5). For DMUs 3, 6, 7, and 8 in the figure 5 and coupling this value we obtain cogestion efficiency as 0.91, 0.96, 0.97 and 0.98 respectively. Around 36% of the supply chains have exhibited input congestion under VRS technologies. The inputs technological functionality and sales order by FTE in a VRS technology shows the congestion of sales order by FTE is 18.36% of the corresponding technological functionality input level.

Around 45% of the supply chains have exhibited input congestion under VRS technologies in the replenishment process cycle. In the replenishment process cycle we focus on DMUs 2, 3, 6, 7, and 11. We obtain congestion efficiecies of 0.98, 0.97, 0.66, 0.98 and 0.96 for these supply chains. The inputs technological functionality and sales order by FTE same as the customer order cycle, in a VRS technology shows the congestion of sales order by FTE is 26.66% of the corresponding technological functionality input level.

In the manufacturing cycle, the focus DMU points are 3, 4, 5, 6 and 7 which are the ones that satisfy the conditions of congestion specified in equation (5). The congestion efficiencies for these DMUS are 0.66, 0.87, 0.79, 0.77, and 0.66 respectively. The inputs bill-of-materials (BOM), usage quantity, independent demand ratio shows congestion by 15.2%, 22.4%, and 2.5% respectively. The residual score in manufacturing cycle largely indicates the scope for efficiency improvements resulting from less efficient work practices and poor management, but also reflect differences between operating environments in these five supply chains.

The DMUS 2, 3, 5, 8 and 10 of the procurement cycle exhibits the presence of congestion. The congestion efficiency for these supply chains are found to be 0.94, 0.94, 0.66, 0.93, and 0.90 respectively. The inputs purchased item shows congestion by 23.3% of the correspond input direct material cost.

Starting with input (in the form of technological functionality, order by FTE, BOM, usage quantity, independent demand ration, purchased items, direct material cost) at x=0 the output, y, measured in fill rate, cycle inventory, inventory replenishment cycle time, finished product cycle time, end time, on time ship rate and DSA, can be increased at an increasing rate until x_o is reached at output y_o. This can occur, for instance, because an increase in the technological functionality, usage quantity, purchased items makes it possible to perform tasks in a manner that would not be possible with a smaller number of inputs. From x_o to x_1 however, total output continues to increase, but at a decreasing rate, until the maximum

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possible output is reached at y_1. Using more input results in a decrease from this maximum so that at x_2 we have $y_2 < y_1$ and $y_1 - y_2$ is the amount of output lost due to congestion. Under congestion, the inability to dispose of unwanted inputs increases costs.

3.2 Classification of Supply Chains

We have identified best-practice/performance of various supply cycles in supply chains and examined their congestion. However, we have not classified the supply chains which is required for a step-wise improvement, otherwise not possible with the traditional DEA. To classify the set of supply chains, we modify the algorithm developed by [21] to segment the supply chains into three classes namely, best-in-class, average, and laggard chains. The modified algorithm is as follows:

Assume there are n DMUs, each with m inputs and s outputs. We define the set of all DMUs as $J^1, J^1 = DMU_j, j = 1, ..., n$ and the set of efficient DMUs in J^1 as E^1. Then the sequences of J^1 and $E^1$are defined interactively as $J^{l+1} = J^l - E^l$ where $E^l = DMU_p \in J^l | \phi_p^l = l$, and ϕ_p^l is the optimal value to the following linear programming problem:

$$max_{\lambda_i, \phi} \phi_p^l = \phi$$

s.t.

$$\sum_{i \in F(J^l)} \lambda_i x_{ji} - x_{jp} \leq 0 \forall j$$

$$\sum_{i \in F(J^l)} \lambda_i y_{ki} - \phi y_{kp} \geq 0 \forall k$$

$$\lambda_i \geq 0, i \in F(J^l)$$

where $k = 1$ to s, $j = 1$ to m, $i = 1$ to n, y_{ki} = amount of output k produced by DMU_{i*}; x_{jp} = input vector of DMU_p, x_{ji} = amount of input j utilized by DMU_i; y_{kp} = output vector of DMU_p. $i \in F(J^l)$ in other words $DMU_i \in J^l$, i.e. $F(.)$ represents the correspondence from a DMU set to the corresponding subscript index set.
The following algorithm accomplishes subsequent stratum.

Step 1: Set $l = 1$. Evaluate the entire set of DMUs, J^l, to obtain the set, E^1, of first-level frontier DMUs (which is equivalent to classical CCR DEA model), i.e. when $l = 1$, the procedure runs a complete envelopment model on all n DMUs and E^1 consists of all of the DMUs on the resulting overall best-practice efficient frontier.

Step 2: Exclude the frontier DMUs from future DEA runs and set $J^{l+1} = J^l - E^l$

Step 3: If $J^{l+1} = 3E^{l+l}$, then stop. Otherwise, evaluate the remaining subset of inefficient DMUs, J^{l+1}, to obtain the new best-practice frontier E^{l+1}.

Stopping Rule: The algorithm stops when $J^{l+1} = 3E^{l+l}$.

We analyzed the aggregated metrics of the companies using the modified algorithm of [21] to determine whether their performance ranked as best-in-class (36%), average (27%), or laggard (37%). In addition to having common performance levels, each class also shared characterstics in four process cycles: (1) customer order cycle (balances customer demand with supply from manufacturers); (2) replenishment process cycle (Balances retailer demand with distributor fill rate); (3) manufacturing cycle (balances the percentage mix of demand for an item from independent (outside sources) vs dependent (inside sources) across all supply chain stages); (3) procurement process cycle (balances Delivery Schedule adherence (DSA) for the timeliness of deliveries from suppliers). The characterstics of these performance metrics serve as guideline for best practices, and correlate directly with best-in-class performance.

Based on the findings in figure 6 derived from the context dependent DEA algorithm (modified), the best-in-class supply chains reveal the optimal utilization of technological functionality along with the use of state-of-art technology. The average and laggard supply chains on the other hand must upgrade their technological functionality towards fast, responsive, and structured supply chains where customer responsiveness, and collaboration are necessary ingredients for continued and relentless inventory, margin, working capital, and perfect order-related success.

Best-in-class supply chains processes sales order by full time employees 24 - 32% more than the average and laggard chain in the replenishment process cycle. As well as the fill rate and the time required to deploy the product to the appropriate distribution center is 28% higher than the average and laggard supply chains.

In the manufacturing cycle front the inventory optimization goals are well served by best-in-class chains. They work closely with their trading partners, including suppliers, distributor, and retailers to reduce the pressure of increased lead times and potentially lower inventory levels for the chain. Due to this close collaboration, the finished product cycle time (average time associated with analyzing activities, such as: package,stock, etc.) and end item (the final product sold to a customer) less relative to average and laggard supply chains by 34.5%.

On time ship rate (percent of orders where shipped on or before the requested ship date) and delivery schedule adherence (DSA)(a business metric used to calculate the

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	Best-in-Class (E^1)	Average (E^2)	Laggards (E^3)
Classes of efficient chains in %	36 %	27 %	37 %
Customer Order Cycle	Balances customer demand with supply from manufacturers		
	66 %	53 %	48 %
Replenishment Process Cycle	Balances retailer demand with distributor fill rate		
	55 %	31 %	23 %
Manufacturing Cycle	Balances the percentage mix of demand for an item from independent (outside sources) vs dependent (inside sources) across all supply chain stages		
	65 %	44 %	36 %
Procurement Process Cycle	Balances Delivery Schedule adherence (DSA) for the timeliness of deliveries from suppliers.		
	52 %	48 %	45 %

Figure 6: Results of stratified supply chains

timeliness of deliveries from suppliers) in the procurement cycle does not show any significant difference among the best-in-class, average and laggard supply chains. There is only a 5% difference in the perfomance of this supplier manufacturer interface.

4 Conclusion

This paper analyzes the process cycles of 12 supply chains using an innovative DEA model. Close to 45% of the supply chains were inefficient in four process cycles namely - customer order cycle, replenishment process cycle, manufacturing cycle and procurement cyle. Further, most supply chains exhibited DRS in manufacturing cycle and procurement cycle, while some of them exhibited IRS in customer order cycle and replenishment process cycle. This suggests that up-stream components of the supply chain may have a negative effect on finished product cycle time and end item. Having examined performance at process cycle of a supply chain, the current study employs a procedure by FGL[12] to identify the presence of congestion in the chains that may hinder improvement projection of the inefficent chains costlessly. Then a context-dependent DEA model is used to classify the chains into three categories - best-in-class, average, and laggard chains. The characterstics of these performance metrics serve as guideline for best practices, and correlate directly with best-in-class performance. Finally, our examination of supply chain data set indicates that the gap in performance is higer in the down-stream relative to up-stream.

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