29

Simulation Modeling and Analysis of the Impacts of Component Commonality and Process Flexibility on Integrated Supply Chain Network Performance

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1. Introduction

A supply chain can be defined as an integrated business process wherein a number of various business entities (i.e., suppliers, manufacturers, distributors, and retailers) work together. Supply chain configuration is concerned with determining supply, production and stock levels in raw materials, subassemblies at different levels of the given bills of material (BOM). End products and information exchange through (possibly) a set of factories, distribution centers of a given production and service network to meet fluctuating demand requirements. Through the evaluation of the supply chain network configurations, performance indicators of the supply chain such as fill rate, customer service level, associated cost and response capability can be obtained under different network configurations. Different network configurations include: (1) different stocking levels in raw materials, subassemblies and end products; (2) safety stock location; (3) production policy (make-to-stock or make-to-order); (4) production capacity (amount and flexibility); (5) allocation rules for limited supplies; and (6) transportation modes.

Reconfiguration of the supply chain network from time to time is essential for businesses to retain their competitive edge. Supply chain performance optimization consists of deciding on the safety stock level, reorder point, stocking location, production policy (make-to-stock or make-to-order), production capacity (quantity and flexibility), assignment of distribution resources and transportation modes while imposing standards on the operational units for performance excellence. Therefore, the aim of supply chain performance optimization is to find the best or the near best alternative configuration with which the supply chain can achieve a high-level performance.

Source: Manufacturing the Future, Concepts - Technologies - Visions , ISBN 3-86611-198-3, pp. 908, ARS/plV, Germany, July 2006, Edited by: Kordic, V.; Lazinica, A. & Merdan, M.

In integrated supply chains, performance evaluation becomes more challenging since not only the distribution function but also the manufacturing function will be considered. In addition, there are many variables involved in the performance evaluation. More important, there exist interactions between some variables.

Problems with the integrated characteristics given above are difficult to be transformed into mathematical optimization models. When possible, often there are tens of thousands of constraints and variables for a deterministic situation. However, traditional deterministic optimization is not suitable for capturing the truly dynamic behavior of most real-world applications. The main reason is that such applications involve data uncertainties that arise because information that will be needed in subsequent decision stages is not available to the decision maker when the decision must be made (Beamon, 1998). Poorly integrated enterprise logistic system components and processes make it more difficult for firms to compete and differentiate themselves. Only with an integrated approach to supply network performance analysis and management can firms locate and remove sources of inefficiency and waste (Ross, Venkataramanan and Ernstberger, 1998). Through the performance evaluation, the impacts of different factors such as reorder point, safety stock, degree of component commonality and manufacturing flexibility can be investigated. Thus, simulation study can help us gain insight in network configuration problem. In turn, this can assist companies' decision-making in their supply chain management.

Due to the shortened product life cycle and the dynamics of the product market, a company has to improve current products and/or add new products to its existing product line. There are a few strategies available for a supply chain to simultaneously deal with product variety and keep high levels of productivity. Some of these are supply chain integration, component part commonality, and process flexibility. Different products may share common components (therefore, common inventories) and resources (facilities and capacities). Correspondingly, this requires that the company to reconfigure its supply chain network structure. The configuration of a supply chain network, including the links between entities and operational policies, is changeable and aimed at delivering products to customers in an efficient and effective way. The issue is how to evaluate and then change the structure of the network. The evolution aspect of the supply chain network structure provides the basis for the change.

The development of analytical measures describing product structure characteristics is a prerequisite to understanding the relationships between product structure and supply chain performance. One characteristic of product structures is the degree of common components in a sub-assembly, a single product or any product family. The traditional MRP methodologies are completely blind to commonality and consequently are unable to exploit it in any way (Miguel, et al., 1999).

There exist a rich literature studying component commonality. However, the majority of work published so far has concentrated on the related effects of inventory and safety stock levels only. It has been clearly demonstrated in the literature that introducing a common component that replaces a number of unique components reduces the level of safety stock required to meet service level requirements.

Collier (1981) initiates an interest in taking advantage of the commonality situation. He finds that increased commonality reduces production costs through larger production lot sizes and reduces operation costs through increased standardization.

Eynan and Rosenblatt (1996) study the effects of increasing component commonality for a single-period model. They develop optimal solutions for the commonality and non-commonality models and provide bounds on the total savings resulting from using commonality. They demonstrate, under general and specific component cost structures, that some forms of commonality may not always be a preferred strategy. Furthermore, they present conditions under which commonality should not be used.

Hillier (1999) develop a simple multiple-period model with service level constraints to compare the effects of commonality in the single-period and multiple-period case. The results are drastically different for these two cases. When the common component is more expensive than the components it replaces, commonality is often still beneficial in the single-period model, but almost never in the multiple-period model.

Hong and Hayya's paper (1998) consider the effects of component commonality in a single-stage manufacturing system of two products manufactured in a single facility. They consider two economic lot schedules: the common cycle (CC) and basic period (BP) schedules. For each lot schedule, an expression for the total relevant cost for the system was given in their paper.

In an environment where demands are stochastic, it seems a good strategy to store inventory in the form of semi-finished products (vanilla boxes) that can serve more than one final product. However, finding the optimal configura-

tions and inventory levels of the vanilla boxes could be a challenging task. Swaminathan and Tayur (1998) model the above problem as a two-stage integer program with recourse. By utilizing structural decomposition of the problem and sub-gradient derivative methods, they provide an effective solution procedure.
Product structure (or bill of material) is a key input to an integrated supply chain design. The product structure may have a significant impact on component demand patterns, work-in-process inventory, and fill-rate performance. However, the effect of alternate product structures on integrated supply chains is not well understood. The simulation study in this chapter is designed to investigate the impacts of component commonality on the integrated supply chain network.
Process flexibility, whereby a production facility can produce multiple products, is a critical design consideration in multi-product supply chains facing uncertain demand. The challenge is to determine a cost-effective flexibility configuration that is able to meet the demand with high likelihood (Graves and Tomlin 2003). In a make-to-order environment, this flexibility can also be used to hedge against variability in customer orders in the short term (Bish, Muriel and Biller 2005). Graves and Tomlin (2003) present a framework for analyzing the benefits from flexibility in multistage supply chains. However, these analytical results are only suitable for simplified supply chains.

The remainder of this chapter is organized as follows. Section 2 provides an integrated modeling framework for multi-stage supply chains. In section 3, a state and resource based simulation modeling approach is proposed. Section 4 defines the new analytical measure for component commonality index. This commonality index is used to evaluate the impacts of component commonality on supply chain network performance in section 5. Section 6 investigates the effects of process flexibility on supply chain performance. Section 7 summarizes this research.

2. An Integrated Modeling Framework for Supply Chain Networks

Supply chains may differ in the network structure (serial, parallel, assembly and arborescent distribution), product structure (levels of Bill-Of-Materials), transportation modes, and degree of uncertainty that they face. However, they have some basic elements in common.

2.1 Sites and Stores

A supply chain network can be viewed as a network of functional sites connected by different material flow paths. Generally, there are four types of sites: (1) *Supplier sites*: they procure raw materials from outside suppliers; (2) *Fabrication sites*: they transform raw materials into components; (3) *Assembly sites*: they assemble the components into semi-finished products or finished goods; and (4) *Distribution sites*: they delivery the finished products to warehouses or customers. All sites in the network are capable of building parts, subassemblies or finished goods in either make-to-stock or make-to-order mode. The part that a site produces is a single-level BOM.

2.2 Links

All stores in the supply chain are connected together by links that represent supply and demand processes. Two types of links are defined: *internal link* and *external link*. Internal links are used to connect the stores within a site, i.e., they represent the material flow paths from input stores to output stores within a site. Associated with an internal link connecting an input store i to an output store j is a usage count, u_{ij}, which indicates the number of SKUs in the input store i required to produce a SKU in the output store j. Along with the usage counts, the internal links connecting input stores and output stores constitute the single-level BOM for that output store. A link connecting an output store of one site to an input store of another site is called an external link. This kind of link represents that the output store provides replenishments to the specified downstream input store. In the network topology, we define that a downstream input store has only one link between it and its upstream output store (Figure 1).

2.3 The Relationships Between Stores

Let ***ST*** be the collection of stores in a supply network and i be a store in ***ST***. The set of directly upstream supplying stores of store i is denoted as *UPST*(i). The set of directly downstream receiving stores from store i is denoted as *DOWNST*(i). If i is an input store, then *UPST*(i) is a singleton set, i.e., it contains only one upstream supplying store. That is, each input store can obtain replenishment from only one supplier. On the other hand, *DOWNST*(i) consists of one or more output stores at the same site. If i is an output store, then *UPST*(i) is either empty, in which case i is a *source* store (e.g., a supplier), or contains one or more stores, which are input stores at the same site. For *DOWNST*(*i*), it is either empty, in which case *i* is an *end* store, or contains one or more input stores at its downstream site.

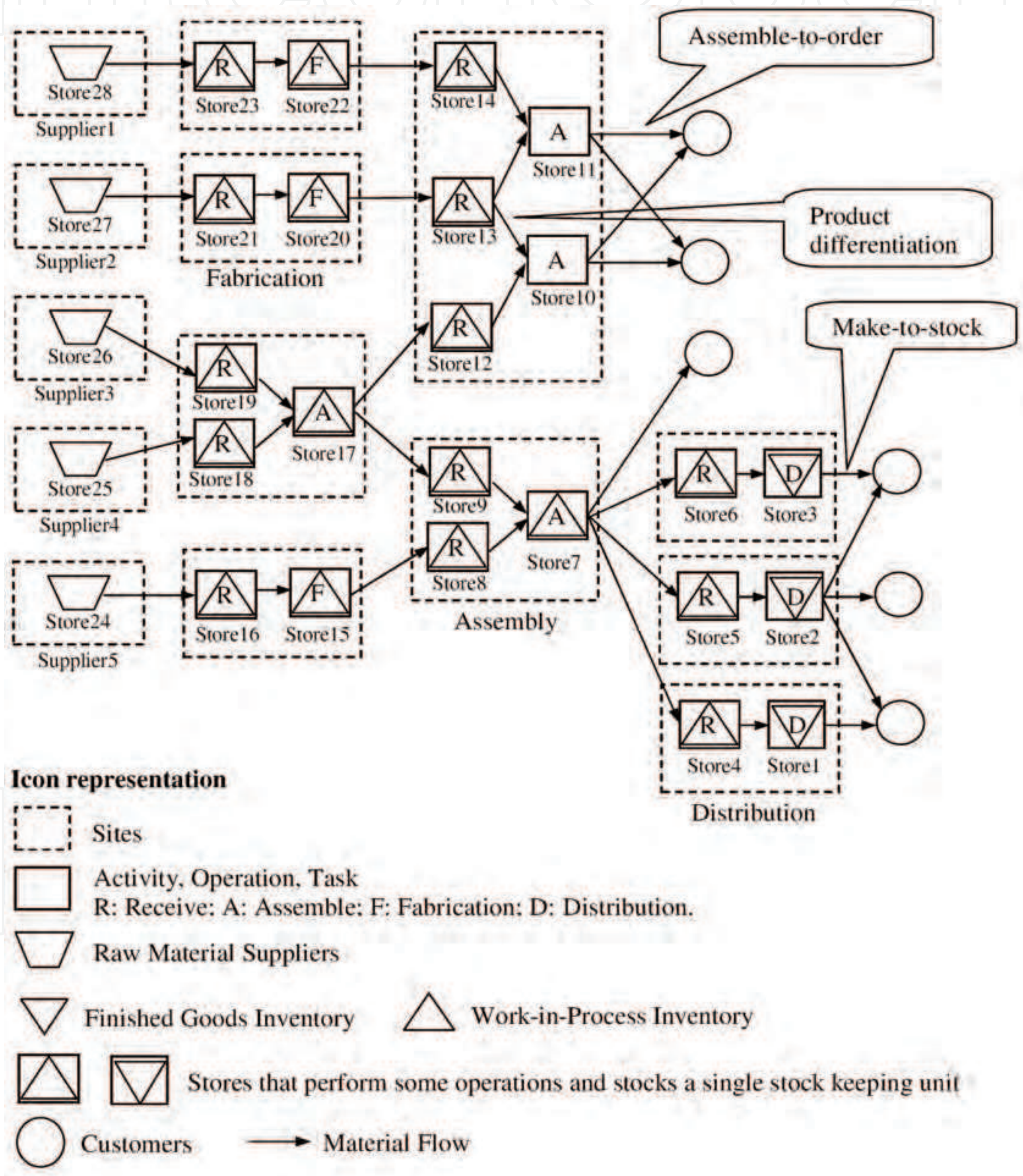


Figure 1. An Integrated Modeling Framework for Supply Chains

3. A Component based Simulation Modeling Approach

From a system perspective, a supply chain process consists of the flow of materials, information and services, and the monitoring and control of these flows. Typical activities include: raw material procurement, inventory management, order processing, warehousing, transportation, distribution and production. Supply chain management is concerned with the development of functions to support these activities.
Several methods to develop a model of a system have been proposed. Top down development starts with a model at a high abstraction level, this model is refined by a number of disaggregation (or decomposition) steps until the desired level of detail has been reached. Bottom up development starts with some subsystems that are detailed descriptions of some aspect or part of the systems. Then, these sub-models are composed into a model of the entire system. In this research, a mixture of top down and bottom up development is employed to build simulation models.
Practical experiences show that some supply chain networks have subsystems that have a lot in common. For example, a distribution center and a production unit have transportation subsystems for internal transport. To support the modeling process it is useful to reuse some typical subsystems, often called *components* or *building blocks*. Reusing these components reduces the modeling effort. And, from these reusable components, the rapid reconfiguration of a supply chain network can be achieved.
Some requirements on the components include:

1. they can be parameterized, which make them tailored for a specific situation;
2. they have to be robust in the sense that it can handle various inputs, i.e. the number of assumptions about the environment of the component is as few as possible.

Some typical components in a supply chain network are given as follows:

- Raw material supplier: the beginning of the chain
- Production unit: the manufacturing of goods (transforming, assembling, splitting up)
- Distribution center: the rearrangement and the distribution of goods
- Transportation center: the transportation of goods
- Consumer: the end of the chain

3.1 Stroboscope - A State and Resource based Simulation Language

STROBOSCOPE is a general-purpose discrete-event simulation language based on activity scanning and activity cycle diagrams (ACDs). A subset of the STROBOSCOPE modeling concepts are directly analogous to those used in timed stochastic colored Petri-nets, but use a different terminology (token=resource; place=queue; transition=activity; arc=link).
STROBOSCOPE tokens can be colored with any number of properties and methods. The entire state of the model (e.g., number of tokens in a place, number of times a transition has fired) and the colors of tokens are accessible via variables. Arcs can enable transition firing based on the truth of any expression; allowing arcs to be inhibitors, activators, or to take on any other role. Transition timing can be defined with any valid expression (functions that sample from various probability distributions are available). STROBOSCOPE also includes many powerful extensions not found in Petri-nets (Martinez 1996).

STROBOSCOPE's ability to dynamically access the state of the simulation and the properties of the resources involved in an operation differentiates it from other simulation tools. The state of the simulation refers to such things as the number of products in the inventory, the current simulation time, the number of times an activity has occurred, and the last time a particular activity started. Access to properties of resources means that operations can be sensitive to resource properties, such as quantity and holding cost, on an individual or an aggregate basis. The employment of state and resource in simulation will facilitate the implementation procedure since they are strong in modeling dynamic systems with highly interdependent components subject to activity startup conditions.

3.2 Network Elements

3.2.1 Resources

Resources are things required to perform tasks. These can be machinery, space, materials, labor, permits, or anything else needed to perform a particular task.
The most important characteristic of a resource is its type. The type of a resource places the resource within a category of resources that share common traits or characteristics.

3.2.2 Queues

Queues are nodes in which resources spend time passively (they are either stored there, or waiting to be used). Each queue is associated with a particular resource type. Queues that hold discrete resources have attributes that control the ordering of the individual resources within the Queue.

3.2.3 Activities

Activities are nodes that represent work or tasks to be performed using the necessary resources. Resources spend time in activities actively (performing a task). Resources involved in activities are productive, sometimes in collaboration with other resources.

Combi activities: represent tasks that start when certain conditions are met.

Normal activities: represent tasks that start immediately after other tasks end. Among all nodes in a network, only activity instances represent tasks that end and release resources. For this reason, only other activities can be predecessors to a *Normal Activity*.

3.2.4 Links

Links connect network nodes and indicate the direction and type of resources that flow through them. Links have many attributes that can be used to control the flow of resources from the predecessor node to the successor node.

4. Commonality Index (CI)

The commonality index is a measure of how well the product design utilizes standardized components. A component item is any inventory item (including a raw material) other than an end item that goes into higher-level items. An end item is a finished product or major subassembly subject to a customer order. The commonality index given by Collier (1981) cannot differentiate the product lines with same components but different quantities for each component.

Different from Collier, two types of commonality indexes are defined in this paper. One is called component-level (denoted as CI_i), which is to provide an indicator on the percentage of a component being used in different products. The other is called product-level (denoted as CI_P). There are three variables that will affect the commonality index, which are, number of unique components (denoted as *u*), number of total components along the product line (denoted as *c*), and final number of product varieties offered (denoted as *n*). To get the appropriate product-level CI, all these three variables along with component-level CI should be considered. The basic idea is that, by ranking the different component-level CI values, the average for the differences of CI values is computed. Then, this average difference will be multiplied by a weight, which is the ratio of (*c*-*n*) and *u*. A special case appears when all component-level CI values are same, $u<c$ and $n<c$. In this case, instead of the average difference, product-level CI is obtained by multiplying anyone component-level CI and the weight. Therefore, to calculate CI_P, we first find out the difference between the maximal component-level CI and the minimal component-level CI, which is same as the summation of differences among component-level CI values. Then, we divide the difference by number of unique components to get the average CI difference. Finally, the average CI difference is multiplied by (*c*-*n*) so that the information on how broad the components spread in product line is captured.

The following formula is used to calculate the component-level CI:

$$CI_i = \frac{\sum_j f_{ij} \cdot d_j}{\sum_{i,j} f_{ij} \cdot d_j} \qquad (1)$$

f_{ij} = number of component *i* in product *j*
d_j = demand of product *j*
$0 \le CI_i \le 1$

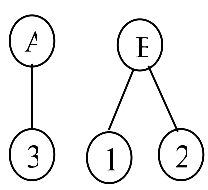
The lower bound of the component-level CI is 0 (no commonality). The upper bound on the degree of commonality is 1. Complete commonality results when the total number of distinct components (*u*) equals one.

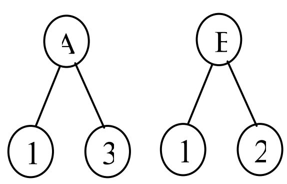
In reality, it is reasonable to assume that number of total components along the product line is greater than final number of product varieties offered, i.e., $c > n$. The product-level CI is computed as follows:

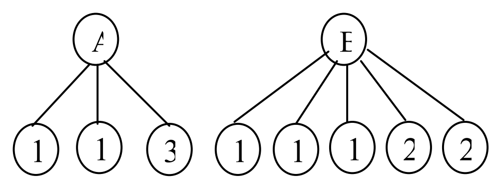
u = number of unique components
n = final number of product varieties offered
c = total number of components along the product line

$$CI_p = \begin{cases} \dfrac{CI_i}{u} \times (c-n), & when \quad \max\limits_i\{CI_i\} = \min\limits_i\{CI_i\} \quad and \quad c > u \\ \left[\dfrac{\left(\max\limits_i\{CI_i\} - \min\limits_i\{CI_i\} \right)}{u} \right] \times (c-n), & otherwise \end{cases} \qquad (2)$$

In general, a higher CI is better since it indicates that the different varieties within the product family are being achieved with more common components.

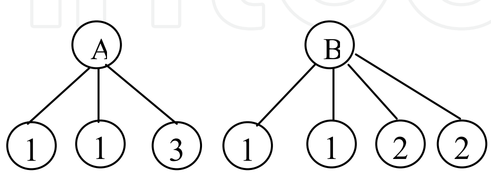


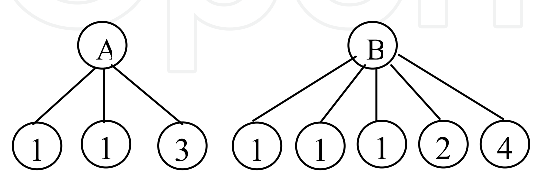




$CI_1 = CI_2 = CI_3 = \frac{1}{3}$ $\quad CI_1 = \frac{1}{2}, CI_2 = CI_3 = \frac{1}{4}$ $\quad CI_1 = \frac{5}{8}, CI_2 = \frac{2}{8}, CI_3 = \frac{1}{8}$

$CI_p = \left(\frac{1}{3} - \frac{1}{3} \right) \times 1 \div 3 = 0$ $\quad CI_p = \left(\frac{1}{2} - \frac{1}{4} \right) \times 2 \div 3 = \frac{1}{6}$ $\quad CI_p = \left(\frac{5}{8} - \frac{1}{8} \right) \times 6 \div 3 = 1$





$CI_1 = \frac{4}{7}, CI_2 = \frac{2}{7}, CI_3 = \frac{1}{7}$ $\quad CI_1 = \frac{5}{8}, CI_2 = \frac{1}{8}, CI_3 = \frac{1}{8}, CI_4 = \frac{1}{8}$

$CI_p = \left(\frac{4}{7} - \frac{1}{7} \right) \times 5 \div 3 = \frac{5}{7}$ $\quad CI_p = \left(\frac{5}{8} - \frac{1}{8} \right) \times 6 \div 4 = \frac{3}{4}$

$$CI_1 = \frac{2}{6}, CI_2 = \frac{2}{6}, CI_3 = \frac{2}{6}$$

$$CI_p = \frac{2}{6} \times 4 \div 3 = \frac{4}{9}$$

$$CI_1 = \frac{4}{8}, CI_2 = \frac{4}{8}$$

$$CI_p = \frac{4}{8} \times 6 \div 2 = \frac{3}{2}$$

Figure 2. Computational examples for the degree of commonality index

Figure 2 illustrates the use of the CI measures for seven sets of two end products (labeled as A and B). Calculation of the CI is shown below each case. Here, we assume that all demands of products are same, i.e., $d_1 = d_2$.

5. Impact of Component Commonality on Integrated Supply Chain Performance

A multi-level inventory system is often controlled either by an installation stock reorder point policy or by an echelon stock reorder point policy. An *installation stock policy* means that ordering decisions at each installation are based exclusively on the inventory position at this installation. Here, *inventory position* means the stock on hand and on order minus the backlog. When using an echelon stock policy, ordering decisions at each installation are instead based on the echelon inventory position. The *echelon inventory position* is obtained by adding the installation inventory positions at the installation and all its down-stream installations. It is previously known that echelon stock policies dominate installation stock reorder point policies for serial and assembly multi-level inventory systems.

The purpose of the simulation study is to evaluate the performance of "integrated supply chain with component commonality" versus "integrated supply chain without component commonality." The simulation model for an integrated supply chain network with echelon stock policy and commonality index of 1 is shown in Figure 3. This simulation model is a comprehensive model since it contains raw material procurement, manufacturing processes, assembly operations, warehousing, and distribution functions.

Three different performance measures are employed in the experiment: order fill rate, delivery time and total cost. The experimental results for fill rate, delivery time, total cost and resource utilization rate are summarized in Table 1.

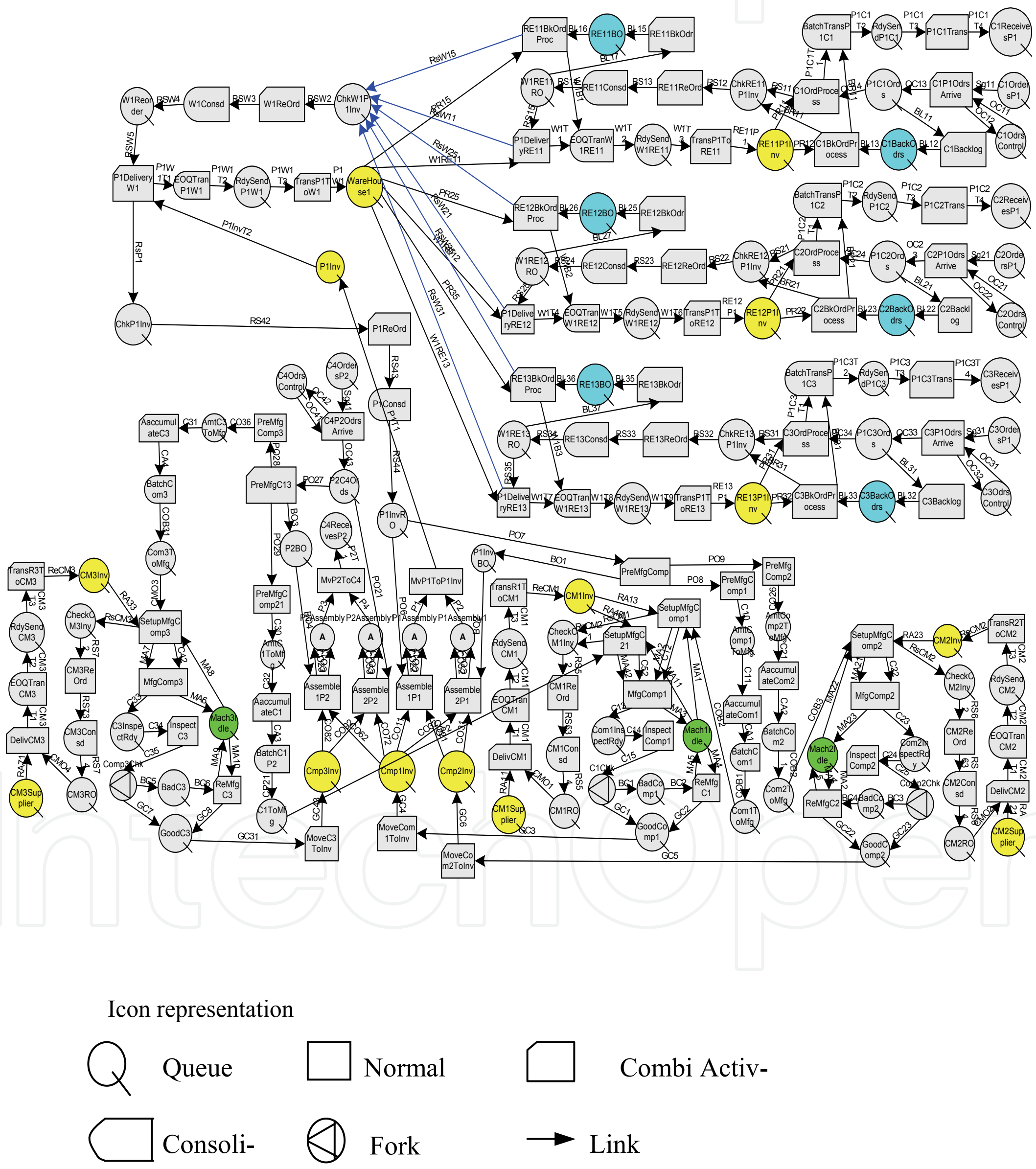


Figure 3. Simulation model for an integrated supply chain network with echelon stock policy and commonality index of 1

CI	Rep	Delivery	R1 Fill	R2 Fill	R3 Fill	M1UtilRate	M2UtilRate	M3UtilRate
	1	4223.63	0.918	0.952	0.918	0.981	0.952	0.901
	2	4250.13	0.882	0.963	0.940	0.976	0.947	0.903
	3	4222.55	0.915	0.964	0.897	0.981	0.952	0.867
	4	4230.74	0.911	0.956	0.934	0.979	0.950	0.917
	5	4240.48	0.881	0.952	0.942	0.977	0.949	0.911
	…	…	…	…	…	…	…	…
1	**496**	4175.87	0.918	0.939	0.971	0.991	0.962	0.888
	497	4207.11	0.960	0.953	0.888	0.984	0.956	0.889
	498	4228.98	0.929	0.966	0.888	0.980	0.952	0.879
	499	4260.51	0.934	0.960	0.888	0.973	0.944	0.899
	500	4249.00	0.956	0.945	0.916	0.976	0.947	0.916
	Me	4239.24	0.920	0.955	0.919	0.978	0.948	0.901
	SD	146.91	0.107	0.044	0.105	0.031	0.030	0.068
	1	8288.54	0.840	0.909	0.838	0.991	0.958	0.839
	2	8284.00	0.844	0.883	0.873	0.991	0.959	0.840
	3	8290.37	0.850	0.908	0.834	0.991	0.959	0.838
	4	8286.03	0.844	0.927	0.811	0.991	0.959	0.840
	5	8286.22	0.815	0.914	0.865	0.991	0.958	0.840
	…	…	…	…	…	…	…	…
1/6	**496**	8294.76	0.846	0.927	0.819	0.991	0.958	0.838
	497	8287.80	0.838	0.913	0.834	0.991	0.958	0.839
	498	8290.99	0.828	0.941	0.819	0.991	0.958	0.838
	499	8285.17	0.859	0.871	0.872	0.991	0.958	0.839
	500	8298.49	0.803	0.923	0.848	0.991	0.957	0.837
	Me	8294.51	0.816	0.939	0.829	0.991	0.958	0.838
	SD	18.14	0.072	0.069	0.077	0.001	0.003	0.003
	1	10211.95	0.758	0.908	0.775	0.686	0.778	1.000
	2	10208.29	0.728	0.904	0.785	0.686	0.778	1.000
	3	10198.74	0.761	0.895	0.761	0.687	0.779	1.000
	4	10206.93	0.762	0.907	0.767	0.686	0.779	1.000
	5	10202.91	0.760	0.904	0.778	0.687	0.778	1.000
	…	…	…	…	…	…	…	…
0	**496**	10212.09	0.745	0.906	0.767	0.685	0.777	1.000
	497	10208.49	0.722	0.896	0.802	0.686	0.778	1.000
	498	10202.85	0.747	0.902	0.802	0.686	0.779	1.000
	499	10203.70	0.763	0.894	0.781	0.686	0.778	1.000
	500	10201.42	0.746	0.918	0.772	0.686	0.779	1.000
	Me	10210.21	0.740	0.907	0.786	0.686	0.778	1.000
	SD	29.80	0.057	0.031	0.071	0.002	0.003	0.000

Table 1. Simulation results for fill rate, delivery time, and resource utilization rate

For each performance measurement, an analysis of variance (ANOVA) is conducted to compare the performance of "integrated supply chain with different component commonality indexes" and "integrated supply chain without component commonality." Here, the performance measures include delivery time and fill rates for different retailers. In the ANOVA, the level of confidence is set as $\alpha = 0.05$.

H_0: $\mu_1 = \mu_2 = \mu_3$.
H_1: At least two of the means are not equal.
The ANOVA are conducted as follows:

(1) Analysis-of-variance for delivery time

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
CI=1	500	2114450	4228.9	594.0537555
CI=1/6	500	4144618.5	8289.237	20.70920108
CI=0	500	5102868.5	10205.737	20.28362331

ANOVA

Source of Variation	*Sum of Squares*	*Degrees of Freedom*	*Mean Square*	*Computed f*	*P-value*	*f critical*
Between Groups	186272964.43	2	93136482.21	439982.602	1.18E-61	3.00
Within Groups	316888.24	1497	211.6821933			
Total	186589852.67	1499				

Table 2. Analysis-of-variance for delivery time

Decision: Since $P<0.05$, or computed $f > f_{critical}$, reject H_0 and conclude that the average delivery time are not all the same.
However, we still don't know which of the delivery-time means are equal and which are different. We need to perform the further multiple comparison tests. Here, we adopt Tukey's test (Walpole et al., 1997). This test allows formation of simultaneous 100(1-α)% confidence intervals for all paired comparisons. The method is based on the studentized range distribution.

From the analysis-of-variance table, we know that the error mean square is s^2= 211.68 (1497 degrees of freedom). The sample means are given by (ascending order):

4239.24, 8294.51, 10210.21

With α = 0.05, the value of $q(0.05, 3, 1497) = 3.32$. Thus all absolute differences are to be compared to

$$3.32\sqrt{\frac{211.68}{500}} = 2.16$$

As a result, the following represent means found to be significantly different using Tuksy's procedure:

1 and 2, 2 and 3, 1 and 3.

Therefore, we conclude that the delivery time of integrated supply chain with higher commonality index is significantly (with 95% C.I.) less than that of integrated supply chain with lower commonality index.

(2) Analysis-of-variance for retailers' fill rates

Anova: Single

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
CI=1	500	460.2	0.9204	0.00069449
CI=1/6	500	418.35	0.8367	0.00028468
CI=0	500	374.6	0.7492	0.00021218

ANOVA

Source of Varia-	*Sum of*	*Degrees of Freedom*	*Mean*	*Computed f*	*P-value*	*f criti-*
Between Groups	0.146571	2	0.073285633	184.545201	1.8E-16	3.00
Within Groups	0.59	1497	0.000397115			
Total	0.74	1499				

Table 3. Analysis-of-variance for retailer 1's fill rate

Decision: Since *P<0.05*, or computed $f > f_{critical}$, reject H_0 and conclude that the average fill rate for retailer 1 is not all the same.

The Tukey's test is conducted as follows.

From the analysis-of-variance table, we know that the error mean square is s^2= 0.000397 (1497 degrees of freedom). The sample means are given by (ascending order):

0.74, 0.816, 0.92

With α = 0.05, the value of $q(0.05, 3, 1497) = 3.32$. Thus all absolute differences are to be compared to

$$3.32\sqrt{\frac{0.000397}{500}} = 0.00296$$

As a result, the following represent means found to be significantly different using Tuksy's procedure:

1 and 2, 2 and 3, 1 and 3.

Similarly, for retailer 2, we have:

Anova: Single

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
CI=1	500	477.5	0.955	7.4444E-05
CI=1/6	500	455.8	0.9116	0.00044027
CI=0	500	451.7	0.9034	5.2267E-05

ANOVA

Source of Varia-	*Sum of*	*Degrees of*	*Mean Square*	*Computed f*	*P-value*	*f criti-*
Between Groups	0.015377867	2	0.007688933	40.6837815	7.1E-09	3.00
Within Groups	0.283	1497	0.000188993			
Total	0.298	1499				

Table 4. Analysis-of-variance for retailer 2's fill rate

Decision: Since *P<0.05*, or computed $f > f_{critical}$, reject H_0 and conclude that the average fill rate for retailer 2 is not all the same.

The Tukey's test is conducted as follows.

From the analysis-of-variance table, we know that the error mean square is s^2= 0.000189 (1497 degrees of freedom). The sample means are given by (ascending order):

0.907, 0.939, 0.955

With α = 0.05, the value of $q(0.05, 3, 1497) = 3.32$. Thus all absolute differences are to be compared to

$$3.32\sqrt{\frac{0.000189}{500}} = 0.00204$$

As a result, the following represent means found to be significantly different using Tuksy's procedure:

1 and 2, 2 and 3, 1 and 3.

For retailer 3, we have:

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
CI=1	500	459.1	0.9182	0.00080773
CI=1/6	500	420.65	0.8413	0.00050934
CI=0	500	389.5	0.779	0.00019733

ANOVA

Source of Variation	*Sum of Squares*	*Degrees of Freedom*	*Mean Square*	*Computed f*	*P-value*	*f critical*
Between Groups	0.097238467	2	0.048619233	96.313147	5.1E-13	3.00
Within Groups	0.756	1497	0.000504804			
Total	0.853	1499				

Table 5. Analysis-of-variance for retailer 3's fill rate

Decision: Since $P<0.05$, or computed $f > f_{critical}$, reject H_0 and conclude that the average fill rate for retailer 3 is not all the same.

The Tukey's test is conducted as follows.

From the analysis-of-variance table, we know that the error mean square is s^2= 0.0005048 (1497 degrees of freedom). The sample means are given by (ascending order):

0.786, 0.829, 0.919

With α = 0.05, the value of $q(0.05, 3, 1497) = 3.32$. Thus all absolute differences are to be compared to

$$3.32\sqrt{\frac{0.0005048}{500}} = 0.003336$$

As a result, the following represent means found to be significantly different using Tuksy's procedure:

1 and 2, 2 and 3, 1 and 3.

From the above analysis, it can be shown that the fill rates of retailers 1, 2 and 3 of the integrated supply chain with higher commonality index are significantly (with 95% C.I.) higher than those of retailers 1, 2 and 3 of the integrated supply chain with lower commonality index, respectively.
Therefore, the fill rates of integrated supply chain with higher commonality index are significantly (with 95% C.I.) higher than those of integrated supply chain with lower commonality index. Furthermore, the relative benefits from component commonality increase with the difference of commonality index values for two supply chain commonality configurations.

(3) Resource utilization rates

By comparing the machines' utilization rates for the network configurations with different degree of commonality (see Table 1), it can be shown that the integrated supply network with higher commonality index will generate more balanced machines' utilization rates than the one with lower commonality index.

6. Production Capacity Flexibility in Integrated Supply Chain Networks

6.1 Manufacturing Flexibility in Supply Chains

In terms of graph theory, a chain is a connected graph. Within a chain, a path can be traced from any product or machine to any other product or machine via the product assignment links. No product in a chain is manufactured by a machine from outside that chain; no machine in a chain produces a product from outside that chain (Jordan and Graves 1995, Graves and Tomlin 2003, Bish, Muriel and Biller 2005). Figure 4 shows different flexibility configurations for a four-product four-machine stage.

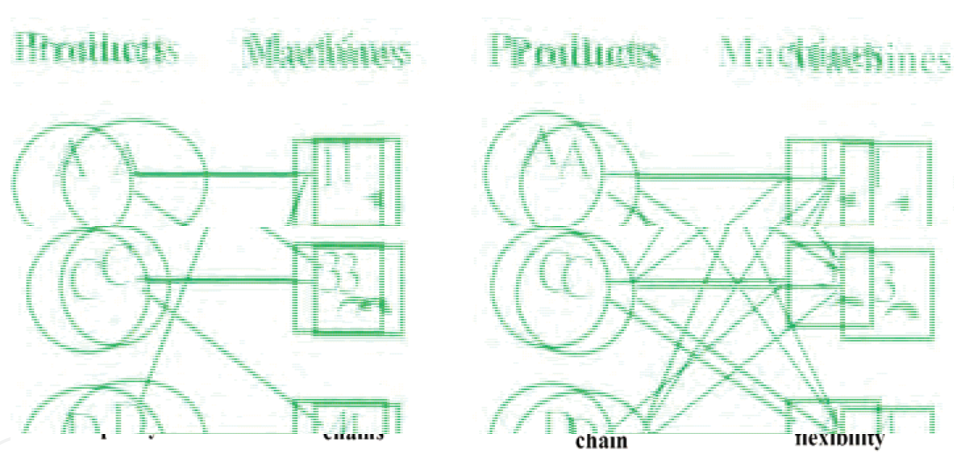


Figure 4. Configurations for manufacturing flexibility in supply chains

Jordan and Graves (1995) demonstrated that the complete chain configuration, in which all products and machines are contained in one chain and the chain is "closed," significantly outperforms the configuration with two distinct chains.
If demands are uncertain, multi-stage supply chains face an issue that does not arise in single-stage systems; the bottleneck stage can vary with demand, where the bottleneck stage is that stage that limits throughput. Therefore, one important issue in this research is to examine to what extent the findings of Jordan and Graves apply to multi-stage supply chains. In addition, this chapter

will also investigate the impact of manufacturing flexibility in integrated supply chain networks with different degree of component commonality.

6.2 Design of Experiments

The simulation model for an integrated supply chain network with echelon stock policy and "one complete chain" is shown in Figure 5. Two factors are considered in the simulation study, i.e., manufacturing flexibility and degree of commonality. The design points are described as follows: (1) levels for factor 1 (commonality index): 0 (-), 5/8 (+); and (2) levels for factor 2 (manufacturing flexibility): dedicated capacity (-), one complete chain (+).

First, the manufacturing capacity is assumed to be less than or equal to 75% expected demand. After 500 replications of runs, the simulation results are given as follows:

CI	Flexibility	R1 Fill Rate	R2 Fill Rate	R3 Fill Rate	M1UtilRate	M2UtilRate	M3UtilRate
5/8	One Complete Chain	0.906	0.952	0.944	0.679	0.653	0.663
	Dedicated Capacity	0.92	0.955	0.919	0.978	0.948	0.901
0	One Complete Chain	0.736	0.905	0.785	0.613	0.688	0.699
	Dedicated Capacity	0.74	0.907	0.786	0.686	0.778	1

Table 6. Simulation results for integrated supply chains with "one complete chain" and "dedicated capacity

The 2^k factorial design matrix is shown in the following Table:

Points	Factor 1 (C) Commonality	Factor 2 (F) Flexibility	Responses R1 Fill Rate	R2 Fill Rate	R3 Fill Rate
1	-	-	0.74	0.907	0.786
2	-	+	0.736	0.905	0.785
3	+	-	0.92	0.955	0.919
4	+	+	0.906	0.952	0.944
		$e_C =$	0.175	0.0475	0.146
		$e_F =$	-0.009	-0.0025	0.012
		$e_{CF} =$	-0.005	-0.0005	0.013

Table 7. 2^k factorial design matrix with “one complete chain” and “dedicated capacity” (low demand)

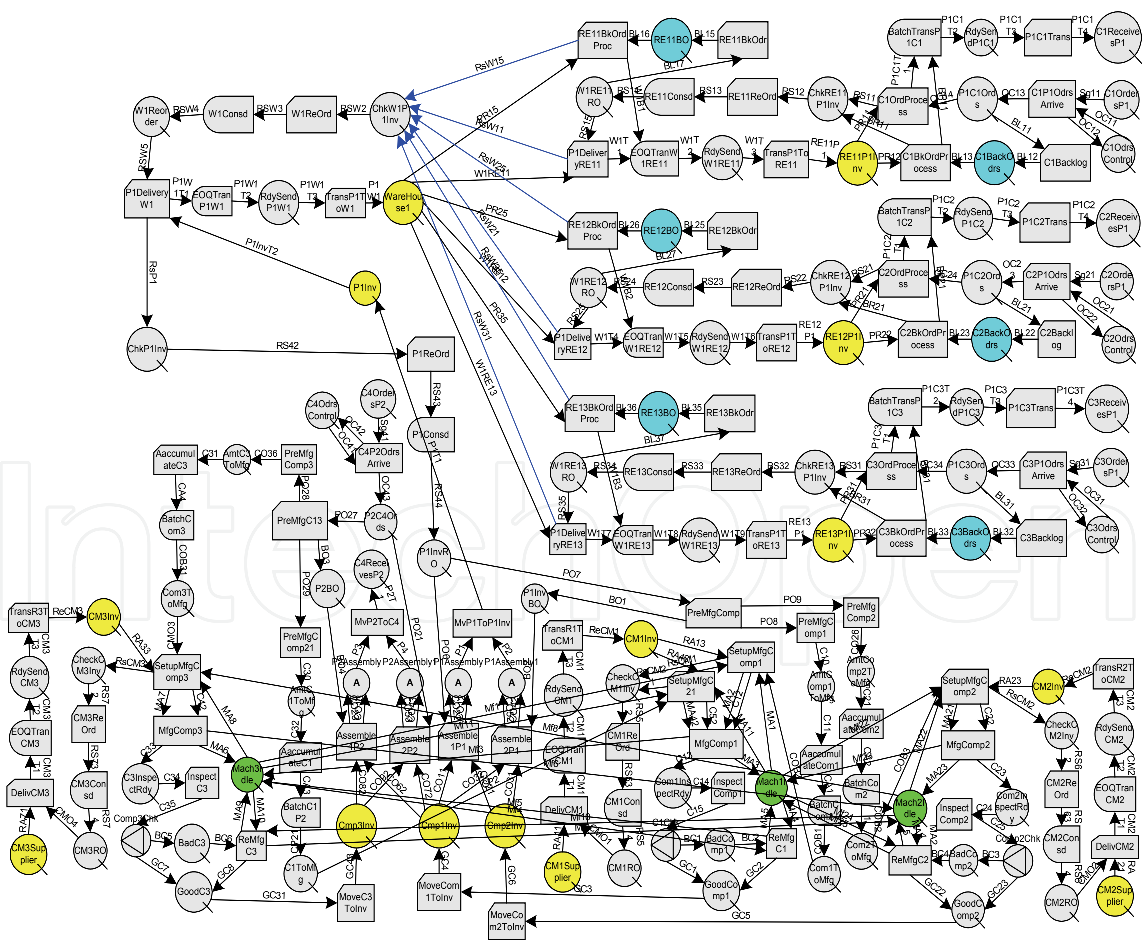


Figure 5. Simulation model for an integrated supply chain network with echelon stock policy and “one complete chain”

The average effect of increasing degree of commonality from 0 to 5/8 is to increase the retailer 1's fill rate by 0.175 (23.7%), increase retailer 2's fill rate by 0.0475 (5.24%) and increase retailer 3's fill rate by 0.146 (18.6%).
On the other hand, the average effect of changing manufacturing flexibility from "dedicated capacity" to "one complete chain" is to decrease the retailer 1's fill rate by 0.009 (1.1%), decrease retailer 2's fill rate by 0.0005 (0.27%) and increase retailer 3's fill rate by 0.013 (1.4%). Therefore, it can seen that, when manufacturing capacity is less than or equal to 75% expected demand, the effect of changing the manufacturing flexibility is not significant as changing the degree of commonality. The t-test shows that there is no significant (with 95% C.I.) difference on fill-rate performance between an integrated supply chain with "one complete chain" and an integrated supply chain with "dedicated capacity."
The interaction effect can be used to judge whether the effect of one factor depends on the levels of the others. The values of the interaction effect e_{CF} are very small and the corresponding t-test shows that 95% confidence interval for $C \times F$ contains zero. So degree of commonality and manufacturing flexibility are not interacting.
Similarly, the performance of integrated supply chains with "total flexibility" and "one complete chain" can be evaluated and compared as follows.

CI	Flexibility	R1 Fill Rate	R2 Fill Rate	R3 Fill Rate	M1UtilRate	M2UtilRate	M3UtilRate
5/8	One Complete Chain	0.906	0.952	0.944	0.679	0.653	0.663
	Total Flexibility	0.92	0.942	0.948	0.997	0.997	0.997
0	One Complete Chain	0.736	0.905	0.785	0.613	0.688	0.699
	Total Flexibility	0.747	0.906	0.776	1	1	1

Table 8. Simulation results for integrated supply chains with "one complete chain" and "total flexibility"

The design points are described as follows: (1) levels for factor 1 (commonality index): 0 (-), 5/8 (+); and (2) levels for factor 2 (manufacturing flexibility): one complete chain (-), total flexibility (+).

Design Points	Factor 1 (C) Commonality	Factor 2 (F) Flexibility	Responses R1 Fill Rate	R2 Fill Rate	R3 Fill Rate
1	-	-	0.736	0.905	0.785
2	-	+	0.747	0.906	0.776
3	+	-	0.906	0.952	0.944
4	+	+	0.92	0.942	0.948
		e_C =	0.1715	0.0415	0.1655
		e_F =	0.0125	-0.0045	-0.0025
		e_{CF} =	0.0015	-0.0055	0.0065

Table 9. 2^k factorial design matrix with "one complete chain" and "total flexibility" (low demand)

The average effect on fill-rate performance by changing manufacturing flexibility from "one complete chain" to "total flexibility" is less than 2%. Therefore, when manufacturing capacity is less than or equal to 75% expected demand, the effect of changing the manufacturing flexibility is not significant. The corresponding t-test shows that there is no significant (with 95% C.I.) difference on fill-rate performance between an integrated supply chain with "one complete chain" and an integrated supply chain with "total flexibility".
Furthermore, it can be observed that the utilization rates of machines become more balanced with the increase of manufacturing flexibility.
In the following, the manufacturing capacity is assumed to be approximately equal to expected demand. After 500 replications of runs, the simulation results are given as follows:

CI	Flexibility	R1 Fill Rate	R2 Fill Rate	R3 Fill Rate	M1UtilRate	M2UtilRate	M3UtilRate
5/8	Total Flexibility	0.913	0.942	0.972	1	1	1
	One Complete Chain	0.892	0.938	0.968	0.899	0.64	0.461
	Dedicated Capacity	0.835	0.884	0.888	0.668	1	0.184
0	Total Flexibility	0.811	0.903	0.834	1	1	1
	One Complete Chain	0.803	0.894	0.826	0.63	0.627	0.743
	Dedicated Capacity	0.744	0.863	0.769	0.999	0.687	0.992

Table 10. Simulation results for integrated supply chains with different flexibility configurations

The 2^k factorial design matrix is shown in the following Table:

Design Points	**Factor 1 (C) Commonality**	**Factor 2 (F) Flexibility**	**Responses R1 Fill Rate**	**R2 Fill Rate**	**R3 Fill Rate**
1	-	-	0.744	0.863	0.769
2	-	+	0.803	0.894	0.826
3	+	-	0.835	0.884	0.888
4	+	+	0.892	0.938	0.968
		e_C =	0.09	0.0325	0.1305
		e_F =	0.058	0.0425	0.0685
		e_{CF} =	-0.001	0.0115	0.0115

Table 11. 2^k factorial design matrix with "one complete chain" and "dedicated capacity" (equal demand)

The average effect of increasing degree of commonality from 0 to 5/8 is to increase the retailer 1's fill rate by 0.09 (11.6%), increase retailer 2's fill rate by 0.0325 (3.7%) and increase retailer 3's fill rate by 0.1305 (16.4%).

The average effect of changing manufacturing flexibility from "dedicated capacity" to "one complete chain" is to increase the retailer 1's fill rate by 0.058 (7.35%), increase retailer 2's fill rate by 0.0425 (4.87%) and increase retailer 3's fill rate by 0.0685 (8.27%). Therefore, it can seen that, when manufacturing capacity is approximately equal to expected demand, the effect of changing the manufacturing flexibility is significant. The t-test shows that there is a significant (with 95% C.I.) increase on fill-rate performance by changing from an integrated supply chain with "dedicated capacity" to an integrated supply chain with "one complete chain."

The values of the interaction effect e_{CF} are very small and the corresponding t-test shows that 95% confidence interval for C × F contains zero. So the degree of commonality and the manufacturing flexibility are not interacting.

Similarly, for equal demand situation, the performance of integrated supply chains with "total flexibility" and "one complete chain" can be evaluated and compared as follows.

Design Points	Factor 1 (C) Commonality	Factor 2 (F) Flexibility	Responses		
			R1 Fill Rate	R2 Fill Rate	R3 Fill Rate
1	-	-	0.803	0.894	0.826
2	-	+	0.811	0.903	0.834
3	+	-	0.892	0.938	0.968
4	+	+	0.913	0.942	0.972
		e_C =	0.0955	0.0415	0.14
		e_F =	0.0145	0.0065	0.006
		e_{CF} =	0.0065	-0.0025	-0.002

Table 12. 2^k factorial design matrix with "one complete chain" and "total flexibility" (equal demand)

The average effects (for three retailers) on fill-rate performance by changing manufacturing flexibility from "one complete chain" to "total flexibility" are less than 2%. Therefore, when manufacturing capacity is approximately equal to expected demand, the effect of changing the manufacturing flexibility is not significant. The corresponding t-test shows that there is no significant (with 95% C.I.) difference on fill-rate performance between an integrated supply chain with "one complete chain" and an integrated supply chain with "total flexibility."
Same as the low demand situation, it can be observed that the utilization rates of machines become more balanced with the increase of manufacturing flexibility.

7. Conclusions

Effective configuration of the supply chain networks is nowadays recognized as a key determinant of competitiveness and success for most manufacturing organizations. This paper focuses on the simulation study of integrated supply chain network configurations and performance analysis.
First, this paper presents an integrated modeling framework for supply chains that can be used to model the different network topologies such as serial, parallel, assembly and arborescent structures. Second, a component-based simulation modeling approach is suggested. The advantage of the component-based simulation framework is that the reconfiguration of supply chain networks for different design alternatives can be easily achieved. To keep the op-

erations at a high level of efficiency, in the presence of a large product variety, companies resort to certain strategies, important of which are product component standardization and machine flexibility. Component commonality can greatly reduce the inventory of a supply chain and improve its performance. Similarly machine flexibility would enable the machine process different operations and components, to keep a low machine idle time. In this research, design of experiments and Tukey's test are employed to investigate the effects of component commonality and manufacturing flexibility on supply chain performance criteria such as delivery time, fill rate and cost in an integrated environment.

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Manufacturing the Future

Edited by Vedran Kordic, Aleksandar Lazinica and Munir Merdan

ISBN 3-86611-198-3

Hard cover, 908 pages

Publisher Pro Literatur Verlag, Germany / ARS, Austria

Published online 01, July, 2006

Published in print edition July, 2006

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