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A systematic approach for supply chain improvement using design structure matrix

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Abstract Supply chain is a complex system that involves many system elements from various functional areas. Performance of a supply chain heavily depends on the effectiveness of communication and coordination among these system elements and functional areas. However, a large and complex supply chain usually makes it difficult to coordinate and thus degrades its performance. This paper focuses on the development of a systematic approach with the following objectives: (1) to identify and quantify the interactions among the system elements in a supply chain; (2) to decompose the large interdependent group of system elements into smaller and manageable sub-groups; and thus (3) to improve the structure of the supply chain system. A supply chain system is first decomposed into subsystems and system elements from which the interactions (i.e., independent, dependent and interdependent relationships) are studied and documented by design structure matrix (DSM). Next, the interaction strengths among the related system elements are quantified. Cluster analysis is used to decompose the large interdependent group into smaller ones in order to provide a better supply chain system structure. The effectiveness of this systematic approach is demonstrated by an illustrative example. The result shows that it is able to improve the system structure of a supply chain that will be useful for the supply chain reengineering.

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Introduction

In the modern manufacturing industry, supply chain management has become a critical issue for most manufacturing organizations to gain their competitive edge in today's market. Supply chain is a complex system that involves many system elements from various functional areas. Performance of a supply chain heavily depends on the effectiveness of communication and coordination among these system elements and functional areas. Due to the increasing complexity and size of supply chain in manufacturing industry, it is common that a system element is related or inter-related with dozens of the other elements within a supply chain. The effectiveness of communication decreases as the number of related elements increases. In addition, a large and complex supply chain usually makes it difficult to coordinate and thus degrades its performance. This motivates this study to develop a systematic approach that helps improve the system structure of a supply chain. The objectives of this research are three folds: (1) to identify and quantify the interactions (i.e., independent, dependent and interdependent relationships) among the system elements in a supply chain, so that the supply chain system designers and managers will have a clear view of the entire system; (2) to decompose the large interdependent group of system elements into smaller and manageable sub-groups that allow the closely related elements to communicate efficiently and efficiently; and thus (3) to improve the structure of the supply chain system.

Related literature review

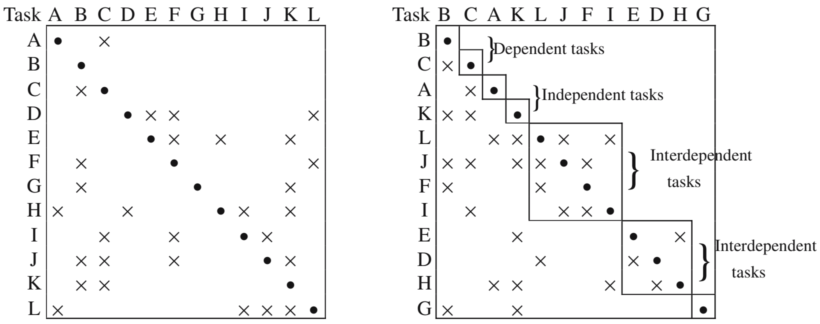
Supply chain system

Nowadays, more and more companies have become to realize that the efficiency of their supply chain management (SCM) is the key to survive in the competitive market. Supply chain today is not simply "chains" any more. With the fierce competition, increasing uncertainties, and market globalization, supply chain becomes a network with much more complexity than a chain (Srinivasan & Moon, 1999).

Although supply chain has gained much more attention than before, research in some areas of supply chain is still limited. O'Neil and Iveson (1992) noted that in the supply chain management literature, analytical models that incorporate many dimensions of a logistics strategy are rare. It was also noted that most of analytical models existing for logistics strategy evaluation include a focus on only one dimension of the logistics strategy. With the current development of supply chain and the increasing complexity in supply chain network, researchers begin to realize that they need to study the interaction of more dimensions of supply chain from a more systematic perspective. Some models with aggregate consideration were developed. Cohen and Lee (1998), in an analysis of integrated production–distribution systems, categorized four different modeling approaches using stochastic, deterministic and cost based models. However, these approaches were more descriptive than analytical and were not general approaches to be easily used in other circumstances. Beamon (1998), in a comprehensive analysis of various logistic chains, developed a list of decision variables to demonstrate the complexity of a general supply chain. Yan, Yu, and Cheng (2003) proposed a strategic production–distribution model for supply chain architecture with the consideration of bills of materials (BOM) and the relationships were formulated as logical constraints in a mixed integer-programming (MIP) model. Of particular interest was the model proposed by Scott, Mauricio, Farris, and Kirk, (2003) to integrate the distribution planning functions of supply chain and to examine the total cost benefits achieved through the increased global visibility provided by an integrated system. Experimental results demonstrated the potential for this integrated paradigm to improve customer service, save costs, and reduce lead-time variability. Cetinkaya & Bookbinder (2003) indicated that most studies on supply chain management have taken an inventory point of view, thus neglecting the issues of dynamics in logistics and missing important opportunities for cost savings, as cost is one of the most important performance measures in supply chain. From a systematic perspective, the coordination of distribution planning becomes imperative for cost reduction (Burley, 2002). Several other researchers have also recognized the need to integrate the logistic systems and developed theories and tools for integration (Cohen & Lee, 1989; Cooper, Ellram, Gardner, & Hanks,, 1997a; Cooper, Lambert, & Pagh, 1997b). The Supply Chain Operations Reference (SCOR) Model released by Supply Chain Council (SCC) in Supply Chain Council (1996) has been widely studied and used in research and industry. Researchers and practitioners have found the SCOR Model a good reference that integrates most of the business processes of an organization in a cross-functional framework. SCOR is based on five distinct management processes, namely Plan, Source, Produce, Deliver and Return. These five processes form the top level of the SCOR model. Each process is further decomposed into lower levels. Level two is called configuration level where a company implements its strategy by configurations. Level three is the process elements level to fine-tune the detailed operations. Level four is the implementation level that directly deals with the practices and activities. Recent research and models in supply chain reviewed above, as Burley (2002) remarked, have focused on the performance, design and analysis of supply chain as a whole. Romano (2003) commented that various literatures on supply chain have emphasized the importance of coordination and integration mechanisms to manage logistics processes across supply networks.

The systematic view of supply chain enables researchers to explore the weak links or the source of competitiveness of a network. From our literature review, it has been found that most research in supply chain and distribution systems can be improved by systems analysis, so that the organizational structure of a supply chain network and the interactions among system elements in the network can be better understood and thus enhanced. The computational model by Chandra and Fisher (1994), which examines the value of coordinating production and distribution planning, claimed the need for organizational changes in order to achieve effective coordination. Olsmats, Edghill, and Towill, (1988) utilized the input–output technique to build a simulation model to help integrate production and distribution systems. Stock, Greis, & Kasarda, (2000) augmented the need for integration by remarking that the emergence of globally dispersed and strategically aligned organizations has brought the new attention to how organizations coordinate the flows of information, materials, functions and products across the supply chains. The authors used a configuration approach to test whether the globally dispersed network organizations that adopted the practice of enterprise logistics are able to achieve a higher

Fig. 1 A binary design structure matrix



(a) Original binary matrix (unpartitioned) **(b)** Reordered binary matrix (partitioned)

organizational performance. The results indicated that enterprise logistics is a necessary tool for the coordination of supply chain operations. Chopra (2003) explored the possibilities in the design and selection of distribution network for a supply chain that contains various products with manufacturer storage, distributor storage, and retailer storage allowing for different types of delivery options. The results demonstrated that the integrated paradigm is able to improve efficiency and reduce lead-time variability. In addition, systems analysis also helped improve the flexibility and agility for supply chain network (Tsay, 1999; Chandra, 2001; Das & Abdel-Malek, 2003; Garavelli, 2003).

The recent Internet development has made it possible to improve the structure and effectiveness of supply chain management. Cetinkaya & Bookbinder (2003) pointed that e-commerce and the associated business-to-business have changed the way that a supply chain operates. The fast growth of the web-based technologies has shown researchers the perspective of changing supply chain structure by the new technologies. While technologies provide convenient access to the data through which we are able to control and monitor our supply chain network, applying such technologies without a systematic planning and integrated functionality can greatly increase the complexity of the flows within the network. The improper flows of information, materials and functions in supply chain can lead to excess inventory, increased lead-time, and decreased agility in responding customer demands.

Design structure matrix (DSM)

Design structure matrix (DSM) is a useful tool that is suitable for engineers to analyze a complex system by providing a clear view of the system as well as the interdependencies between its system elements. DSM is first introduced by Steward (1981) to analyze the process of engineering design. Figure 1 shows an example of DSM that is a square matrix with n rows and columns, and m non-zero elements, where n is the number of nodes, tasks or system elements and m is the number of edges or links of dependencies in the network of the system. If there is an edge from node i to node j, the value of element ij is a unity or a marked sign in the matrix, otherwise the value of the element is zero or empty. In DSM, information links among tasks are clearly revealed by the systematic mapping. For example, in Fig. 1(a), the non-zero elements in row D represent that task D will receive information input from task E, task F and task L before task D is started. Likewise, the non-zero elements in column A represent that task A will provide information output to task H and task L after task A is completed. According to Steward's partitioning algorithm, the task sequence on the row and on the column can be rearranged and then turn the original DSM into a well-organized manner in which three basic task types (independent, dependent, and interdependent tasks) are clearly revealed as shown in Fig. 1(b).

There are various research in the past regarding the systems decomposition and architecture for product design and development. Alexander (1964) described the design process by decomposing designs into minimally coupled groups. Base on the DSM technique, Steward (1981) and Eppinger, Whitney, Smith, and Gebala (1990)analyzed parameter-level interactions to create design parameter groupings that must be solved iteratively. Kusiak and Wang (1993) focused on the decomposition of DSM to structure tasks and parameters in the detailed design stage. Ulrich and Eppinger (1995) developed a method for product architecture, but interactions are considered only after the architecture is chosen. They defined several types of product architecture in terms of how functional elements are mapped onto physical components and related the strategic importance of architecture choice to firm performance. Smith and Eppinger (1997a,b) described decomposition as a fundamental approach to handling complexity in engineering design. Kusiak and wang (1993) used binary interactions to develop physical design layouts. Lovejoy (1992) related design decomposition to the organizational structure of complex product design processes. The author noted that an approach to solving complex problems lies in controlling the interactions between the elements. The author also proposed that interactions between elements in a design vary in strengths that relate to the speed of the development process. McCord and Eppinger (1993) used interactions between components to structure system teams in a development project. Chen and Lin (2002, 2003) quantified the task coupling strengths for the interdependent task group decomposition in a notion to simultaneously consider various downstream activities throughout the entire product life cycle. The authors further concluded that numerical DSM is more appropriate and efficient than binary DSM at revealing the interrelationships among system elements. From the research reviewed above, DSM is good at capturing the interactions or interrelationships among the system elements and grouping them according to their coupling strengths.

Pimmler and Eppinger (1994) analyzed the decomposition of product design by understanding the complex interactions between components of a design, which helps define the product architecture and organize the development teams. The authors proposed four types of interactions among the design tasks, such as spatial, energy, information and material interactions. Multiple DSMs were constructed based on each of these interaction types. Systems analysis can be performed either aggregately by combining different interaction types of DSMs together or separately on each interaction type of DSM, so that the underlying structure for a complex system will be better understood and revealed.

As for the purpose of decomposing large size of numerical coupling DSM, cluster analysis is useful to help cluster the strongly coupled tasks into the same group. Cluster analysis has been widely used by many researchers in clustering similar objects or data into groups that ensure the objects within a group are similar to one another (Chu, 1989; Duran & Odell, 1974; Everitt, 1980; Gordon, 1981; Hartigan, 1975; Kusiak, 1990). Chen and Lin (2003) provided a comprehensive review of clustering methods and proposed an approach to clustering a large coupling DSM into smaller and manageable sizes based on numerical coupling strengths. The authors compared two types of clustering methods (i.e., similarity coefficient methods and sorting-based algorithms) and concluded that similarity coefficient methods are more appropriate for clustering the numerical coupling DSM. The authors also introduced a performance measure, numerical interaction density (NDd) that measures the total coupling strength outside the block diagonal of DSM, to select the best solution from several alternatives after the clustering process.

In summary, the previous research in DSM has inspired a new way to effectively manage the large-scale systems such as supply chain. DSM helps identify the interdependencies within the supply chain network. Multiple dimensions of a given supply chain system can be characterized by several DSMs with different interaction types. Numerical DSM with quantifiable measures shows the various degrees of interactions among system elements in supply chain. Finally clustering technique helps to decompose a complex supply chain system into smaller and manageable components or sub-systems.

Methodology

Due to many interactions among system elements, designers and engineers of a supply chain system often have troubles with knowing which functional departments and members are involved in these interactions and how important these interactions are. What makes the problem even more difficult is that these interactions are hidden in different forms. From a system designer's perspective, these interactions must be understood before the structural design or improvement for a supply chain system can start. From the engineer's perspective, knowing the interactions will help understand the job relationships among a complex supply chain system.

In this paper, a systematic approach using DSM to capture the complex interactions, understand the underlying relationships among the system elements, and finally improve the supply chain structure is developed. Figure 2 provides an overview of the research framework. In the framework, a supply chain system is first decomposed into subsystems and system elements from which the interactions are studied and documented in a binary DSM, therefore the underlying structure of a complex supply chain can be better understood and analyzed. However the binary DSM assumes that all the interaction (or coupling) strengths between the related system elements are either "0" or "1", which provide only limited information. The related system elements, especially in a complex supply chain system, usually carry various degrees of coupling strengths. Therefore, the coupling strengths among the related system elements are quantified in the next. Different interaction types of DSMs (i.e., information, material and functional interactions) are each assigned a weight and then are combined into an aggregated numerical DSM. Clustering technique is applied to search for a better structure for the supply chain system, based on the Numerical Interaction Density (NDd) performance measure, so the strongly related subsystems or elements in the supply chain will be clustered into the same group. Results

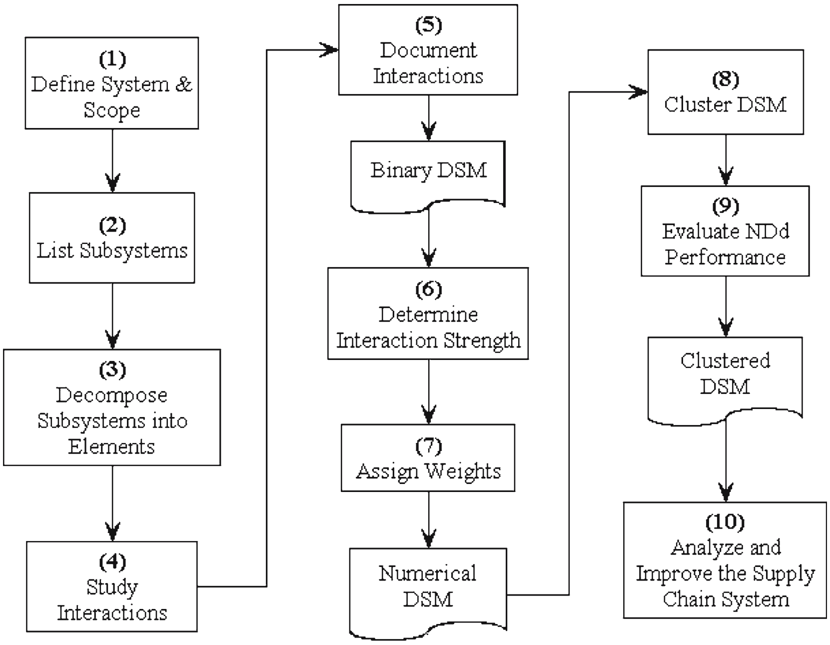


Fig. 2 The research framework

from this framework will be useful for the supply chain reengineering and improvement because the position of each system element in the supply chain and its relationships with the other elements are clearly shown.

Step 1: Define system and scope

Supply chain networks are complex systems that often consist of many enterprises or organizations. Studying and optimizing the interactions among organizations will greatly improve the performance of the entire network. Each organization has to handle both the inbound interactions among different functional departments within its own small-scaled supply chain system and the outbound interactions with the other entities in the entire supply chain network. The organizational structure of supply chains can be different from one to another. This paper focuses on the study of the inbound interactions of a supply chain system using DSM in order to improve the system's structure from the organizational perspective.

Step 2: List subsystems

Subsystems of an organization are always closely related with the organizational structure. Although there are different organizational structures, functional organization is the most common organizational structure used in businesses and projects (Badiru & Pulat, 1995). The structure of functional organization in terms of functional departments can usually be a good starting point for the list of subsystems, such as Plan, Source, Produce, Deliver and Return based on the top level of the SCOR model. In addition to these five functional areas, systems engineers also have to consider the other important resource constraints such as warehouse layout and personnel-related work. It is noted that the functions of warehousing are geographically separated from the other activities and are primarily performed in the warehouse. A considerable personnel-related work is spent on taking care of the customer orders. Therefore, the list of subsystems also includes Warehouse and Order.

Step 3: Decompose subsystems into elements

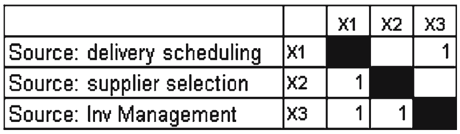
System elements are components of subsystems. For example, Sourcing Department has three major tasks in a business cycle: (1) schedule the arrival of raw materials; (2) choose suppliers from the available candidates in terms of price, quality, capacity, service and relationship; and (3) manage the material inventory. Therefore, the "Sourcing" subsystem can be decomposed into three key elements (or components): "Delivery Scheduling", "Supplier Selection" and "Inventory Management". To select a supplier, a list of qualified and available suppliers is made out and the price, quality, capacity and service of each supplier are evaluated for decision-making. Thus "Supplier Selection" can be further decomposed into several sub-components in the next lower level such as "Price Comparison", "Quality Control", "Capacity Evaluation" and "Service Level", etc. Any component from a subsystem can also be another subsystem to its lower level of sub-components. The level of details in the decomposition is system-dependent and is determined by the system scope in Step 1.

Step 4: Study interactions between elements

A supply chain can be viewed as a system that contains different types of input/output flows (i.e., business strategies, customer needs, information, materials/parts/products deliveries, functional requirements, management hierarchies, etc.). The business cycle and logistics of a supply chain system can be represented by various flows that link subsystems and elements together. The system elements of a supply chain interact with each other to facilitate the flows. For example, the three system elements “Delivery Scheduling”, “Supplier Selection” and “Inventory Management” not only work closely together to meet the functional requirements by the Sourcing Department, they also interact with the other elements from different departments. “Supplier Selection” has to work with “Delivery Scheduling” and “Inventory Management” in the same “Sourcing” subsystem in order to obtain the required/scheduled order release for the arrival times of incoming materials and to ensure the required materials are available. At the same time, “Supplier Selection” also needs to interact with the element of “Business Strategy” from the “Planning” subsystem to help determine the required quality and service level for choosing a better pricing strategy. Three important types of interactions/flows among system elements in a supply chain are information, material and functional interactions. Information interactions specify customer needs, pricing information, system status, and/or other information that is required to maintain the functionality of a supply chain element. Material interactions are the physical flows and processes from raw materials to finished parts/products. Functional interactions are the communication and coordination flows among different functional departments (e.g., to determine or change task due date, supplier, quality requirements, product design, material usage or other specifications). Functional interactions can be as general as setting a strategic goal for business or as detailed as making a slight change for product design. These interactions can be identified by interviewing managers and experts from different functional areas and task groups. In this step, the purpose is to identify the interactions, such as what elements are related to each other and what type of interactions it is between the related elements.

Step 5: Document interactions by DSM

The DSM technique is used here to document the interactions among system elements. Each system element is represented by one row and one corresponding column in DSM. An entry of “1” or “x” in the matrix at row *i* and column *j* means that element *i* requires an input from element *j*, while no entry means the two elements are not related to each other. The interactions of different types are recorded by three binary DSMs in terms of information, material and functional interactions. Figure 3 shows a simple DSM example for documenting the information interactions among three system elements under the subsystem “Source”. The two entries “1” in row X3 represent the system element X3 needs information inputs from the elements X1 and X2 before X3 can start. Similarly, the two entries “1” in column X1 represent the system element X1 has to provide information outputs to the elements X2 and X3 after X1 is completed.



		X1	X2	X3
Source: delivery scheduling	X1	■		1
Source: supplier selection	X2	1	■	
Source: Inv Management	X3	1	1	■

Fig. 3 Documenting interactions

Step 6: Determine interaction strengths

In this step, the strengths of interactions are studied in terms of frequency, effect and magnitude of dependencies. Each interaction is assigned a strength ranging from 0.0 to 1.0 by managers and experts based on their experience and expertise of the related elements. The scales shown in Fig. 4 help managers and experts to determine the ratings. A “complete” interaction receives a score of 1.0 and a 0.0 score is given if there is no interaction between the elements. A strong interaction is considered important or critical between the two-related elements, while a weak interaction may be considered optional. When all the interaction strengths are determined for each of the three interaction types (i.e., information, material and functional interactions), the numerical values of interaction strengths replace the marks (i.e., “1” or “x”) in each of the three binary DSMs developed in Step 5 accordingly.

Step 7: Assign weights

A weighted average $DSM_{i,j}$ combining the three interaction types of DSMs is calculated by the equation below:

$$DSM_{i,j} = W_a * A_{i,j} + W_b * B_{i,j} + W_c * C_{i,j} \tag{1}$$

Where:

$A_{i,j}, B_{i,j}$, and $C_{i,j}$ is the three numerical DSMs representing each of the following three interaction types respectively: information, material and function.

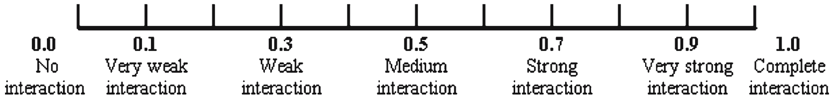


Fig. 4 Scales for determining the interaction strength

W_a, W_b, and W_c is weights for information, material and functional interactions respectively.

$W_a + W_b + W_c = 1.0.$

The weights will be assigned by a group of systems managers and designers after a heavy discussion and brainstorming. The weights to be assigned are dependent on each organization's focus area in the supply chain system. For example, in a manufacturing organization, the group may decide to assign a higher weight to the material interaction, while information interaction may be more important to a distribution organization. This step results in an integrated numerical DSM representing the aggregated interactions from three interaction types.

Step 8: Cluster DSM

Now that DSM has recorded the relationships among system elements, partitioning algorithm proposed by Steward (1981) can be performed to identify the interdependent groups of system elements. Research has concluded that the effectiveness of communication depends on the number of communication links among the related tasks or system elements. Therefore an effective and efficient communication will be difficult to achieve as the size of the interdependent group increases (Johnson & Johnson, 1991; Clark & Wheelwright, 1992; Carmel, 1994; Chung & Guinan, 1994; Lanigan, 1994). Chen and Lin (2002, 2003) realized that the large interdependent task groups usually make it difficult for task coordination and team organization and thus delay the project completion. The authors developed a model to decompose the large interdependent task group into smaller and manageable sub-groups based on numerical DSM and clustering technique. This decomposition model with the following two procedures will be used in this step (Chen & Lin, 2002, 2003):

(1) *Symmetrical task interaction matrix*: Since DSM is a matrix that only offers the information of task dependency for their 'from-to' descriptions, we need to further understand the task interaction by transforming numerical DSM into a symmetrical task interaction matrix for clustering purposes in the next step. If we assume that the input and output connections carry the same weight, the amount of interaction can be calculated by averaging each pair of symmetrical elements in a numerical DSM, because the interaction of any two tasks contain both information input and output connections. This symmetrical task interaction matrix, $Sym\text{-}DSM_{i,j}$, is expressed mathematically in the following for each pair of row *i* and column *j*:

$$SymDSM_{i,j} = (NumericalDSM_{i,j}+NumericalDSM_{j,i})/2 \quad (2)$$

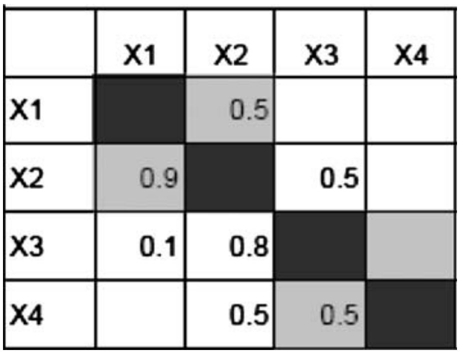
(2) *Decomposition of large interdependent group*: A large interdependent group is decomposed into smaller sub-groups using clustering technique. The key is to calculate the distance measures for the matrix. Quantified interaction strengths in the symmetrical matrix, $SymDSM_{i,j}$, are used to calculate the distance measures using Squared Euclidean Distance, which is able to handle both binary and numerical measures and is appropriate for numerical DSM. When clustering the elements, any two elements with the lowest distance measure are first grouped together before those elements with higher distance measures. Using a robust approach, the average-linkage method, clusters are formed by evaluating the interactions between all elements rather than only each pair of elements (i.e., the case with the single-linkage method). This method is robust to outliers, hence small changes of the coupling values in the matrix do not affect the clustering results.

Step 9: Evaluate cluster performance by Numerical Interaction Density (NDd)

For an n × n matrix, there are n-1 possible clustering results. To select the best solution from all possible clustering results, we need a performance measure to evaluate the clustering performance from each result and determine the final groups. Chen and Lin (2003) developed a performance measure, Numerical Interaction Density (NDd), to help select the best clustering result. *NDd*, measuring the numerical interaction strengths outside the block diagonal of the clustered matrix, is formulated as follows:

$$NDd = Ne/Outer - Cells \quad (3)$$

Where, *Ne* is the total coupling strengths outside the block diagonal of the clustered matrix.



	X1	X2	X3	X4
X1	■	0.5		
X2	0.9	■	0.5	
X3	0.1	0.8	■	▨
X4		0.5	0.5	■

Fig. 5 A simple example for the NDd calculation

Outer-Cells is total number of cells outside the block diagonal of the clustered matrix.

For example, a clustered matrix in Fig. 5 shows that elements X1 and X2 are clustered in the same group while elements X3 and X4 are in another group. The value of *Ne* is calculated by $(0.1 + 0.8 + 0.5 + 0.5) = 1.9$ and the number of *Outer-Cells* is 8, so that *NDd* is equal to $(1.9/8) = 0.2375$.

Step 10: Analyze and improve the supply chain system

DSM is easy to understand and can represent the important characteristics of a supply chain system both qualitatively and quantitatively. Steps 1–7 study and document three different types of interactions of a supply chain system, and then transform and combine the three binary DSMs into an integrated numerical DSM. Steps 8 and 9 cluster the large interdependent group into smaller and manageable sub-groups where the system elements with strong interaction strengths can work closely together.

The quantitative study of this paper can improve a supply chain system in several ways. First, the restructured DSM after clustering (Steps 8 and 9) provides a better and efficient scheme for organizing the functional departments and the supply chain elements. The system elements within the same cluster have stronger interactions and require much attention on communication and coordination among each other, so the supply chain designers may deploy these strongly related elements in the same department or as close as possible. In addition, since DSM is easy to understand and suitable to express the complex interactions among system elements, the use of DSM will help provide managers and engineers not only with a better understanding of the system interactions, but also with a clear view for the entire supply chain structure.

An illustrative example

This section shows the effectiveness of our research framework by an illustrative example.

System scope, sub-systems, and system elements

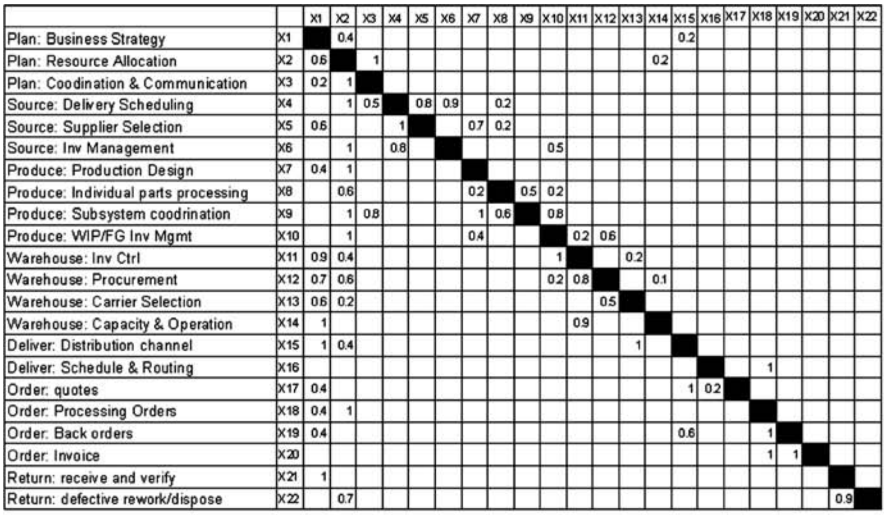
This section covers steps 1, 2 and 3 in the framework. The example uses a general supply chain model of a manufacturing organization with its own warehouse and distribution system. Considering the business cycle and the functional organization structure, the supply chain system is divided into 7 subsystems: Plan, Source, Produce, Warehouse, Deliver, Order and Return.

Planning is to provide a macro-view of the organization and to establish long-term and mid-term strategies and guidelines. Sourcing deals with acquisition, transportation and storage for raw materials. Production consists of design, manufacturing, subassembly and work-in-process management. Warehousing considers inventory control, procurement, carrier selection, capacity and operations. Delivery includes channel selection, scheduling and routing. Order involves quotes, order processing, back order handling and invoice. Returning is responsible for receiving and verifying the defects, and then reworking or disposal of the defects. Although any system elements under a subsystem can be further decomposed into sub-elements (or sub-components), this example focuses on one level of system elements instead of multiple levels for the illustrative purpose. There are 22 system elements (see Fig. 6) under 7 subsystems in this example.

Determine interactions and interaction strengths

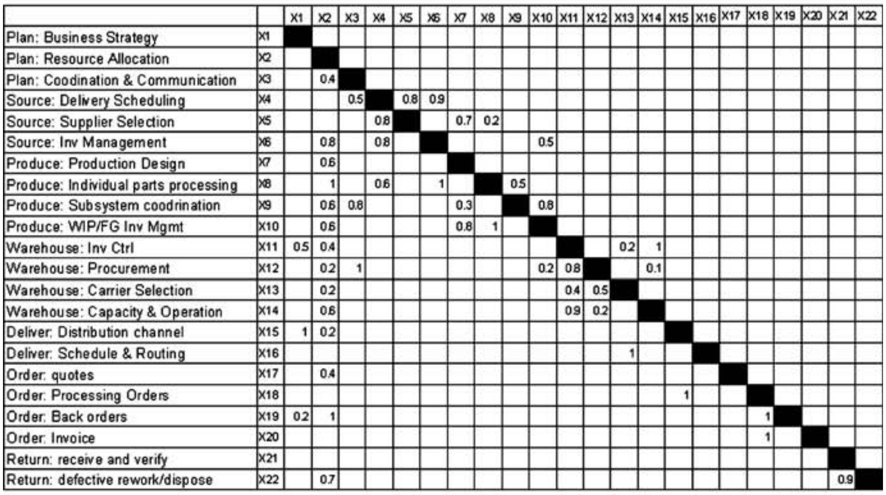
Steps 4, 5 and 6 in the research framework are carried out by interviewing managers and experts from each specific area to identify the interactions between elements and to determine the interaction strengths based on the scales developed in Step 6 of the framework. Managers from different functional departments (i.e., planning, sourcing, manufacturing, warehousing, delivering, order and return management, etc.) have experience and knowledge about their functional area. Their jobs mainly involve in coordinating tasks within their department and cooperating with the other departments. They know how the flows of information, material and functional work in their functional department and how they interact with the others. The experts are the system designers and engineers. They understand the entire big picture of the supply chain system. Their opinions serve as the direction or "future state" of the supply chain improvement. The outcomes are documented by

Fig. 6 Documenting the three types of interactions with numerical DSMs



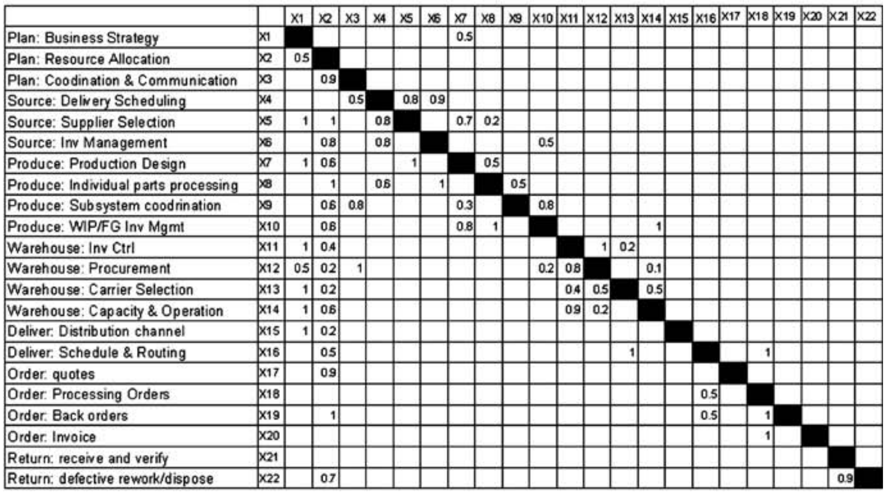
		X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15	X16	X17	X18	X19	X20	X21	X22
Plan: Business Strategy	X1	■	0.4													0.2							
Plan: Resource Allocation	X2	0.6	■	1											0.2								
Plan: Coodination & Communication	X3	0.2	1	■																			
Source: Delivery Scheduling	X4		1	0.5	■	0.8	0.9		0.2														
Source: Supplier Selection	X5	0.6			1	■		0.7	0.2														
Source: Inv Management	X6		1		0.8		■				0.5												
Produce: Production Design	X7	0.4	1					■															
Produce: Individual parts processing	X8		0.6					0.2	■	0.5	0.2												
Produce: Subsystem coodrination	X9		1	0.8				1	0.6	■	0.8												
Produce: WIP/FG Inv Mgmt	X10		1					0.4			■	0.2	0.6										
Warehouse: Inv Ctrl	X11	0.9	0.4								1	■		0.2									
Warehouse: Procurement	X12	0.7	0.6								0.2	0.8	■		0.1								
Warehouse: Carrier Selection	X13	0.6	0.2										0.5	■									
Warehouse: Capacity & Operation	X14	1										0.9			■								
Deliver: Distribution channel	X15	1	0.4											1		■							
Deliver: Schedule & Routing	X16																■		1				
Order: quotes	X17	0.4														1	0.2	■					
Order: Processing Orders	X18	0.4	1																■				
Order: Back orders	X19	0.4														0.6			1	■			
Order: Invoice	X20																		1	1	■		
Return: receive and verify	X21	1																				■	
Return: defective rework/dispose	X22		0.7																			0.9	■

(a) Numerical DSM of Information Interactions



		X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15	X16	X17	X18	X19	X20	X21	X22
Plan: Business Strategy	X1	■																					
Plan: Resource Allocation	X2		■																				
Plan: Coodination & Communication	X3		0.4	■																			
Source: Delivery Scheduling	X4			0.5	■	0.8	0.9																
Source: Supplier Selection	X5				0.8	■		0.7	0.2														
Source: Inv Management	X6		0.8		0.8		■				0.5												
Produce: Production Design	X7		0.6					■															
Produce: Individual parts processing	X8		1		0.6		1		■	0.5													
Produce: Subsystem coodrination	X9		0.6	0.8				0.3		■	0.8												
Produce: WIP/FG Inv Mgmt	X10		0.6					0.8	1		■												
Warehouse: Inv Ctrl	X11	0.5	0.4									■		0.2	1								
Warehouse: Procurement	X12		0.2	1							0.2	0.8	■		0.1								
Warehouse: Carrier Selection	X13		0.2									0.4	0.5	■									
Warehouse: Capacity & Operation	X14		0.6									0.9	0.2		■								
Deliver: Distribution channel	X15	1	0.2													■							
Deliver: Schedule & Routing	X16													1			■						
Order: quotes	X17		0.4															■					
Order: Processing Orders	X18															1			■				
Order: Back orders	X19	0.2	1																1	■			
Order: Invoice	X20																		1		■		
Return: receive and verify	X21																					■	
Return: defective rework/dispose	X22		0.7																			0.9	■

(b) Numerical DSM of Material Interactions



		X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15	X16	X17	X18	X19	X20	X21	X22
Plan: Business Strategy	X1	■						0.5															
Plan: Resource Allocation	X2	0.5	■																				
Plan: Coodination & Communication	X3		0.9	■																			
Source: Delivery Scheduling	X4			0.5	■	0.8	0.9																
Source: Supplier Selection	X5	1	1		0.8	■		0.7	0.2														
Source: Inv Management	X6		0.8		0.8		■				0.5												
Produce: Production Design	X7	1	0.6			1		■	0.5														
Produce: Individual parts processing	X8		1		0.6		1		■	0.5													
Produce: Subsystem coodrination	X9		0.6	0.8				0.3		■	0.8												
Produce: WIP/FG Inv Mgmt	X10		0.6					0.8	1		■				1								
Warehouse: Inv Ctrl	X11	1	0.4									■	1	0.2									
Warehouse: Procurement	X12	0.5	0.2	1							0.2	0.8	■		0.1								
Warehouse: Carrier Selection	X13	1	0.2									0.4	0.5	■	0.5								
Warehouse: Capacity & Operation	X14	1	0.6									0.9	0.2		■								
Deliver: Distribution channel	X15	1	0.2													■							
Deliver: Schedule & Routing	X16		0.5											1			■		1				
Order: quotes	X17		0.9															■					
Order: Processing Orders	X18																0.5		■				
Order: Back orders	X19		1														0.5		1	■			
Order: Invoice	X20																		1		■		
Return: receive and verify	X21																					■	
Return: defective rework/dispose	X22		0.7																			0.9	■

(c) Numerical DSM of Functional Interactions

DSM with numerical interaction strengths. For example, Fig. 6(a) shows that the element "Source: Supplier Selection (X5)" requires "complete" information input from the element "Source: Delivery Scheduling (X4)" with a 1.0 interaction strength, while the element "Warehouse: Procurement (X12)" only needs "very week" information input from the element "Warehouse: Capacity & Operation (X14)" with a 0.1 interaction strength. Following the same way, the interactions among system elements in the forms of information, material and function are recorded by three DSMs, respectively. Figure 6 shows the results of these three numerical DSMs after each type of interactions and the corresponding interaction strengths are identified and determined by the managers and experts.

Assign weights

In this step, the three numerical DSMs from Fig. 6 are combined into an aggregated DSM by assigning a weight to each interaction type. For example, the DSM with information interactions is given a 0.5 weight because the managers and experts consider the information flows are to be more important than the other two interaction types in the supply chain system. The other two interaction types, material and functional interactions, are assigned weights of 0.3 and 0.2 respectively in this example. With the weights assigned, the value of each row i and column j in the aggregated numerical DSM is calculated by Eq. (1):

$$\begin{aligned} AggregateDSM_{i,j} = {} & InformationDSM_{i,j} * 0.5 \\ & + Material_{i,j} * 0.3 \\ & + FunctionDSM_{i,j} * 0.2 \end{aligned}$$

For example, the value of row X1 and column X2 in the aggregated DSM is calculated by $(0.4 \times 0.5 + 0.0 \times 0.3 + 0.0 \times 0.2) = 0.2$. Figure 7 shows the aggregated numerical DSM.

Partition, cluster system elements and evaluate

According to the partitioning algorithm (Steward, 1981), system elements in the aggregated numerical DSM are rearranged to a partitioned DSM shown in Fig. 8 where the independent, dependent, and interdependent elements are revealed. Handling independent elements is easy because the elements can be completed in any order without affecting each other. Dealing with dependent elements is also straightforward since they can be performed sequentially. The most challenge to managers and engineers arises from the interdependent elements due to iterations.

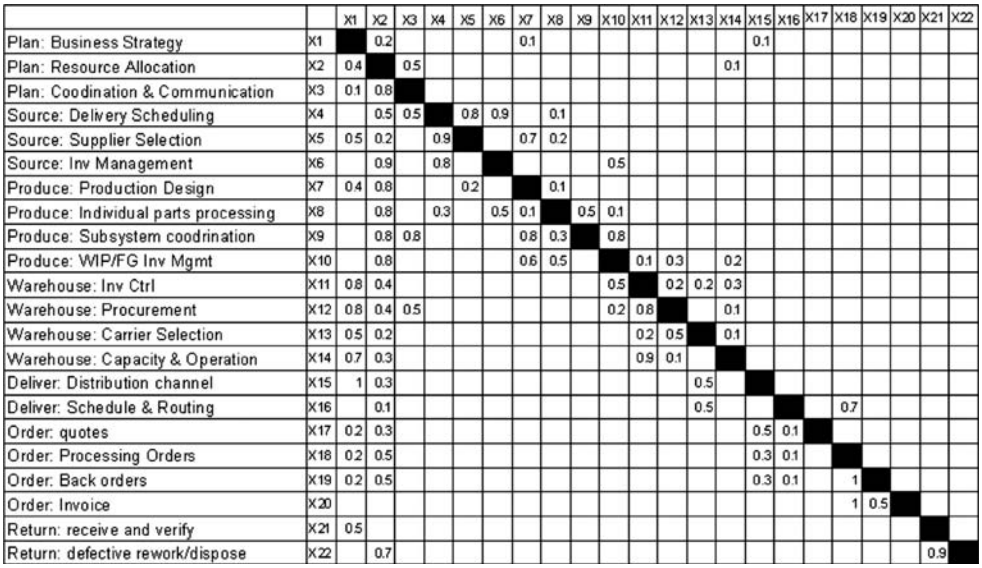
The partitioned DSM results in two interdependent groups shown by the shaded areas in Fig. 8. One of the groups contains 15 elements, which is large and complex to handle. Further decomposition of this large interdependent group into smaller and manageable sizes is recommended. The decomposition follows two procedures (Chen & Lin, 2002, 2003):

1) *Symmetrical task interaction matrix*: Figure 9 shows the result of the first procedure that converts the 15-element large interdependent group of numerical DSM into a "symmetrical matrix" based on Eq. (2). For example, the value in $SymDSM_{2,3}$ is equal to $(NumericalDSM_{2,3}+NumericalDSM_{3,2})/2 = (0.5+0.8)/2 = 0.65$.
2) *Decomposition of large interdependent group*: Squared Euclidean Distance and the average-linkage method are used to help decompose the 15-element large interdependent group into smaller ones. The average-linkage method clusters the elements hierarchically, beginning with each element in an individual cluster and continues to join clusters until all 15 elements have been joined into one cluster. Figure 10 shows the "Dendrogram" containing 14 possible clustering results generated by Minitab. The higher the similarity measure (or the lower the distance measure) between two elements, the more likely they should be put in the same cluster.

Since there are 14 possible clustering results, to select the best one, the NDd performance measure using Eq. (3) helps evaluate the clustering performance from each of the 14 results. For example, Fig. 11 shows one possible clustering result ($NDd = 0.0708$) with 2 clusters where three elements X4, X5 and X6 are put in the first cluster and the rest of 12 elements are in the second cluster. Consequently, the 15-element interdependent group is decomposed into three smaller groups shown in Fig. 12 that yields the lowest NDd value, 0.0681.

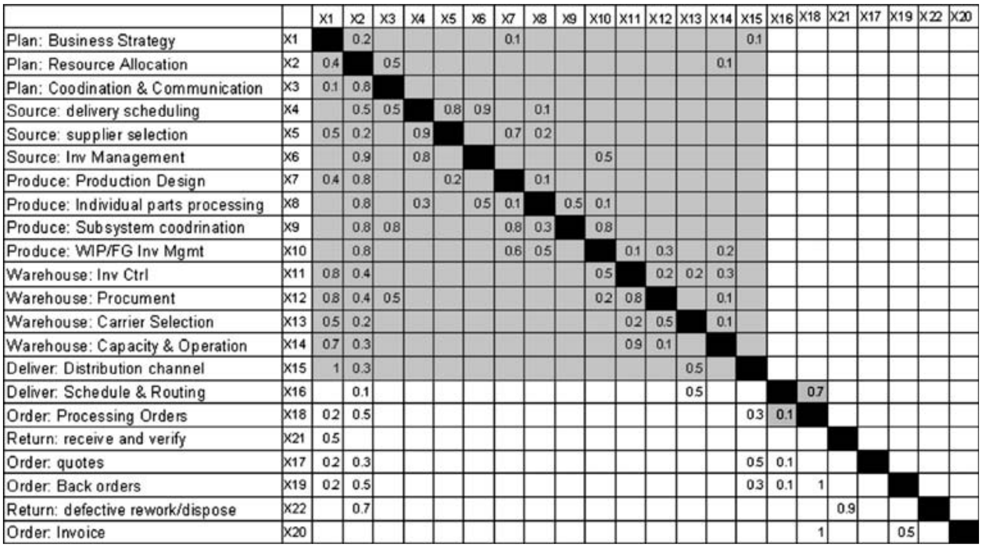
Analyze the results and improve the supply chain system

According to our research framework, the original supply chain system in the example is documented by different interaction types of DSMs (Fig. 6), which are then combined into an aggregated numerical DSM (Fig. 7). The aggregated numerical DSM is partitioned to reveal the interdependent groups in the matrix. Finally this supply chain system example is restructured and improved by decomposing the large interdependent group into smaller and manageable sub-groups as shown in Fig. 13.



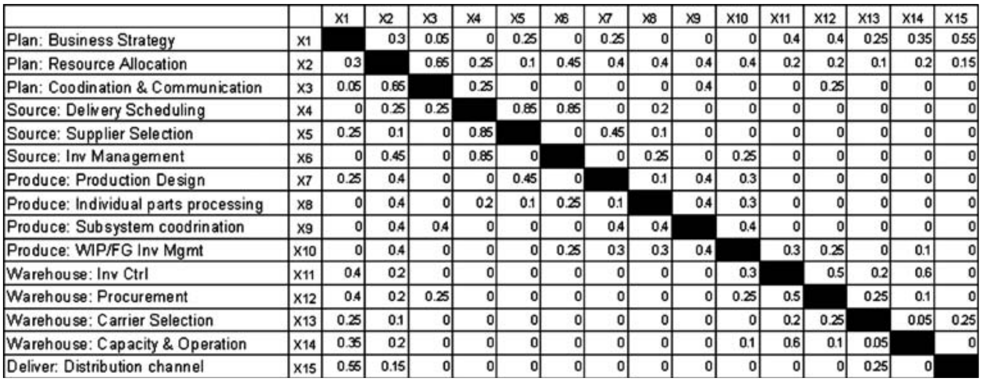
		X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15	X16	X17	X18	X19	X20	X21	X22
Plan: Business Strategy	X1	■	0.2					0.1								0.1							
Plan: Resource Allocation	X2	0.4	■	0.5											0.1								
Plan: Coodination & Communication	X3	0.1	0.8	■																			
Source: Delivery Scheduling	X4		0.5	0.5	■	0.8	0.9		0.1														
Source: Supplier Selection	X5	0.5	0.2		0.9	■		0.7	0.2														
Source: Inv Management	X6		0.9		0.8		■				0.5												
Produce: Production Design	X7	0.4	0.8			0.2		■	0.1														
Produce: Individual parts processing	X8		0.8		0.3		0.5	0.1	■	0.5	0.1												
Produce: Subsystem coodrination	X9		0.8	0.8				0.8	0.3	■	0.8												
Produce: WIP/FG Inv Mgmt	X10		0.8					0.6	0.5		■	0.1	0.3		0.2								
Warehouse: Inv Ctrl	X11	0.8	0.4								0.5	■	0.2	0.2	0.3								
Warehouse: Procurement	X12	0.8	0.4	0.5							0.2	0.8	■		0.1								
Warehouse: Carrier Selection	X13	0.5	0.2									0.2	0.5	■	0.1								
Warehouse: Capacity & Operation	X14	0.7	0.3									0.9	0.1		■								
Deliver: Distribution channel	X15	1	0.3											0.5		■							
Deliver: Schedule & Routing	X16		0.1											0.5			■		0.7				
Order: quotes	X17	0.2	0.3													0.5	0.1	■					
Order: Processing Orders	X18	0.2	0.5													0.3	0.1		■				
Order: Back orders	X19	0.2	0.5													0.3	0.1		1	■			
Order: Invoice	X20																		1	0.5	■		
Return: receive and verify	X21	0.5																				■	
Return: defective rework/dispose	X22		0.7																			0.9	■

Fig. 7 The aggregated numerical DSM



		X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15	X16	X18	X21	X17	X19	X22	X20
Plan: Business Strategy	X1	■	0.2					0.1								0.1							
Plan: Resource Allocation	X2	0.4	■	0.5											0.1								
Plan: Coodination & Communication	X3	0.1	0.8	■																			
Source: delivery scheduling	X4		0.5	0.5	■	0.8	0.9		0.1														
Source: supplier selection	X5	0.5	0.2		0.9	■		0.7	0.2														
Source: Inv Management	X6		0.9		0.8		■				0.5												
Produce: Production Design	X7	0.4	0.8			0.2		■	0.1														
Produce: Individual parts processing	X8		0.8		0.3		0.5	0.1	■	0.5	0.1												
Produce: Subsystem coodrination	X9		0.8	0.8				0.8	0.3	■	0.8												
Produce: WIP/FG Inv Mgmt	X10		0.8					0.6	0.5		■	0.1	0.3		0.2								
Warehouse: Inv Ctrl	X11	0.8	0.4								0.5	■	0.2	0.2	0.3								
Warehouse: Procument	X12	0.8	0.4	0.5							0.2	0.8	■		0.1								
Warehouse: Carrier Selection	X13	0.5	0.2									0.2	0.5	■	0.1								
Warehouse: Capacity & Operation	X14	0.7	0.3									0.9	0.1		■								
Deliver: Distribution channel	X15	1	0.3											0.5		■							
Deliver: Schedule & Routing	X16		0.1											0.5			■	0.7					
Order: Processing Orders	X18	0.2	0.5													0.3	0.1	■					
Return: receive and verify	X21	0.5																	■				
Order: quotes	X17	0.2	0.3													0.5	0.1			■			
Order: Back orders	X19	0.2	0.5													0.3	0.1	1			■		
Return: defective rework/dispose	X22		0.7																0.9			■	
Order: Invoice	X20																	1			0.5		■

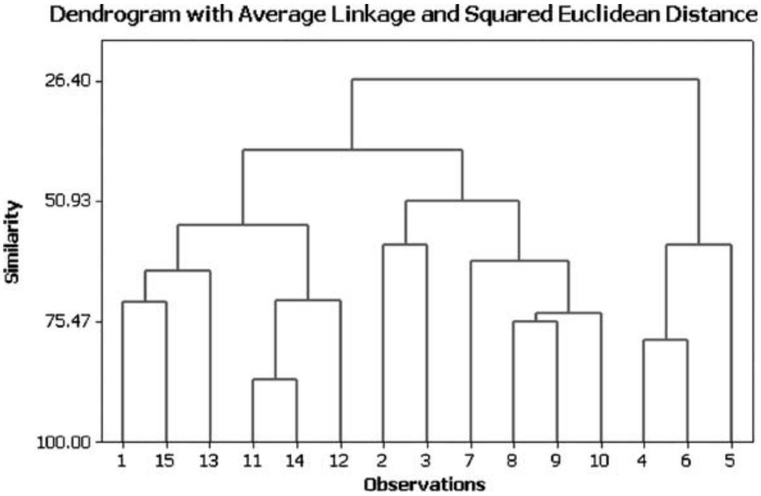
Fig. 8 The aggregated numerical DSM after Partitioning

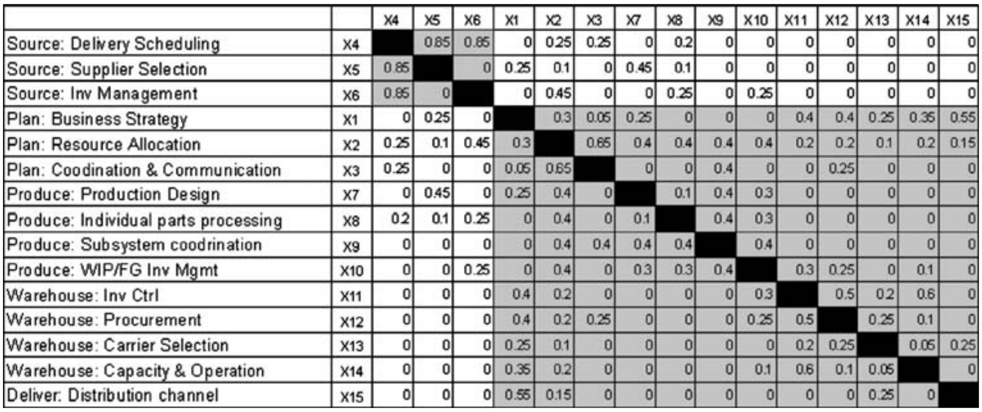


		X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15
Plan: Business Strategy	X1	■	0.3	0.05	0	0.25	0	0.25	0	0	0	0.4	0.4	0.25	0.35	0.55
Plan: Resource Allocation	X2	0.3	■	0.65	0.25	0.1	0.45	0.4	0.4	0.4	0.4	0.2	0.2	0.1	0.2	0.15
Plan: Coodination & Communication	X3	0.05	0.65	■	0.25	0	0	0	0	0.4	0	0	0.25	0	0	0
Source: Delivery Scheduling	X4	0	0.25	0.25	■	0.85	0.85	0	0.2	0	0	0	0	0	0	0
Source: Supplier Selection	X5	0.25	0.1	0	0.85	■	0	0.45	0.1	0	0	0	0	0	0	0
Source: Inv Management	X6	0	0.45	0	0.85	0	■	0	0.25	0	0.25	0	0	0	0	0
Produce: Production Design	X7	0.25	0.4	0	0	0.45	0	■	0.1	0.4	0.3	0	0	0	0	0
Produce: Individual parts processing	X8	0	0.4	0	0.2	0.1	0.25	0.1	■	0.4	0.3	0	0	0	0	0
Produce: Subsystem coodrination	X9	0	0.4	0.4	0	0	0	0.4	0.4	■	0.4	0	0	0	0	0
Produce: WIP/FG Inv Mgmt	X10	0	0.4	0	0	0	0.25	0.3	0.3	0.4	■	0.3	0.25	0	0.1	0
Warehouse: Inv Ctrl	X11	0.4	0.2	0	0	0	0	0	0	0	0.3	■	0.5	0.2	0.6	0
Warehouse: Procurement	X12	0.4	0.2	0.25	0	0	0	0	0	0	0.25	0.5	■	0.25	0.1	0
Warehouse: Carrier Selection	X13	0.25	0.1	0	0	0	0	0	0	0	0	0.2	0.25	■	0.05	0.25
Warehouse: Capacity & Operation	X14	0.35	0.2	0	0	0	0	0	0	0	0.1	0.6	0.1	0.05	■	0
Deliver: Distribution channel	X15	0.55	0.15	0	0	0	0	0	0	0	0	0	0	0.25	0	■

Fig. 9 The symmetrical DSM for the 15-element large interdependent group

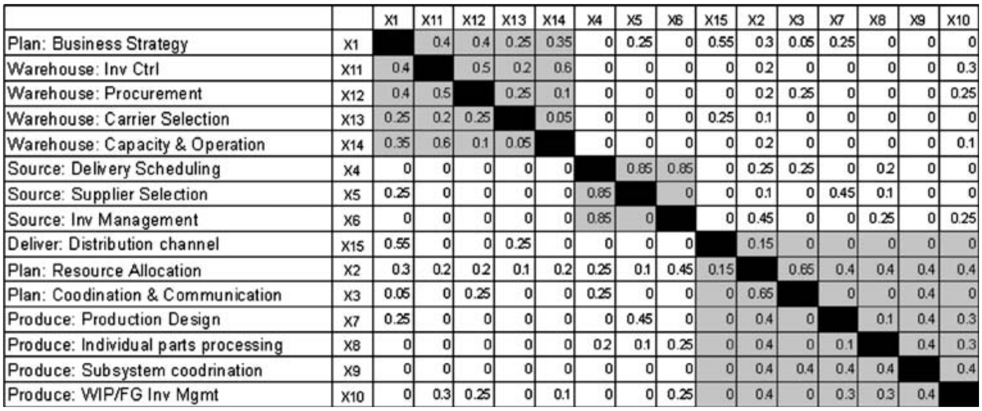
Fig. 10 Dendrogram of the clustering results by Minitab





		X4	X5	X6	X1	X2	X3	X7	X8	X9	X10	X11	X12	X13	X14	X15
Source: Delivery Scheduling	X4		0.85	0.85	0	0.25	0.25	0	0.2	0	0	0	0	0	0	0
Source: Supplier Selection	X5	0.85		0	0.25	0.1	0	0.45	0.1	0	0	0	0	0	0	0
Source: Inv Management	X6	0.85	0		0	0.45	0	0	0.25	0	0.25	0	0	0	0	0
Plan: Business Strategy	X1	0	0.25	0		0.3	0.05	0.25	0	0	0	0.4	0.4	0.25	0.35	0.55
Plan: Resource Allocation	X2	0.25	0.1	0.45	0.3		0.65	0.4	0.4	0.4	0.4	0.2	0.2	0.1	0.2	0.15
Plan: Coodination & Communication	X3	0.25	0	0	0.05	0.65		0	0	0.4	0	0	0.25	0	0	0
Produce: Production Design	X7	0	0.45	0	0.25	0.4	0		0.1	0.4	0.3	0	0	0	0	0
Produce: Individual parts processing	X8	0.2	0.1	0.25	0	0.4	0	0.1		0.4	0.3	0	0	0	0	0
Produce: Subsystem coodrination	X9	0	0	0	0	0.4	0.4	0.4	0.4		0.4	0	0	0	0	0
Produce: WIP/FG Inv Mgmt	X10	0	0	0.25	0	0.4	0	0.3	0.3	0.4		0.3	0.25	0	0.1	0
Warehouse: Inv Ctrl	X11	0	0	0	0.4	0.2	0	0	0	0	0.3		0.5	0.2	0.6	0
Warehouse: Procurement	X12	0	0	0	0.4	0.2	0.25	0	0	0	0.25	0.5		0.25	0.1	0
Warehouse: Carrier Selection	X13	0	0	0	0.25	0.1	0	0	0	0	0	0.2	0.25		0.05	0.25
Warehouse: Capacity & Operation	X14	0	0	0	0.35	0.2	0	0	0	0	0.1	0.6	0.1	0.05		0
Deliver: Distribution channel	X15	0	0	0	0.55	0.15	0	0	0	0	0	0	0	0.25	0	

Fig. 11 One possible clustering result with 2 clusters



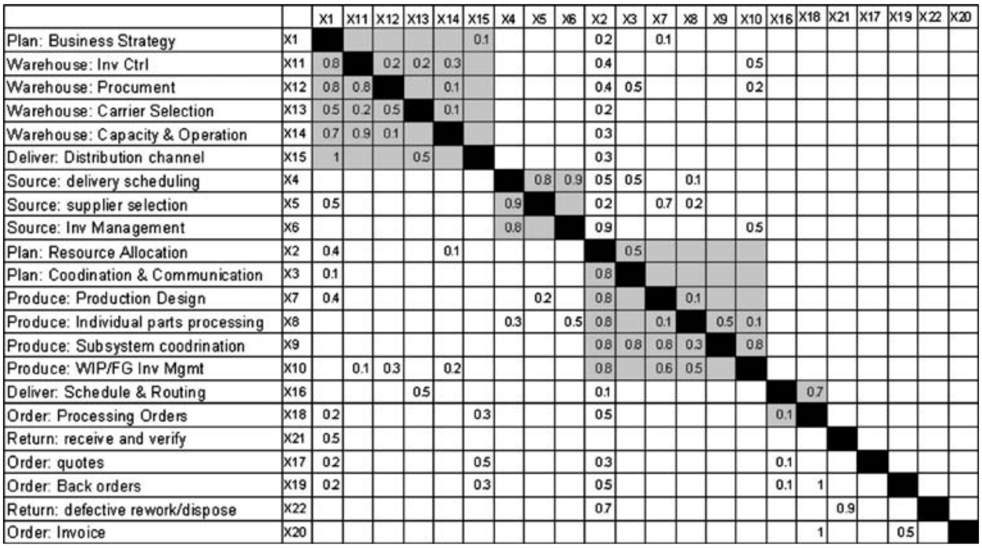
		X1	X11	X12	X13	X14	X4	X5	X6	X15	X2	X3	X7	X8	X9	X10
Plan: Business Strategy	X1		0.4	0.4	0.25	0.35	0	0.25	0	0.55	0.3	0.05	0.25	0	0	0
Warehouse: Inv Ctrl	X11	0.4		0.5	0.2	0.6	0	0	0	0	0.2	0	0	0	0	0.3
Warehouse: Procurement	X12	0.4	0.5		0.25	0.1	0	0	0	0	0.2	0.25	0	0	0	0.25
Warehouse: Carrier Selection	X13	0.25	0.2	0.25		0.05	0	0	0	0.25	0.1	0	0	0	0	0
Warehouse: Capacity & Operation	X14	0.35	0.6	0.1	0.05		0	0	0	0	0.2	0	0	0	0	0.1
Source: Delivery Scheduling	X4	0	0	0	0	0		0.85	0.85	0	0.25	0.25	0	0.2	0	0
Source: Supplier Selection	X5	0.25	0	0	0	0	0.85		0	0	0.1	0	0.45	0.1	0	0
Source: Inv Management	X6	0	0	0	0	0	0.85	0		0	0.45	0	0	0.25	0	0.25
Deliver: Distribution channel	X15	0.55	0	0	0.25	0	0	0	0		0.15	0	0	0	0	0
Plan: Resource Allocation	X2	0.3	0.2	0.2	0.1	0.2	0.25	0.1	0.45	0.15		0.65	0.4	0.4	0.4	0.4
Plan: Coodination & Communication	X3	0.05	0	0.25	0	0	0.25	0	0	0	0.65		0	0	0.4	0
Produce: Production Design	X7	0.25	0	0	0	0	0	0.45	0	0	0.4	0		0.1	0.4	0.3
Produce: Individual parts processing	X8	0	0	0	0	0	0.2	0.1	0.25	0	0.4	0	0.1		0.4	0.3
Produce: Subsystem coodrination	X9	0	0	0	0	0	0	0	0	0	0.4	0.4	0.4	0.4		0.4
Produce: WIP/FG Inv Mgmt	X10	0	0.3	0.25	0	0.1	0	0	0.25	0	0.4	0	0.3	0.3	0.4	

Fig. 12 The best clustering result with the lowest NDd value

Numerical DSM reveals and records the interactions and their strengths for the related system elements that can be helpful for the supply chain system in several perspectives:

(1) DSM is easy to learn and understand. Managers and engineers can easily detect the related and/or interdependent elements for a supply chain system by looking at the DSM matrix. Therefore the system can be better understood and the system improvement can focus on those closely related elements.

(2) For a supply chain business cycle, DSM is useful to identify the flows or sequences of the system elements. As shown in Fig. 13, the elements near the bottom of DSM will need inputs from those related



		X1	X11	X12	X13	X14	X15	X4	X5	X6	X2	X3	X7	X8	X9	X10	X16	X18	X21	X17	X19	X22	X20
Plan: Business Strategy	X1	■					0.1				0.2		0.1										
Warehouse: Inv Ctrl	X11	0.8	■	0.2	0.2	0.3					0.4					0.5							
Warehouse: Procument	X12	0.8	0.8	■		0.1					0.4	0.5				0.2							
Warehouse: Carrier Selection	X13	0.5	0.2	0.5	■	0.1					0.2												
Warehouse: Capacity & Operation	X14	0.7	0.9	0.1		■					0.3												
Deliver: Distribution channel	X15	1			0.5		■				0.3												
Source: delivery scheduling	X4							■	0.8	0.9	0.5	0.5		0.1									
Source: supplier selection	X5	0.5						0.9	■		0.2		0.7	0.2									
Source: Inv Management	X6							0.8		■	0.9					0.5							
Plan: Resource Allocation	X2	0.4				0.1					■	0.5											
Plan: Coodination & Communication	X3	0.1									0.8	■											
Produce: Production Design	X7	0.4							0.2		0.8		■	0.1									
Produce: Individual parts processing	X8							0.3		0.5	0.8		0.1	■	0.5	0.1							
Produce: Subsystem coodrination	X9										0.8	0.8	0.8	0.3	■	0.8							
Produce: WIP/FG Inv Mgmt	X10		0.1	0.3		0.2					0.8		0.6	0.5		■							
Deliver: Schedule & Routing	X16				0.5						0.1						■	0.7					
Order: Processing Orders	X18	0.2					0.3				0.5						0.1	■					
Return: receive and verify	X21	0.5																	■				
Order: quotes	X17	0.2					0.5				0.3						0.1			■			
Order: Back orders	X19	0.2					0.3				0.5						0.1	1			■		
Return: defective rework/dispose	X22										0.7								0.9			■	
Order: Invoice	X20																	1			0.5		■

Fig. 13 The restructured numerical DSM

elements above them in the matrix. Therefore the upper elements in DSM should be given higher priority for the business cycle in order to provide the required inputs for the lower elements.

(3) For those strongly interdependent elements, the decision makers may like to locate these elements into the same functional department or to place them closer by changing the physical layout of the supply chain. The restructured DSM in Fig. 13 suggests a better organizational and layout structure for the supply chain system in the example. For example, Fig. 13 shows that the element "Deliver: Distribution Channel (X15)" relates to more elements under the "Warehouse" sub-system than the "Deliver" sub-system. Although the element X15 originally is a system element belonging to the "Delivery Department", the managers may wish to restructure their supply chain system by switching X15 to "Warehousing Department" for better communication and coordination.

(4) Research has indicated that team size should have limit due to effective and efficient communication among team members Johnson and Johnson (1991); Clark and Wheelwright (1992); Carmel (1994); Chung and Guinan (1994); Lanigan (1994). Successful supply chain implementation and integration rely on effective and efficient communication. In our research framework, any large interdependent groups are further decomposed into smaller and manageable sub-groups so that the personnel will be able to work closely together for the strongly related system elements in the same sub-group.

Conclusions

From our literature reviews, it is clear that a systematic and analytical tool will be needed to integrate the multiple dimensions of supply chain, and to better understand, improve and model the structure of supply chain. Therefore the goal of reducing complexity, improving flexibility and agility, and saving cost for supply chain management will be achieved. It is also desirable that such systematic and analytical tool is easy to understand and is able to represent the behavior and characteristics of a supply chain system without neglecting the interrelationships among system elements. The major contribution of this study is that our systematic approach using DSM is able to analyze three important types of interactions in supply chain (i.e., information, material and functional interactions) with quantifiable measures and to understand the underlying structure among the system elements for supply chain improvement.

This paper focuses on the interactions among the supply chain system elements. The increased complexity of modern supply chain systems makes system managers and designers more difficult to understand the system interactions and hard to obtain a clear picture for the entire system structure. To solve the problem, this study develops a systematic approach to identify and quantify the system interactions, and to decompose the large interdependent group of system elements into smaller and manageable sub-groups, therefore the manufacturing system managers and designers will be able to improve their supply chain systems intelligently and objectively where not only the flows or sequences of system elements are clearly identified, but also the strongly related elements are able to work closely together within each sub-group. This research has also shown that design structure matrix (DSM) is able to capture the complex interactions and their quantifiable strengths in a straightforward manner. Using the multi-layer DSMs to document different interaction types (i.e., information, material, and functional interactions) and then combining them into an aggregated DSM allow the system managers to integrate the entire supply chain system with different forms of interactions. Moreover, based on partitioning algorithm (Steward, 1981) and the decomposition model (Chen & Lin, 2002, 2003), large interdependent groups of system elements in a DSM are decomposed into smaller sub-groups where the related elements hold stronger interactions among each other. The outcomes help the system managers and designers to restructure or reengineer the entire supply chain system since the position of each system element in the supply chain and its relationships with the other elements are clearly shown.

In this research, the outcomes of supply chain improvement are evaluated qualitatively. Our future research extension will focus on developing a computer simulation model to quantitatively evaluate the supply chain performance (i.e., time and cost) between the original structure versus the new structure suggested by the research framework in this paper. Some other issues in supply chain (e.g., inventory policies and transportation) will be considered as well. Furthermore, the current DSM approach is able to capture the system "interactions" but no consideration for the supply chain system "constraints", which are also important when carrying out the supply chain reengineering. Another future research can focus on improving and extending the DSM method that allows DSM to handle the system "constraints".

References

Alexander, C. (1964). *Notes on the synthesis of form*. MA: Harvard University Press.

Badiru, A. B., & Pulat, P. S. (1995). *Comprehensive project management: Integrating optimization models, management principles, and computers*. Prentice Hall, NJ.

Beamon, B. M. (1998). Supply chain design and analysis: Models and methods. *International Journal of Production Economics, 55*(3), 281–294.

Burley, H. (2002). Supply chain modeling: An overview of practice and methodology. *Business Research Papers*, University of Southern Queens Land, 22–35.

Carmel, E. (1994). Time-to-completion in software package startups. *Proceedings of the IEEE International Conference on System Sciences, 4*, 498–507.

Cetinkaya, S., & Bookbinder, J. H. (2003). Stochastic models for the dispatch of consolidated shipments. *Transportation Research Part B, 37*(8), 747–768.

Chandra, P., & Fisher, M. L. (1994). Coordination of production and distribution planning. *European Journal of Operational Research, 72*(1), 503–517.

Chandra, C. (2001). Enterprise architectural framework for supply-chain integration. *Industrial Management and Data Systems, 101*(5), 290.

Chung, W. Y., & Guinan, P. J. (1994). Effects of participative management. *Proceedings of the ACM SIGCPR Conference*, 252–260.

Chopra, S. (2003). Designing the distribution network in a supply chain. *Transportation Research Part E, 39*(2), 123–140.

Chen, S. J., & Lin, L. (2002). A project task coordination model for team organization in concurrent engineering. *Concurrent Engineering: Research and Applications, 10*(3), 187–203.

Chen, S.-J., & Lin, L. (2003). Decomposition of interdependent task group for concurrent engineering. *Computers & Industrial Engineering, 44*, 435–459.

Chu, C.-H. (1989). Cluster analysis in manufacturing cellular formation. *OMEGA, 17*(3), 289–295.

Clark, K. B., & Wheelwright, S. C. (1992). Organizing and leading "heavyweight" development teams. *California Management Review, 34*(3), 9–28.

Cohen, M. A., & Lee, H. L. (1989). Resource deployment analysis of global manufacturing and distribution networks. *Journal of Manufacturing Operations Management, 15*(2), 81–104.

Cooper, M. C., Ellram, L. M., Gardner, J. T., & Hanks, A. M. (1997a). Meshing multiple alliances. *Journal of Business Logistics, 18*(1), 67–88.

Cooper, M. C., Lambert, D. M, & Pagh, J. D. (1997b). Supply chain management: More than a new name for logistics. *International Journal of Logistics Management, 8*(1), 1–13.

Das, S. K., & Abdel-Malek, L. (2003). Modeling the flexibility of order quantities and lead-times in supply chains. *International Journal of Production Economics, 85*(2), 171–181.

Duran, B. S., & Odell, P. L. (1974). *Cluster analysis: A survey*. Springer, NY.

Eppinger, S. D., Whitney, D. E., Smith, R. P., & Gebala, D. (1990). Organizing the tasks in complex design projects. *ASME: Design Theory and Methodology*, Chicago, IL, 39–46.

Everitt, B. (1980). *Cluster analysis*. Wiley, NY.

Garavelli, A. (2003). Flexibility configurations for the supply chain management. *International Journal of Production Economics, 85*(2), 141–153.

Gordon, A. D. (1981). *Classification: Methods for the exploratory analysis of multivariate data*. Chapman and Hall, NY.

Hartigan, J. A. (1975). *Clustering algorithms*. Wiley, NY.

Johnson, D., & Johnson, F. (1991). *Joining together: Group theory and group skills*. Prentice Hall, NJ.

Kusiak, A. (1990). *Intelligent manufacturing systems*. Prentice-Hall, NJ.

Kusiak, A., & Wang, J. (1993). Efficient organizing of design activities. *International Journal of Production Research,31*(4):753–769.

Lanigan, M. J. (1994). Task estimating: Completion time versus team Size. *Engineering Management Journal, 4*(5), 212–218.

Lovejoy, W. S. (1992). Rationalizing the design process. *Proceedings of the Design Management Conference*, Anderson Graduate School of Management, UCLA, CA.

McCord, K. R., & Eppinger, S. D. (1993). Managing the integration problem in concurrent engineering. *MIT Working paper 3594*.

O'Neil, B.F., & Iveson, J. L. (1992). Strategically managing the logistics function. *Logistics and Transportation Review, 27*(4), 359–377.

Olsmats, C. M.G., Edghill, J. S., & Towill, D.R. (1988). Industrial dynamics model building of a close-coupled production-distribution system. *Engineering Costs and Production Economics, 13*(1), 295–310.

Pimmler, T.U, & Eppinger, S. D. (1994). Integration analysis of product decompositions. *ASME: Design Theory and Methodology*. Minneapolis, MN.

Romano, P. (2003). Coordination and integration mechanisms to manage logistics processes across supply networks. *Journal of Purchasing and Supply Management, 9*(3), 119–134.

Scott J.M., Mauricio, P., Farris, J. F., & Kirk, R. G. (2003). Integrating the warehousing and transportation functions of the supply chain. *Transportation Research Part E, 39*(2), 141–159.

Smith, R. P., & Eppinger, S. D. (1997a). Identifying controlling features of engineering design iteration. *Management Science, 43*, 276–293.

Smith, R. P., & Eppinger, S. D. (1997b). A predictive model of sequential iteration in engineering design. *Management Science, 43*, 1104–1120.

Srinivasan, M., & Moon, Y. B. (1999). Comprehensive clustering algorithm for strategic analysis of supply chain networks. *Computers & Industrial Engineering, 36*(3), 615–633.

Steward, D. V. (1981). The design structure system: A method for managing the design of complex systems. *IEEE Transactions on Engineering Management, 28*(1), 71–74.

Stock, G. N., Greis, N. P., & Kasarda, J. D. (2000). Enterprise logistics and supply chain structure: The role of fit. *Journal of Operations Management, 18*(5), 531–547.

Supply Chain Council. (1996). Supply chain operations reference (SCOR) model. *Overview of SCOR Version 5.0*.

Tsay, A. A. (1999). Quality flexibility contract and supplier-customer incentives. *Management Science, 45*(10), 1339–1358.

Ulrich, K. T., & Eppinger, S. D. (1995). *Product design and development*. McGraw-Hill, NY.

Yan, H., Yu, Z., & Cheng, T. C. E. (2003). A strategic model for supply chain design with logical constraints: Formulation and solution. *Computers and Operations Research, 30*(14), 2135–2155.