A Decision Support System for the Supply Chain Configuration

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Abstract – The design of a supply chain network provides the main structure for supply chain operations, since the network is a key element in the competitiveness and investments of an extended production system. The configuration of the network is essential for business to pursue a competitive advantage. We adopt a methodology based on three layers. In the first layer, the performance of the entities candidate to join the network is evaluated and efficient elements are individuated. The second layer develops a model to configure the network. Finally, the third layer is devoted to evaluate and validate the solution proposed in the first two levels. The overall decision process is the result of the interaction of the modules dedicated to each decision layer.

Keywords: Supply chain management, Network design, Decision support systems.

1 Introduction

The global market economy is constantly forcing companies to focus on the production of high-value-adding core components. Customers' expectations in terms of cost, quality, and services has put industries under pressure to become more agile, provide time, and cost effective deliveries under highly dynamic market and supply conditions.

It is necessary to establish partnership agreements, which make continuous improvement possible in those aspects critical for getting a competitive edge, therefore enhancing the long-term competitiveness of each party involved. The introduction of optimization methods has proved to be helpful in the production management within single plants, but at the same time has revealed the inefficiencies in relations between different facilities. Therefore, the competitiveness of a company is increasingly tied to the dynamics of the supply chain. Then, the challenge becomes how to deal with these inefficiencies and identify methods for the performance analysis and an adequate network configuration or re-configuration.

The network configuration is a strategic decision since it has a lasting effect on the supply chain involving issues related to plant, warehouse and retailer characteristics. In this context, network design methods are in general based on mixed-integer programming models and are used to decide what products to produce and for what retailers, and using what resources.

This paper proposes a decision support system for integrated production network design considering also the e-business relationships between operators and the network's environmental impact. In this context, the firm must deal with different tradeoffs and its decisions are crucial determinants of whether the supply chain is an efficient channel for the manufacturing and the distribution of the products. The methodology is based on three decision layers. In the first layer, the performance of the entities candidate to join the network is evaluated and efficient elements are individuated. The second layer develops a model to configure the network. We consider a mathematical representation of the supply chain structure based on directed graphs. In this way, the proposed algorithms can exploit the combinatorial characteristics provided by the particular representation. In order to solve the tradeoffs, the system contains a module implementing multi-objective optimization algorithms. Finally, the third layer is devoted to evaluate and validate the solution proposed in the first two levels.

This paper is organized as follows. In Section 2 we discuss the context and the related literature. In Section 3 the framework of the proposed DSS is described and the adopted integrated network model is illustrated. Section 4 describes and discusses the layout of the DSS is discussed. Finally, conclusions are in Section 5.

2 The context

Computer and information technology has been employed to support logistics for many years [4]. Information technology is perceived as the key factor that will affect the future growth and development of logistics [16]. Indeed, it is the most important factor in an integrated supply chain, also playing an important role in the executive decision-making process. Information technology solutions such as decision support systems (DSS) based on expert systems,
Simulation and optimization systems are indicated as the way to directly support decision making on Supply Chain Management SCM [6,12].

A DSS incorporates information from the organization’s database into an analytical framework with the objective of easing and improving the decisions making. A critical element on a DSS for logistics decision is the analysis of data used as input of the systems. Therefore, in any implementation, efforts should be made to collect accurate data [1,8]. Optimization methods, either exact or heuristic, when incorporated to a DSS for SCM, can significantly contribute to the decision process [19], especially taking into consideration the increased complexity of the logistics problem [6].

The Internet has quickly transformed the way in which the world conducts business and business partners interact between themselves. In e-commerce, business partners and customers connect together through Internet or other electronic communication system to participate in commercial trading or interaction [12,13,16]. Certainly, e-commerce requires new and hard issues to the company’s logistics systems, involving in some cases new distribution concepts and a new design of the supply chain.

Accordingly, companies are experiencing a growing need for requiring DSSs that help them to make the best decisions in an uncertain and rapid changing world as the one related with e-commerce and e-business [12,16]. Many of the problems in the decision making process may be considered as extensions of the old ones, as for example, the transportation management, while others are completely new with some added complexity, such as the uncertainties associated with the evolution of the commerce on the web. This is the case of the environmental aspects related to the supply chain [11,15]. The concerns about environment have never been as important as today. The new regulations regarding removal, recycling and reusing are increasing and this puts reverse logistics and environmental conscious logistics into the key topics of the logistics research [2,5,13]. Reverse logistic is related to the process of recycling, reusing and reducing the material. The issues faced in reverse logistics are not just the reverse issues of a traditional supply chain, they can be more complex, as for example, aspects related to the transportation and disposal of dangerous materials and call for a product life-cycle engineering approach [20]. The environmental conscious logistics usually deals with the activities related with choosing the best possible means of transportation, load carriers and routes to reduce the environmental impact of the complete supply chain. Some of the areas clearly affected are packaging of products, transportation means and product development, as many others. Logistics is also involved in removal and disposal of waste material left over from the production, distribution or packaging process, as the recycling and reusable products [2,3,5].

In the previously described context, many companies have to re-organize their supply chains and even extend them to be able to return, reuse or dispose of their product and materials. Hence, many new and challenging questions may be singled out in the research area of logistics.

### 3 The DSS Framework

The general methodology for the supply chain configuration process is presented in Figure 1. Since the input data to decision making is very important to the process, it is useful to refer to a knowledge base including:
- logistical and distribution processes;
- operating procedures and performances;
- market trends;
- quantitative and qualitative tools.

![Figure 1. The decision making process.](image)

The analysis both the characteristics of the entities candidate to join the supply chain, and the performances of members of the network is a crucial step of the decision process related to the configuration of the overall system. As the decision-maker is often a heterogeneous team of experts, the proposed analysis tools have to be quite simple to use and to understand [15]. Moreover, tools should be applicable to different supply chain entities.

Similar arguments involve the flexibility of the whole DSS. In fact, the decision process is an expert-team based process guided by consensus. Then the DSS may be required to give different solutions or, for example, the team can introduce new constraints or should ask to consider some particular scenario. In the sequel, we propose a three-layer approach to solve the supply chain
configuration (or re-configuration) decision problem, which is structured as follows:

**First layer**: A multi-criteria data analysis is applied on the company’s database in order to create a pool of ranked candidates to join the supply chain project.

**Second layer**: A graph-based optimization model is used to generate a number of least-cost solutions at an aggregate level, taking into account the most important cost functions.

**Third layer**: Discrete event models or simulation models are applied to evaluate and validate the solutions generated in the previous stages.

![Diagram of the DSS scheme](image)

Figure 2. The DSS scheme.

Figure 2 presents the scheme of the proposed DSS combining data analysis, simulation and optimization. The user should analyze different scenarios within the same time framework if the applied optimization methods are able to yield families of solutions according to the required objectives of the problem. From this point of view, the DSS can be customized for a specific company or organization.

Optimization methods help to take system decisions within a certain parameters and environment and then, simulation techniques can be applied to analyze the system behavior in presence of more details or uncertainties. Simulation-based tools take in account the dynamics of the system and are capable of characterizing system performance for a given solution (or decision). One of the limitations of the simulation models is that they only represent a pre-specified system. On the contrary, the combination optimization-simulation can provide very interesting ideas about the design of the supply chain. On the other hand, the mathematical programming models and techniques are able to find the best solutions, but they are not able to evaluate the behavior and effects of a particular decision in presence of uncertainties.

Hence the decision making process can strongly benefit by having a system that is able to identify and evaluate/validate the optimal or near optimal solution.

### 3.1 The Integrated E-Supply Chain

An integrated e-supply chain (IESC) network can be defined as a hyper-network of material flows overlaid with an e-business information network. In our DSS framework we refer to the general model for IESC recently introduced in [13]. In the sequel and in Figures 3 and 4, we recall the characteristics of the adopted IESC model. The IESC model allows to consider supply chains containing different stages: raw material supply, intermediate supply, manufacture, distribution, retail, customers, and de-manufacture or re-cycling. After the de-manufacture stage, recovered material, components or energy feedback suitable to supply chain stages. Hence, this structure is able to extend the traditional Supply Chain, in a more sustainable and integrated production system. The focal point is still production operations, but the upstream and downstream parts cover the whole product/business chain. In the IESC structure, partners contain autonomous or semi-autonomous business entities collectively responsible for the full lifecycle of a product. An m-link represents the physical transportation link between two partners. Multiple m-links are allowed between two nodes to model different transportation modes or split delivery routes. An e-link is an e-Business relationship between business entities for stream-lining the material flow efficiently and effectively. An e-link can speed up the communication process and thus reduce the response time affecting such measures as cost, productivity and energy use of partners and m-links in the material flow network.

E-supply chains can bring about a more cooperative business environment, since their elements are involved in production, communication, transportation activities, and warehousing. Placement and selection of these elements are parts of the supply chain configuration or re-configuration decision process, that is the purpose of our DSS.

### 3.2 The Network model.

This section describes the generic IESC network using the model presented in [13]. In the following we list the basic components of the model.

- **Product supply chain system:**
  a network contains consecutive supply chain stages as shown in Figure 3;
- **Supply chain stage** \( k \):
  Stage Partner set \( P_k = \{ p_{1}^k, p_{2}^k, p_{3}^k, \ldots, p_{nk}^k \} \); stage \((k-i)\) is called upstream stages of \( k \) and stage \((k+i)\) downstream stages of \( k, i > 0 \).
  Stock keeping unit (SKU) set \( S_k^i \) is the finished products set of \( p_{i}^k \).
  Bill of material (BOM) set \( B_k \) of stage \( k \),
  \( B_k \subseteq \cup S_{k-1} \), \( B_1 = \emptyset \) (raw material supplier).
The BOM of stage \( k \) is a list of materials and components required for processes in this stage as shown in Figure 3;

\[
\text{Stage 1} \quad \text{Stage 2} \quad \text{Stage 3} \quad \text{Stage M}
\begin{align*}
{p_1^1} & \quad {p_1^2} & \quad {p_1^3} & \quad {p_1^M} \\
{p_2^1} & \quad {p_2^2} & \quad {p_2^3} & \\
{p_3^1} & \quad {p_3^2} & \quad {p_3^3} & \quad {p_3^M} \\
{p_4^1} & \quad {p_4^2} & \quad {p_4^3} & \quad \ldots \\
\vdots & \quad \vdots & \quad \vdots & \quad \vdots \\
{p_k^1} & \quad {p_k^2} & \quad {p_k^3} & \quad {p_k^M} \\
\end{align*}
\]

Figure 3. A product supply chain (PSC).

- Supply chain partner set \( P \):
  \( P = \{ P_1 \cup P_2 \cup \ldots \cup P_k \cup \ldots \cup P_U \} \).
- Material flow link, or \( m \)-link of stage \( k \):
  Link set \( L_{mk} = (P_k \rightarrow P_{k+j}) \). All existing physical directed links from a \( k \)th stage partner to a \( (k+j) \)th stage partner.
  Multiple links are allowed between two partners.
- Set of all \( m \)-links: \( L_m = \bigcup L_{mk} \);

Figure 4. Stage partner, BOM and SKU of a supply chain.

- Material flow network:
  \( (P, L_m) \), with node set \( P \) and link set \( L_m \).
- Supply chain information link, or \( e \)-link \( L_e \) of stage \( k \):
  Link set \( L_{ek} = (P_k \leftrightarrow P_{k+j}) \). All existing e-Business information non-directed links between a \( k \)th stage partner to a \( (k+j) \)th stage partner. These links affect the characteristics of the corresponding material flow network.
- Set of all \( e \)-links: \( L_e = \bigcup L_{ek} \);
- E-Business information network: \( (P, L_e) \), with node set \( P \) and link set \( L_e \);
- Integrated supply chain network:
  two overlaid networks: \( (P, L) = (P, L_m) + (P, L_e) \);
- A product’s supply chain (PSC):
  \( PSC \subseteq (P \cup L_m) \), a subset of appropriate partners (nodes) and links from \( (P \cup L_m) \).

A PSC is a sub-net of IESC consisting of connected nodes and links through and along which products travel from original suppliers to consumers, then to end-of-life processor. There must be at least one manufacturer node and one customer/consumer node in the pathway;

- General performance vector:
  \( m = (m_1, m_2, \ldots, m_q) \). Each element in \( m \) corresponds to a performance measure. Typical measures include cost, cycle time, product quality, energy consumption, and environmental impact;
- Performance vector for each partner \( P_i: m(P_i), P_i \in P \);
- Performance vector for each link \( L_i: m(L_i), L_i \in L \);
- Design issues the system can be addressed as objectives and constraints:
  Given \( m(P_i), P_i \in P \) and \( m(L_i), L_i \in L \), find a PSC such that the concerned objective functions are optimized. These objective functions represent the optimization goals for the entire system, including cost, productivity, reliability, cycle time and environmental performance.

4 The DSS architecture

The architecture of our DSS follows the conceptual scheme described in Figure 2. Moreover, Figure 5 depicts the three-layered structure of the DSS, as introduced in Section 3. In particular, a specific module is devoted to each stage. Interactions between modules allow to obtain and refine proposal configurations for the supply chain. The DSS is able to operate statically, in order to build a new network, as well as dynamically, when changes in the context call for a re-configuration of the supply chain.

4.1 Data Analysis Module

This module is devoted to analyze the performances and the efficiency of either the current members of the supply chain and the candidate to join the organization. The context and the characteristics of the decision maker suggest to consider an input/output analysis. The methodology adopted is the Data Envelopment Analysis (DEA). DEA is an heuristic procedure [7,17] for estimating the relative efficiency of a group of decision units (such as the members of a supply chain). Since the supply chain partnership is based on some measure of efficiency, as well as the supply chain configuration process, DEA is suitable for our application. Moreover, DEA is a multi-criteria analysis based on the linear programming theory and, for this reason, it requires limited and simple computational resources. The output of this module gives a current ranking (on the basis of the efficiency criteria stated by the decision team) of the entities considered as candidates. Hence, for each stage of the supply chain this module produces an ordered list of candidates. The DSS user can decide how many entities (for each supply chain stage) to consider in the
effective configuration process that will be carried out by the network design module.

Figure 5. The three-layered structure of the DSS.

4.2 Network Design Module

This module applies optimization algorithms to the results of the previous level in the DSSS and determines in a IESC network the best sub-net according to the objectives and constraints indicated by the user. The user can consider different objectives: operative cost functions, cycle time, energy saving, ecological costs, multi-objectives are allowed. With the constraints the user can ask for: a certain number of manufacturers (or customers); the presence of a specific link in the solution; the presence of a particular sub-net (e.g. in the case of supply chain expansion) in the solution. The mathematical model is based on the combinatorial characteristics of the IESC and may be a linear program or an integer linear program. In both cases we are interested in considering single-criteria optimization methods as well as multi-criteria techniques. To this aim, we consider methods based on the multi-criteria linear programming [15] and the fuzzy multi-criteria optimization [13].

4.3 Solutions Evaluation/Validation Module

The purpose of this module is to evaluate alternative supply chain designs with respect to quality, lead times and costs. The main interest lies in determining the shapes of the curves indicating the nature on the impact quality levels and lead time costs. Moreover, it is important to increase the understanding of the interrelationships among these and other parameters, relevant for the design and operations of supply chains [14]. In order to capture these relationships we use a discrete event model as well as a simulation model.

In a discrete event model the evolution of the system depends on the complex interaction of the timing of various discrete events such as the arrival of components at the supplier, the truck from the supplier, the start of an assembly at the manufacturer, the arrival of the finished goods at the customer, payment approval by the sellers etc. The state of the system changes only at discrete events times. The discrete event dynamic model allows us to study the dynamics of the supply chain, especially the impact of logistics and interfaces, and the manufacturing philosophies, on the performance measures. In [18] the framework of generalised stochastic Petri nets is used for the analysis of a supply chain. However, a more efficient model can be obtained by using stochastic Colored Petri nets. Because of the complexity of the system colored resource oriented Petri nets can describe the system in a modular and concise way. In particular, places can represent resources such as suppliers, inbound logistics, interfaces, outbound logistics, warehouses, manufactures etc., transitions represent the flow of materials and of information through the supply chains. Moreover, tokens are lots of products and materials in the systems or the messages that pass the supply chain in the material opposite direction. Finally, the performance measures of interest are the average work in process and average finished goods inventories of materials, the lead times for order delivery, and material replenishment cycle times or the supply chain lead times.

In some complex supply chain system [19], a Petri net model can not be enough detailed to handle all the relevant parameters. Hence, a discrete event simulation represents a more general and efficient instrument to evaluate alternative supply chain designs. Very attractive higher-level general purpose simulation packages are now available to model a manufacturing enterprise These include ARENA, SIMPROCESS, Taylor II, to name a few. A comparative simulation study allows us to compare different design and network solutions on the bases of relevant performance measures. Beamon [3] provides a literature survey of performance measures used in supply chain environments. Two types of performance measures dominate; namely cost and customer responsiveness. Costs may include inventory and operating costs, customer responsiveness measures include lead time, stock-out probability and fill rate. The obtained performances are used to validate the presented model and the optimization method employed. Consequently, if the results are not satisfying, the simulation study suggests how to modify the first and the second stages to improve the performance indices. The obtained procedure results in a closed loop DSS.

5 Conclusions

The e-supply chain is a business strategy that incorporates the power of e-commerce to streamline the manufacturing processes. An integrated e-supply chain system has a more complex structure than a traditional supply chain system, in that it embraces the e-business
strategy to establish information links and integrates end-of-life processes into the entire supply chain structure.

The methodology presented in this paper represents an approach to model and optimize the configuration (or re-configuration) of an integrated e-supply chain network structure. Supply chain parameters and system strategies are represented as a mathematical model of the network structure. Interaction and tradeoffs that occur between the components and parameters in the network are analyzed and optimized using a multi-objective optimization approach. The result is an optimal or sub-optimal product supply chain under an e-business strategy for internet-based manufacturing subject to constraints related to previous structural investments (e.g. a network already exists and a re-configuration or extension is considered) or some reliability requirements (e.g. a certain number of specific entities are required in order to limit the network vulnerability).

The evaluation of the performance measures tests the design of the supply chain as obtained from the higher decision levels. Finally, the simulation results can show if it is necessary to modify the higher DSS layers.

References