A Multi-Level Approach for Network Design of Integrated Supply Chains

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Abstract

Integrated e-supply chains are distributed manufacturing systems composed of various resources belonging to different companies and integrated with streamlined material, information and financial flow. The configuration of the supply chain network is essential for business to pursue a competitive advantage and to meet the market demand. This paper proposes a three-level hierarchical methodology for supply chain network design at the planning management level. The integrated supply chain network is described as a set of consecutive stages connected by communication and transportation links and the configuration aim consists in selecting the actors of the stages on the basis of transportation connection and information flow. More precisely, the first level evaluates the performance of the entities candidate to join the network and singles out efficient elements. The second level solves a multi-criteria integer linear optimization problem to configure the network. Finally, the third level is devoted to evaluating and validating the solution proposed in the first two levels. The overall decision process is the result of the interaction of the modules that are dedicated to each decision level. The paper presents some optimization techniques to synthesize the first two levels and illustrates the hierarchical decision process by way of a case study.

Keywords: Integrated e-Supply Chains, Distributed Manufacturing Systems, Network Design, Optimization.

AMS Subject Classification: 93C85, 68M14, 90B30, 90B50.

1 Introduction

Global competition imposes high pressure on product and service providers to improve efficiency and minimize risk and costs. Companies respond to this pressure by
reengineering their operations and by integrating international logistics and information technologies in the production process. This has given rise to the formation of Integrated E-Supply Chain (IESC) networks, defined as a collection of independent companies, possessing complementary skills and integrated with streamlined material, information and financial flow (Luo et al. 2001, Viswanadham and Gaonkar 2003). More precisely, an IESC may be defined as an integrated process wherein a number of business entities (i.e. suppliers, manufacturers, distributors, and retailers) work together to acquire raw materials, convert raw materials into final products and deliver final products to the retailers (Beamon 1998). Moreover, Internet and web-based electronic market places can provide an inexpensive, secure and pervasive medium for information transfer between business units (Graves et al. 1996, Luo et al. 2001, Tayur et al. 1999).

Although several conceptual models for IESC are proposed and discussed in the related literature, research efforts are lagging behind in the development of formal decision models for the IESC design (Talluri and Baker 2002). A systematic way to capture all aspects of Supply Chain (SC) processes is proposed by Chopra and Meindl (2001) and Stevens (1989). This guideline is based on the three levels of the decision hierarchy: strategic, tactical and operational ones. Strategic level planning involves SC design, which determines the location, size and optimal number of suppliers, plants and distributors to be used in the network. It considers time horizons of a few years and requires approximate and aggregate data. Tactical level planning basically refers to supply planning, which primarily includes the optimization of the flow of goods and services through a given SC network. Finally, operational level planning is short-range planning, which involves production scheduling at all plants on an hour-to-hour basis.

The main decision problem of the SC strategic level planning is the network design (Erenguc et al. 1999, Vidal and Goetschalckx 1997), that determines: i) the number, location and type of manufacturing plants and warehouses to use; ii) the set of suppliers to select; iii) the transportation channels to employ; and iv) the amount of raw materials and products to produce and ship among suppliers, plants, warehouses and customers considering Bill Of Materials (BOM) relationships. Hence, in the formation of an effective dynamic IESC network, the selection of partners in each tier of the SC for the fulfilment of each order is extremely important (Viswanadham and Gaonkar 2003, Talluri and Baker 2002). Significant literature deals with the problem of SC component selection and network design and some detailed survey can be found in Pontrandolfo and Okogbaa (1999), Vidal and Goetschalckx (1997) and Min and Zhou (2002). An initial mathematical work in this area is presented by Geoffrion and Graves (1974), who propose a logistics network design model for optimizing annualized finished products flows through the entire SC. Moreover, Cohen and Lee (1989) present a deterministic model for global manufacturing and distribution networks: the deterministic formulation considers the maximization of after-tax profits in all countries, taking into account variable production and purchasing costs, as well as warehousing, transportation and vendor costs. Lee and Billington (1993) introduce an operational model for material management and inventory control in a decentralized SC. Moreover, Arntzen et al. (1995) present a global SC model and a mixed-integer linear program minimizes cost, weighted cumulative production and distribution times subject to demand and capacity constraints. Furthermore, Arntzen et al. (1995), Cohen and Lee (1989) suggest exploiting the BOM to coordinate the behaviour of suppliers with production and distribution activities. In the same direction, Yang et al. (2003) propose a strategic production-distribution model for SC design taking into account the BOM constraints.
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represented by logical constraints. In particular, a mixed integer programming model captures the role of BOM in the selection of suppliers to provide the SC structure. Since the work optimizes an objective function considering purchasing, production and transportation costs, it does not select different solutions on the basis of the relative importance of a performance index on another one.

A multi agent supply chain coordination tool is presented by Sadeh et al. (2001). An overview of a reconfigurable, multilevel agent based planning and scheduling architecture is given. The tool performs different tasks like SC partner selection and coordination, scheduling and BOM configuration. However, the work does not clarify the algorithms and the strategies used by the decision agents.

Wu et al. (1999) formulate partner selection for distributed agile manufacturing as an integer programming problem to choose one and only one candidate for each task of the production process. They minimize the sum of the costs for performing all the tasks and the transportation costs. However, the constraint to select only one candidate for each task is restrictive and affects the flexibility of the resulting network structure.

A novel approach to model and optimize an IESC network that incorporates e-commerce and electronic linkage is presented by Luo et al. (2001). Interaction and tradeoffs occurring between the network components are analyzed and optimized using a fuzzy multi-objective optimization approach. The optimization procedure considers new paradigms for the design of the IESC structure, such as recycling and pollution, which influence the decision process, along with transportation costs and cycle times. The drawback of this approach is that the fuzzy optimization technique provides only one suboptimal network structure and disregards the impact of the solution on the operational level issues.

A linear programming model for integrated SC planning is developed by Gaonkar and Viswanadham (2001), who assume that information is freely shared by the SC partners through an Internet based platform. The linear programming model provides a basis for partner selection such that the cost of operations is minimized. More precisely, the objective is to minimize the cost of procurement, while satisfying the demand of the original equipment manufacturer, subject to various capacity constraints, production and logistic schedules and flow balancing constraints. Moreover, in their subsequent work, Viswanadham and Gaonkar (2003) study and analyze a multi-tier SC by using an optimization technique which takes into account capacities and costs. In such a work, the authors determine the sub-optimal order quantities to be allocated to each of the manufacturers, suppliers and logistics service providers. A multi integer programming model is developed for a dynamic manufacturing network and its objective function maximizes the profit earned by the network subject to various capacity, production and logistics schedules and flow balancing constraints. However, the information necessary to describe and characterize the SC can be so complex and large that the definition of constraints appears critical.

To face the complexities involved in the SC design process, Talluri and Baker (2002) propose a three-phase mathematical programming approach for SC network design which involves multi-criteria efficiency models and linear and integer programming methods. In particular, phases I and II design the network, and phase III addresses operational issues such as the routing of materials.

In order to solve the problem of the decision complexity, Jang et al. (2002) propose a new SC management system consisting of four modules: an SC network design optimization module, a planning module for production and distribution operations from
material suppliers to customers, a model management module and a data management module. The first module aims at minimizing the sum of costs of transports and costs associated with locating and operating plants and warehouses. Moreover, constraints ensure demands and BOM relationships. The second module generates the production and distribution plan of the SC network over the planning horizon. The first and second modules are solved by Lagrangian heuristics and a genetic algorithm, respectively. The model and data management modules relieve managers from dealing with the details of data and mathematical models.

This paper focuses on strategic decision problems and proposes a hierarchical configuration methodology for IESC network design, considering also the e-business relationships between operators and the network environmental impact. For each stage of the SC network, one or more partners (producers, manufacturers, consumers etc.) have to be selected, using the information available on BOM relationships, inventory, transportation costs, distances and pollution. Moreover, the proposed configuration methodology takes into account the influence of the strategic level decisions on the tactical and operational levels. In order to face the complexity of the decision process, the IESC structure design is divided into a hierarchy consisting of three decision levels. The candidate selection level and network design level take decisions referring to the strategic planning, while the solution evaluation/validation level considers tactical and operational decision problems and validates the solutions obtained at the first two levels. In particular, the candidate selection level evaluates the performance of the entities that are candidate to join the network. Three different procedures are considered for estimating the relative efficiency of a group of actors (such as the candidate members of the IESC stages): Electre (Buchanan et al. 1999), the Analytic Hierarchy Process (AHP) (Saaty et al. 2003) and the Data Envelopment Analysis (DEA) (Charnes et al. 1978, Thanassoulis 2001). On the basis of efficiency criteria considering aggregate data stated by the decision team, the output of this module contributes to create a set of candidate entities connected by links representing transportation and communication. Furthermore, the second level receives the stages of the IESC by the first layer and provides as output one or more network structures. More precisely, the IESC network is described by the digraph proposed in Luo et al. (2001), where nodes are partners and edges are links. Different costs are assigned to each link (edge), so that the performance indices can be obtained by the digraph analysis. The data analyzed at this level consider transportation and information connections among stages, costs and transport pollution. In order to configure the IESC network and to select appropriate links among the stages, some multi-criteria objective functions are defined and suited constraints are introduced on the basis of the digraph structure. Hence, a multi-criteria integer linear optimization problem is solved. While the first and second layers help in strategic decision making and produce some possible structures of the IESC network, the third level is devoted to evaluating and validating the solution proposed in the first two levels taking into account tactical and operational issues. In particular, this layer determines and studies the evolution of the IESC and evaluates appropriate performance indices using low level analytical models or simulation models. Moreover, the validation process performed at this layer allows us to verify the IESC structures obtained at the higher levels and helps in the final selection of the network. The paper proposes some optimization techniques to synthesize the first two higher levels (candidate selection and network design). A case study is analyzed and different solutions obtained from the first and second level are presented, showing the flexibility.
of the proposed decision strategy approach. The synthesis of these two levels is obtained with the perspective of realizing the third level and studying the IESC dynamics. This paper is organized as follows. Section 2 describes the proposed hierarchical decision structure for the IESC network design. Moreover, Section 3 presents three methodologies to obtain the candidate selection module and analyzes a case study. In addition, Section 4 synthesizes the network design module, which is applied to the case study in Section 5. Finally, Section 6 discusses the solution/evaluation module and Section 7 summarizes the conclusions.

2 Hierarchical Design of an Integrated e-Supply Chain

2.1 Description of the Integrated e-Supply Chain

We consider a distributed manufacturing process that requires a number of component suppliers, subassembly manufacturers, logistics service providers and users located in different geographical sites. The distributed manufacturing system is arranged as an IESC composed of a sequence of stages connected by material transporters and by information exchange. More precisely, the stage partners can exchange information on their product schedules and costs. The considered IESC contains different stages: raw material supply, intermediate supply, manufacturing, distribution, retail, customers, and de-manufacturing or re-cycling. After the de-manufacturing stage, recovered material, components or energy feedback to suitable supply chain stages are considered. We denote the IESC stages by the set $\{P_1, \ldots, P_{N_s}\}$, where $N_s$ is the number of stages. Each stage $P_k$ is described as a set of partners representing different actors of the SC.

2.2 The Hierarchical Structure of Decisions

Analyzing both the characteristics of the entities candidate to join the IESC and the performance 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 understand (Shapiro 2001), as well as applicable to different SC stages. In this section we describe a three-level approach to solve the supply chain configuration (or reconfiguration) decision problem. The proposed methodology is inspired by the topic of hierarchical control and management used in the study of large scale systems in both theory and applications (Gershwin 2002). More precisely, we decompose the design of the IESC in three hierarchical levels that suggest different solutions analyzing sets of data and considering different scenarios. Figure 1 shows the hierarchical structure of the IESC configuration decision problem and depicts the three levels of the design procedure. A specific module is devoted to each decision stage and the interactions between modules allow us to obtain and refine proposed configurations for the supply chain.

[Insert figure 1 about here]
The levels of the hierarchical structure of decisions are described in the following.

First level: candidate selection module. Some multi-criteria data analysis techniques are applied to the company’s database in order to create a pool of ranked candidates to join a supply chain project. At this level the criteria to select partners are based on aggregate performance indices that are used to analyze the efficiency of the possible members. Hence, we consider different procedures for estimating the relative efficiency of a group of SC partners. The output of this module produces a ranking and classification of the entities considered as candidates for each IESC.

Second level: network design module. This module receives from the first level the set of IESC candidates that compose each stage. Moreover, the transport and information links that connect the candidates have to be specified. More precisely, each link is characterized by a structural description (the two actors that the link connects) and by some relevant performance indices (distances, transportation costs, etc.). At this level the decision module has to select the actors of the stages and the transportation and information links that have to connect the actors. To this aim, an integer multi-criteria linear optimization problem is stated and a set of low-cost solutions are generated. Each solution proposes an IESC network structure that minimizes some selected cost functions, such as transportation costs, CO2 emission, and energy. However, the optimization procedure may provide an unsatisfactory set of networks or fail. This situation can happen because level 1 supplies the module with an insufficient number of stage candidates or with candidates not properly connected. Consequently, in such cases the network design module requires a new application of the candidate selection module.

Third level: solution evaluation and validation module. This module receives as input the set of IESC networks determined by level 2 with the associated performance indices. Moreover, this level gets and takes into account the capacities of each partner and transport, the times employed to process and transport the products and the production deadlines. Hence, at this level the IESC is modelled addressing tactical and operational issues. Accordingly, analytical or simulation models provide operational performance indices to evaluate and validate the solutions generated by the previous levels. Hence, this module allows us to validate the IESC network structures obtained at the previous levels in order to evaluate some lower level performance indices such as lead times, utilization, inventory levels and so on (Viswanadham and Srinivasa Raghavan 2000). As a result, this stage of the design procedure verifies whether the received system structures are suited to perform the IESC tasks. In case the verification is not satisfactory, it is possible to feedback to the higher level to change the IESC network appropriately. For example, if the production capacities provided by the proposed networks are not sufficient, then level 3 asks level 2 for IESC networks having a greater number of manufacturers. More precisely, when the verification fails, level 3 has to single out the stages of the IESC networks that must be modified by level 2.

At this point the reasons leading to the choice of the three hierarchical levels can be clear: the decision structure follows the intuitive procedure to find the optimal network. The first level selects the available actors, the second level builds the possible networks,
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the last level chooses the suitable network on the basis of operational performance indices. The proposed hierarchical structure of the decision making process is able to operate both statically, i.e. to design a new network, and dynamically, i.e. when unsuccessful validations from the third level or changes in the market context call for a reconfiguration of the SC. Moreover, the decision team should analyze different scenarios so that the applied optimization methods are able to yield a family of solutions according to the required objectives of the problem.

3 Candidate Selection Module

The candidate selection module is devoted to analyzing the performance and efficiency of the candidates of each IESC stage. This decision level is modelled as a candidate ranking problem, i.e. a multi-criteria optimization problem in which a number of criteria are defined to measure the impact on the IESC. The output of this module produces a current ranking (on the basis of the efficiency criteria stated by the decision team) of the considered entities, so that for each stage of the SC an ordered list of candidates is provided.

The optimization procedure performed by this module can be described by the following four steps that are iterated for each stage of the SC.

Step 1. Single out the candidate set of the generic stage denoted by \( P_k^c = \{ n_i^c \} \). The set \( P_k^c \) collects all the candidates \( n_i^c \) that may compose the stage \( P_k \) of the SC.

Step 2. Define the most relevant criteria that measure the impact of each alternative. To this aim, the following criteria can be used (Beamon 1999, Buchanan et al. 1999):

- financial (F), including cost and financial return;
- risk management (RM), including risk of plant failure and damage following natural disasters;
- environmental (E), including effect on relationship with resource partners and on access to resources;
- flexibility (FL), representing the capacity of the candidate to adjust market requests;
- operation times (T), representing the ability to respect the decided deadlines;
- quality (Q), evaluating the products and the provided service.

Step 3. Determine a normalized score for each candidate with reference to each criterion. The scores for each criterion are based on a 0 to 100 scale. These data, where each alternative is assessed using each criterion, produce a table of impacts, referred to as performance indices.

Step 4. Perform an optimization process to provide a final ranking of the partners in \( P_k^c \) on the basis of criteria and scores obtained at the previous steps. At this point, the designer is ready to select the candidates in a subset \( P_{k} \subset P_k^c \) denoting the actors of the \( k \)-th stage of the IESC.

To implement this decision level, several well known Multi-Attribute Decision Making (MADM) methodologies can be adopted: e.g. the Electre method (Buchanan et al. 1999, Mousseau et al. 2000, Rogers and Bruen 1998), the Analytic Hierarchy Process (AHP) (Saaty et al. 2003, Zanakis et al. 1998), the Data Envelopment Analysis (DEA) (Charnes et al. 1978, Thanassoulis 2001) and many others (Zanakis et al. 1998), such as for instance fuzzy methods (Farina and Amato 2004). To show an example of the
candidate selection module, we propose a case study in which the candidate ranking and classification are performed using the Electre, AHP and DEA methods.

3.1 Case Study

The considered case study is inspired by an example proposed in (Luo et al. 2001). The target product is a typical desktop computer system consisting of computer, hard disk driver, monitor, keyboard and mouse. The supply chain is composed of $N_S=6$ stages: suppliers, manufacturers, distributors, retailers, consumers and recyclers. As an example, we focus on the partner selection for the second stage, i.e. the manufacturers. Obviously, the methodology proposed for manufacturer selection can be applied to each stage of the IESC. The first step of the procedure determines the candidate set of the second stage, e.g. $P_2^c=\{n_1^c, n_2^c, \ldots, n_{15}^c\}$, where we assume that 15 candidates are competing to join the second stage of the IESC.

Having defined the most relevant criteria in the second step (F, RM, E, FL, T, Q), the third step assigns the scores to each candidate. Table 1 reports the performance matrix assigned to each alternative manufacturer.

3.1.1 Electre Method Solution. The Electre method is a multiple criteria sorting method originally developed to incorporate imprecision and uncertainty in decision making by using the so-called thresholds of indifference, preference and veto. A further feature distinguishes Electre from many MADM solution methods: it is fundamentally non-compensatory. In other words, low scores with reference to some criteria cannot be compensated by high scores on other criteria. To apply the Electre method, the decision makers are required to define a table collecting the indifference, preference and veto thresholds as well as a set of weight-importance coefficients. While thresholds model the non-compensatory nature of the method, the weights deal with preference information, reflecting the relative importance of each criterion according to the decision making team (Buchanan et al. 1999, Mousseau et al. 2000). The thresholds and weights are subjective: once the performance is agreed upon by all decision makers, then the subjective inputs of thresholds and weights can be processed. The thresholds and weights defined for the case study are shown in table 2.

Using the thresholds of table 2, the Electre method seeks for an outranking relation. Table 3 shows the final ranking of the candidates, resulting from the intersection of the results of an ascending and a descending distillation process (Buchanan et al. 1999, Mousseau et al. 2000). In particular, the outranking relation is obtained with a Matlab implementation of the method that employs the intrinsic characteristic of the Matlab programming environment to operate with matrices (The MathWorks Inc. 2002).
According to the results in table 3, the decision maker selects $P_2 = \{n_5^c\}$ if one manufacturer only is to be included in the SC network. On the contrary, if several manufacturers have to be incorporated in the SC, a corresponding number of candidates are selected from table 3 starting from the one with the highest position. For instance, if two manufacturers are to be included in the SC, the decision maker selects $P_2 = \{n_1^c, n_5^c\}$.

### 3.1.2 AHP Method Solution

AHP is a widely used technique for MADM and is based upon pairwise subjective judgement of elements which are used to complete a table. More precisely, a pairwise comparison is performed between each couple of candidates in the SC considering a criterion at a time. In one of the most common versions of AHP, for each difference of candidate performance indices in relation to each criterion the method assesses a score, i.e. it assigns a low value for small differences and a high value for large differences. Obviously, such a score scale is subjective and several variants of the method have been proposed in the related literature according to different scales. For the sake of simplicity, in the following we make use of Saaty’s original AHP scale (Saaty et al. 2003, Zanakis et al. 1998). The first row of table 4 shows the possible range of differences obtained in the comparison and the second row reports the assigned scales. After the pairwise comparisons are completed, AHP produces a ranking of the candidates according to the contribution of each alternative to the total effort of all the candidates. Referring to the input values shown in table 1, table 5 shows the final ranking of the candidates. Similarly to the Electre method, the AHP outranking relation is obtained here in the Matlab framework.

3.1.3 The DEA Method

DEA is a heuristic procedure for estimating the relative efficiency of a group of actors (such as the members of a supply chain). Moreover, DEA is a multi-criteria analysis method based on the linear programming theory and, for this reason, it requires limited and simple computational resources. Let us suppose that we have a set of $n$ possible actors candidate to compose a generic stage of the SC. Hence, a subset of $m$ criteria is considered as inputs and a subset of $s$ criteria are considered as outputs. Therefore, the efficiency $h_j$ of the $j$-th candidate, with $j=1,\ldots,n$ is defined as follows:

$$h_j = \frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i z_{ij}}$$

(1)

where $u_r$ is the weight associated with the output $r$ with $r=1,\ldots,s$;

$v_i$ is the weight associated with the input $i$ with $i=1,\ldots,m$;

$y_{rj}$ is the value of the $r$-th output of candidate $j$;

$z_{ij}$ is the value of the $i$-th input of candidate $j$. 

[Insert table 4 about here]

[Insert table 5 about here]
The DEA method optimizes the efficiency of the generic candidate \( j_0 \) subject to the constraints imposing that all the efficiencies associated with the remaining candidates are minor than or equal to one. On the basis of the notation (1) the optimization problem can be defined as follows:

\[
\max h_0 = \frac{\sum_{r=1}^{s} u_r y_{rj_0}}{\sum_{i=1}^{m} v_i z_{ij_0}}
\]

subject to

\[
\frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i z_{ij}} \leq 1, j = 1, \ldots, n
\]

with

\[
u_r, v_i \geq 0, \quad r = 1, \ldots, s, \quad i = 1, \ldots, m
\]

The problem (2)-(4) can be re-written as a linear programming problem (Charnes et al. 1978, Thanassoulis 2001). In particular, we apply the DEA method to the case study considering RM and E as inputs, representing the costs associated to the candidates under study. Moreover, the remaining criteria, i.e. FL, T and Q, are considered as outputs. The values associated with the inputs are the complement to 100 of the scores reported in table 1 (i.e. values \( z_{ij} \) are the complement to 100 of the elements in the first two rows of table 1) and the values associated with the outputs are the scores of the performance indices (i.e. values \( y_{rj} \) are the elements in the rows from third to last of table 1).

Table 6 reports the efficiencies of the candidates obtained with the DEA method, showing that the best partners according to the technique are \( n_3^c \), \( n_4^c \), \( n_5^c \) and \( n_7^c \), which are associated with a unitary efficiency.

[Insert table 6 about here]

### 3.2 Comparing Electre, AHP and DEA Methods

In the candidate selection methods considered, the determination of the thresholds and weights may present considerable cognitive difficulties. Indeed, most often the decision maker team makes such crucial decisions by reducing the complexity of the objective
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and using heuristic techniques. As a result, while such simplifications facilitate the actual decision process, they inevitably lead to sub-optimal results. In addition, evaluating the behaviour of the three previously used methods, some differences may be observed:

- the Electre method is based on common sense techniques, that are typical in a decision process. However, the main flaw of the methodology is that the resulting candidate ranking depends on the choice of the threshold values, as well as on the number of available alternatives. In fact, when the latter are numerous, taking into account the various performance criteria in the choice of thresholds and weights becomes impractical;
- the advantage of the AHP method is the possibility for the decision makers to use qualitative decisions based on pairwise comparisons of the alternatives. A disadvantage is the necessity to repeat all the pairwise comparisons if a new alternative has to be added;
- the DEA method does not produce an actual classification of the alternatives: it rather carries out, using the linear programming technique, an efficiency evaluation, giving as an output the set of efficient actors. In addition, the technique evaluates the level of inefficiency associated with the remaining candidates. The main advantages of this method are its straightforwardness and flexibility in adding a novel alternative to the existing candidate sets.

A comparison of the results of the Electre, AHP and DEA methods shows that, even though the candidates classification is different in the corresponding solutions (see tables 3, 5 and 6), several manufacturers are assigned a similar ranking position in both procedures: as an example, alternative n5 is evaluated as the best partner by Electre, AHP and DEA; in addition, candidate n9 is assigned low weights both in the Electre and AHP techniques and is not even present in the most efficient solutions set provided by the DEA method.

4 Network Design Module

This module applies optimization algorithms to the IESC resulting from the previous level of the hierarchical decision structure and determines the optimal sub-networks according to the objectives and the constraints indicated by the decision maker. Moreover, the user can select different objectives: operative cost functions, cycle time, energy saving, environmental costs etc. In addition, by imposing the appropriate constraints, the designer can ask for: a certain number of manufacturers (or customers); the presence of a specific link in the solution; the presence of a particular subnet (e.g. in the case of SC expansion) in the solution.

4.1 IESC Network Model

This section describes the model of the generic IESC network. We assume that the network contains a set of consecutive SC stages \( ST = \{P_1, ..., P_k, ..., P_{N_S}\} \), where \( N_S \) is the number of stages. In particular, each stage \( P_k \), obtained according to the procedure reported in Section 3, is described as a set of \( s_k \) partners representing different actors of
the SC, i.e. \( P_k = \{ n_{i_k}, n_{i_k+1}, n_{i_k+2}, \ldots, n_{i_k+s_k-1} \} \), where \( i_k \) is the generic index such that
\[
 i_k = \sum_{h=1}^{k-1} s_h \quad \text{with } k=2,3,\ldots,N_s \text{ and } i_1=1.
\]
We suppose that there are \( N \) partners in the system.

Moreover, the partners of different IESC stages can be connected by material flow and information links. More precisely, a material flow link (i.e. \( m \)-link) represents the physical transportation link between two partners. Multiple \( m \)-links are allowed between two partners to model different transportation modes or split delivery routes. In addition, two partners can be connected by an \( e \)-link, i.e. an e-business relationship between business entities for streamlining the material flow efficiently and effectively. An \( e \)-link can speed up the communication process between entities and thus reduce the response time affecting IESC performance measures such as cost, productivity and energy use of partners and \( m \)-links in the material flow network. Obviously, an \( e \)-link may connect two partners of the IESC also without the presence of an \( m \)-link. Hence, the proposed structure is able to extend the traditional SC into a more sustainable and integrated production system. The set \( L_m = \{ m_{ij} \} \) collects the \( m \)-links, where \( m_{ij} \) is an \( m \)-link starting from \( n_i \in P_k \) and ending in \( n_j \in P_h \), with \( P_k, P_h \in ST \) and \( k \neq h \). Moreover, the set \( L_e = \{ e_{ij} \} \) denotes the \( e \)-link set, where \( e_{ij} \) is an \( e \)-link starting from \( n_i \in P_k \) and ending in \( n_j \in P_h \), with \( P_k, P_h \in ST \) and \( k \neq h \). We assume that two partners can be connected by \( m \)-links and/or by \( e \)-links. Figure 2 depicts a generic IESC network.

We remark that IESC partners belonging to the same stage are not connected by links. Indeed, at this decision level we have to choose among alternative and competitive partners belonging to the same stage. Hence, we assume that there is no connection among the partners of one stage and material and information flow through different stages. On the other hand, detailed flow of material and information between IESC partners could be considered at the operational level, where cooperation among actors of the same stage can be present.

Finally, to define the performance indices associated with the IESC network, we introduce the set \( M = \{ M_1, M_2, \ldots, M_{NM} \} \), where each element \( M_q \in M \) corresponds to a performance measure assigned to each link, considering \( m \)- and \( e \)-links. Particularly, \( M_q(m_{ij}) \) (\( M_q(e_{ij}) \)) with \( q=1,\ldots,N_M \) denotes the value of the performance measure \( M_q \) associated with the link \( m_{ij} \in L_m \) (\( e_{ij} \in L_e \)). Typical indices include cost, cycle time, product quality, energy consumption and environmental impact (Beamon 1999, Viswanadham and Srinivasa Raghavan 2000, Luo et al. 2001).

4.1.1 Case Study (Continued): the IESC Network. We suppose that the supply chain obtained from the first decision module is composed of \( N_S = 6 \) stages (see figure 3): four suppliers, one manufacturer, two distributors, two retailers, one consumer and four recyclers, for a total of \( N = 14 \) partners. Note that the second stage is \( P_2 = \{ n_3 \} \), i.e. one manufacturer only has been included in the SC network by the decision maker, on the
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basis of the Electre (or DEA or else AHP) results. Clearly, with reference to the results obtained in Section 4, actor \( n_5 \) in the supply chain represents the manufacturer previously indicated by \( n_5 \). The IESC exhibits the \( e \)-links \( e_{18}, e_{17}, \) and \( e_{4,10} \), the \( m \)- and \( e \)-links \( m_{18}, e_{78}, m_{79}, e_{79}, m_{7,10}, e_{7,10}, m_{9,10}, e_{9,10}, m_{8,10} \), and \( e_{8,10} \), while the remaining links are \( m \)-links.

The data for the case study are reported in table 7 (Luo et al. 2001) that shows the values of each performance index \( M_q \) with \( q=1,2 \) and 3 associated with the links of the considered IESC. More precisely, the adopted performance indices are total costs (\( M_1 \)), energy (\( M_2 \)) and \( CO_2 \) emission (\( M_3 \)). Furthermore, the performance index values reported in table 7 depend on the type of link (\( m \)- and/or \( e \)-link), the distance between the connected SC partners, the transportation mode (truck, car, airplane etc.) and the type of material to be transported. For example, the first and third rows in table 7 correspond to an \( e \)-link and \( m \)-link respectively. Hence, the values of the indices associated with the latter link are higher. Moreover, the cost and energy performance indices reported in the last two rows of table 7, respectively associated with links \( m_{11,5} \) and \( m_{14,3} \) are negative. In fact, in the recycler stage \( P_6 \) partner \( n_{11} \) is a de-manufacturer, with an output link \( m_{11,5} \) connecting to manufacturer \( n_5 \), and partner \( n_{14} \) is a material recoverer, with an output link \( m_{14,3} \) connecting to supplier \( n_3 \) (see figure 3). Hence, the total cost and energy associated with links \( m_{11,5} \) and \( m_{14,3} \) are negative, i.e. they correspond to recycling material and parts.

4.2 The Digraph Definition

To exhibit the interactions among the stages of the IESC, we define a direct graph \( D=(N,E) \). The node set \( N \) represents the partner set of the network and each node \( n_i \in N \) for \( i=1,...,N \) is associated with partner \( n_i \in P_k \) for \( k \in \{1,...,N_S\} \) of the SC network. For the sake of simplicity, the same symbols indicate nodes and partners. Moreover, the edge set \( E \) is such that an arc \( x_i \) directed from \( n_i \) to \( n_j \) is in \( E \) if and only if there exists an \( m \)-link \( m_{ij} \in L_m \) and/or an \( e \)-link \( e_{ij} \in L_e \). We denote with \( E \) the number of edges in \( D \).

4.2.1 Case Study (Continued): the Associated Digraph. Figure 4 depicts the digraph describing the IESC for the case study. The digraph \( D=(N,E) \) includes \( N=14 \) nodes and \( E=23 \) edges. Edges \( x_1, x_2, \) and \( x_7 \) are associated with \( e \)-links only, edges \( x_{13}-x_{17} \) are associated both with \( m \)- and \( e \)-links and the remaining edges of the digraphs are associated with \( m \)-links only (see table 7).

4.3 The Optimization Model

Having defined the digraph depicting the interactions among the stages of the IESC, it is necessary to develop the optimization model for partner selection by using the available information on costs, \( CO_2 \) emission and energy. The mathematical model is based on the combinatorial characteristics of the IESC and an integer linear programming
problem is obtained considering multi-criteria optimization techniques. The objective of the model is to minimize a multi-criteria cost function subject to a set of constraints (bill of material, path, mutual exclusion and structural constraints). The objective function and the constraints are obtained on the basis of the analysis of the direct digraph describing the IESC structure (Mangini 2003).

Let us consider a performance index $M_q$ that assigns to each link $m_{ij}$ the value $M_q(m_{ij})$. Consequently, $M_q(m_{ij})$ is associated with edge $x_{h} \in E$ connecting $n_i \in P_k$ to $n_j \in P_h$. Analogously, the value $M_q(e_{ij})$ is assigned to link $e_{ij}$ and to the corresponding edge $x_{h} \in E$ connecting $n_i \in P_k$ to $n_j \in P_h$. Let us indicate with $c_q=\begin{bmatrix} c_{q1} & c_{q2} & \cdots & c_{qE} \end{bmatrix}^T$ the vector of $E$ entries where the $h$-th entry is $c_{qh}=M_q(e_{ij})$ and/or $c_{qh}=M_q(m_{ij})$ associated with edge $x_{h} \in E$. Moreover, we denote by $x=\begin{bmatrix} x_1 & x_2 & \cdots & x_E \end{bmatrix}^T$ an integer vector where each element $x_h \in \{0, 1\}$ with $h=1, ..., E$ indicates the presence ($x_h=1$) or the absence ($x_h=0$) of the link $x_{h} \in E$ connecting $n_i \in P_k$ to $n_j \in P_h$ in the IESC structure. The optimization problem is the following:

$$z=\min f(x)$$ (5)

subject to

$$Ax \geq B$$ (6)

$$x_h \in \{0, 1\} \text{ for } h=1, ..., E$$ (7)

where $A$ is the constraint matrix of dimension $v \times E$ and $B$ is a $v$-vector of integers, $v$ representing the number of constraints. Minimizing the objective function $f(x)$ means to minimize a subset of the chosen performance indices, i.e. $f(x)$ represents a multi-objective function defined as follows:

$$f(x)=Cx$$ (8)

where $C = \begin{bmatrix} (c^{q1})^T \\ \vdots \\ (c^{qQ})^T \end{bmatrix}$ is a $qQ \times E$ criteria matrix and $c^{q1}, ..., c^{qQ}$ are vectors associated with performance indices $M_{q1}, ..., M_{qQ}$, respectively.

The multi-criteria linear program solving (5)-(8) for a particular matrix $C$ provides the maximal Pareto face of the solutions set (Ehrgott 2000). More precisely, we obtain a sub-set of solutions $X^*=\{x^*_i\}$ where each $x^*_i \in X^*$ is a Pareto optimal solution corresponding to a sub-digraph $D^*=\langle N^*_i, E^*_i \rangle$ of $D$ where $N^*_i \subseteq N$ and $E^*_i \subseteq E$, respectively. If the $h$-th entry of $x^*_i$ is $x^*_ih=1$ and $x_{h}$ is an edge outgoing from $n_i \in P_k$ and incoming to $n_j \in P_h$, then the solution $x^*_i$ selects edge $x_{h} \in E^*_i$ and the nodes $n_i,n_j \in N^*_i$ for the IESC network structure.
5 Network Design of the Case Study

To illustrate the network design module, the described case study is considered and some computational experiments are performed minimizing cost, CO₂ emission and energy consumption. The solutions are obtained implementing the well-known two-phase simplex method in the Matlab framework (Venkataraman 2001): details on the optimization problem definition can be found in Mangini (2003).

The multi-objective optimization problem is solved considering the following performance indices: costs and CO₂ emission ($f_1$), energy and CO₂ emission ($f_2$), costs, energy and CO₂ emission ($f_3$). Tables 8-10 report for each optimal point on the maximal Pareto faces of the multi-objective functions $f_1$-$f_3$ the corresponding performance indices and the selected arcs of the IESC network.

The obtained results show the efficiency of the proposed method, that is able to provide a set of optimal solutions. For example, solution $x_A$ ($x_C$) obtained minimizing $f_1$ ($f_2$) exhibits the minimum cost (CO₂ emission). However, solution $x_A$ in table 8 corresponds to a large value of CO₂ emission, and solution $x_C$ in table 9 corresponds to a large value of energy. On the contrary, solutions $x_B$ and $x_C$ of table 8 both exhibit a good value of costs and of CO₂ emission. Moreover, minimizing objective function $f_3$ we obtain solution $x_D$ in table 10 featuring satisfactory values of costs, energy and CO₂ emission. In other words, the benefits of using a multi-criteria optimization approach are in the fact that the method enables us to choose among several near-optimal solutions. The digraphs corresponding to solutions $x_C$ in table 8, $x_B$ in table 9 and $x_D$ in table 10 are depicted in figures 5-7, respectively. Moreover, we neglect representing the digraphs corresponding to all the different solutions obtained minimizing $f_1$-$f_3$. In fact, such digraphs may easily be obtained from the last columns in tables 8-10 respectively.

6 Solution Evaluation/Validation Module

The purpose of this module is to evaluate alternative IESC network configurations obtained from the higher levels with respect to tactical and operational performances representing resources (costs, utilization and inventory), output (quality, lead times) and flexibility (lead-time, lead time variability) (Beamon 1999, Persson and Olhager 2002). At this level of the decision process it is necessary to increase the understanding of the interrelationships among parameters, relevant for describing the IESC at the operational level, such as operation and transportation times, global capacities of manufacturing facilities, pull demand from detailers, push raw material from suppliers. In order to
capture these relationships, analytical models and simulation models can be alternatively used. In particular, analytical models include discrete event models that are particularly suitable for the verification of distributed manufacturing systems. In such a modelling approach the evolution of the system depends on the complex interaction of the timing of various discrete events such as arrivals of components at the suppliers, departures of trucks from the suppliers, beginning of assembly operations at the manufacturers, arrivals of finished goods at the customers, payment approvals by the sellers etc. (Viswanadham and Srinivasa Raghavan 2000). Despite the appropriateness of discrete event models to represent IESC, they can not be detailed enough to handle all the relevant parameters of complex supply chain systems. Hence, simulation can represent a more general and efficient instrument to evaluate alternative SC designs and to validate an IESC network configuration (Jansen et al. 2001). Very attractive general purpose simulation packages are now available to model a manufacturing enterprise: these include ARENA, SIMPROCESS, Taylor II, and so forth.

Summing up, comparing different IESC network design solutions and analyzing the system behaviour in the presence of additional details or uncertainties allows us to determine the performance of a given solution (or decision) at the tactical and operational levels. Hence, the decision making process to configure the IESC is closed by this module, that is able to evaluate/validate the optimal or near optimal solution. As specified in Section 2, if the third level results are not satisfying, it may be necessary to select different solutions among the network structures obtained at the first and second levels, in order to improve the IESC performance. The obtained design strategy results in a closed-loop decision making procedure.

7 Conclusions

The Integrated E-Supply Chain (IESC) is a business strategy that incorporates the power of e-commerce to streamline the manufacturing processes. An IESC system has a more complex structure than a traditional Supply Chain (SC) system, since it embraces the e-business strategy to establish information links and integrates end-of-life processes into the entire SC structure.

This paper presents a hierarchical approach to design and configure an IESC at the strategic planning level. A decision making structure composed of three hierarchical levels differing in data requirements, performance index utilization and output solutions is proposed. More specifically, the first level (candidate selection module) uses aggregate performance indices and optimization techniques to obtain a rank of possible candidates for each stage of the IESC. To perform the solutions, some optimization multi-criteria models are proposed and analyzed showing a case study. In the second level (network design module), the structure of the IESC is modelled by a digraph, describing the actors of the stages and the material and information links connecting the stages and an integer multicriteria optimization model is stated. Such a multicriteria optimization methodology is applied to a case study inspired by an IESC producing desktop computers that is described in the related literature. The multi-objective problem solution proposes different structures for the IESC on the basis of a set of chosen performance indices and costs. Finally, the third level (solution evaluation/validation module) analyzes and evaluates the optimal or sub-optimal solution networks obtained at the previous levels by comparing tactical and operational...
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performance indices. The evaluation of the performance measures tests the design of the IESC as obtained from the candidate selection and network design levels and provides some feedback modifications if the performance indices do not fit the tasks of the IESC. However, the third module is not described in detail: the model definition and the performance evaluation at this level of the decision structure are the subject of future research and study.

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References


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Table 1. Performance matrix of manufacturers with scores for each criterion.

Table 2. Thresholds and weights for the Electre method.

Table 3. Manufacturers ranking according to the Electre method for the case study.

Table 4. AHP point ratio scales for the case study.

Table 5. Manufacturers ranking according to the AHP method for the case study.

Table 6. Manufacturers efficiency according to the DEA method for the case study.

Table 7. Data sheet for the network links in the case study.

Table 8. The values of the performance indices corresponding to the optimal solutions of the multi-objective function costs and CO\textsubscript{2} emission (min(f\textsubscript{1})).

Table 9. The values of the performance indices corresponding to the optimal solutions of the multi-objective function energy and CO\textsubscript{2} emission (min(f\textsubscript{2})).

Table 10. The values of the performance indices corresponding to the optimal solutions of the multi-objective function cost, energy and CO\textsubscript{2} emission (min(f\textsubscript{3})).
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Figure 1. The hierarchical structure of the IESC configuration procedure.

Figure 2. The structure of a generic IESC.

Figure 3. The stages of the IECS network for the case study.

Figure 4. The digraph associated with the IESC of the case study.

Figure 5. Digraph representing solution $x_C$ of table 8.

Figure 6. Digraph representing solution $x_B$ of table 9.

Figure 7. Digraph representing solution $x_D$ of table 10.