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A hierarchical optimization technique for the strategic design of distribution networks ☆

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ABSTRACT

The paper addresses the optimal design of the last supply chain branch, i.e., the Distribution Network (DN), starting from manufacturers till the retailers. It considers a distributed system composed of different stages connected by material links labeled with suitable performance indices. A hierarchical procedure employing direct graph (digraph) modeling, mixed integer linear programming, and the Analytic Hierarchy Process (AHP) is presented to select the optimal DN configuration. More in detail, a first-level DN optimization problem taking into account the definition and evaluation of the distribution chain performance provides a set of Pareto optimal solutions defined by digraph modeling. A second level DN optimization using the AHP method selects, on the basis of further criteria, the DN configuration from the Pareto face alternatives. To show the method effectiveness, the optimization model is applied to a case study describing an Italian regional healthcare drug DN. The problem solution by the proposed design method allows improving the DN flexibility and performance.

1. Introduction

Supply chain (SC) design and optimization is a foremost research theme in enterprise management, due to the growing market requirements and recent advances in logistics and information technology (Costantino, Dotoli, Falagario, Fanti, & Mangini, 2012; Dotoli, Fanti, Iacobellis, & Mangini, 2009; Dotoli et al., 2006; Dotoli et al., 2005; Gaonkar & Viswanadham, 2005; Min & Zhou, 2002). Within the SC strategic design issues, distribution is a key driver of the overall profitability of a firm, since it impacts both the SC cost and customer experience (Chopra, 2003; Costantinoet al., 2011). Indeed, the Distribution Network (DN) is a particular example of SC that is built to bring a set of final products (which do not have to undergo assembly or transformation processes) from the producers to the final consumers. Significant DN examples are the distribution chains of big department stores (e.g., Wal-Mart) or those of national health service drug distribution systems.

This paper focuses on the strategic design of the SC distribution part. The literature about SC management offers numerous examples of operations research models for the strategic design and optimization of the SC (Tanonkou, Benyoucef, & Xie, 2008; Nunkaew and Phruksaphanrat (2009), Afshari, Amin-Najeri, & Jaafari, 2010). Some of these models address the distribution issues, and a classification of the contributions to the DN strategic design can be found in (Tanonkou et al., 2008). A simplified approach to the issue of distribution chain configuration is the transportation problem, used when actors of the network already exist: for instance, Nunkaew and Phruksaphanrat (2009) propose a bi-objective lexicographic goal programming method to solve such a problem. The related literature also proposes multi-objective approaches focused on DN design, allowing to choose among different alternative actors (Afshari et al., 2010). However, in most of the existing contributions the DN is usually regarded as a part of the SC: for instance, Jang, Jang, Chang, and Park (2002) divide the SC into three components, namely the outbound network, the distribution network and the inbound network, and select the SC actors by successive optimization procedures. In addition, later on Miranda, Garrido, and Ceroni (2009) propose a collaborative approach based on information sharing throughout the SC for the minimization of storage and transportation costs. As a result, distribution models are generally complex, because many variables and constraints are considered, so that the optimization problem solution usually leads to high computational costs. However, since the distribution part plays a crucial role in the management of a SC,

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a separate analysis and design of the DN from the SC is recommended (Davidrajuh & Ma, 2006). Such an approach to a separate DN plan leads to design problems that are less difficult to solve than those obtained considering the DN as a part of the SC, even when either operational costs and capacity investments are non-linear (Nagurney, 2010a) or a complex optimization framework is considered, e.g., in the case of a set of focal firms converging towards an oligopolistic equilibrium (Nagurney, 2010b). Indeed, in the case of a separate DN plan it is possible to take only final products into account, while otherwise it is necessary to distinguish among raw materials, components, subassemblies, and final products, and to consider bill of materials constraints.

Typically, the existing contributions treat simultaneously DN design problems with different time horizons, i.e., strategic, tactical and operational. For instance, Ambrosino and Scutellà (2005) present an integrated DN decision problem treating simultaneously location, allocation, routing and inventory decisions. Similarly, Tanonkou et al. (2008) propose an inventory-location model taking into account the Economic Order Quantity policy and the cost of safety-stock. Due to the complexity of such an integrated problem, the resulting practical solution of the formulated problem is usually obtained by way of a relaxation procedure. For example, in the cited work by Tanonkou et al. (2008) the obtained non-linear model is solved by means of a Lagrangian relaxation approach.

This paper presents a two level optimization model for efficient strategic configuration (or re-configuration) of the DN from manufacturers to retailers based on direct graph (digraph) modeling, mathematical programming, and the widespread Analytic Hierarchy Process (AHP) decision making technique. In the first level optimization we consider a distributed system composed of different stages connected by material links labeled with suitable performance indices. The DN structure is modeled by a two level digraph. More in detail, the First Level Digraph (FLD) depicts the network structure describing the actors (the nodes of the digraph) and their connections (the edges of the digraph). In addition, the Second Level Digraph (SLD) is a more detailed and extended version of the FLD, in which each first level node is substituted by a sub-digraph detailing the product types available at each actor and the different possible transportation means used by such an actor. Moreover, the edges of the FLD representing the flow of material between two actors are substituted by multiple connections representing different products and different modes for transportations. Each SLD edge is associated with a variable expressing the quantity of product units flowing through an actor of the distribution chain or from a stage to a subsequent one. These variables are used to evaluate the DN performance and choose the actors which can optimize it. In particular, a Mixed Integer Linear Programming (MILP) problem is formulated to optimize the DN configuration considering material connections and providing a set of Pareto face solutions. Since selecting one among such DN configurations may be a complex task, if the dimension of the solutions set is large, we rank the solutions against some further criteria using a second level multi criteria optimization. To this aim, we apply the well-known AHP technique (Saaty, 2004; Saaty, 2008) to rank the optimal alternatives and select the most effective one. AHP is a multi-objective decision technique in which all the decision problem elements (overall goal, criteria, and alternatives) are arranged into a hierarchical structure and objectives are of varying degrees of importance. Although different optimization methods often lead to similar results, here we select AHP because it relies on pairwise comparisons of the solutions, providing an accurate approach to rank alternatives based on their reciprocal assessment. The methodology is flexible in building the optimization constraints, improving agility, performance and re-configurability in the DN design. For instance, it is possible to add or substitute constraints representing the presence or absence of a link and to select different performance indices. To show the efficiency of the two-level strategy, the optimization model is applied to a case study describing an Italian healthcare regional DN. The problem solution by the proposed design method allows improving the DN flexibility and performance.

The remainder of the paper is organized as follows. Section 2 presents the notation used throughout the paper. Hence, Section 3 presents the DN digraph model and Section 4 describes the proposed two-level optimization procedure for the distribution chain strategic configuration. In addition, Section 5 applies the proposed approach to the case study and Section 6 draws the conclusions. Finally, the Appendix reports the case study data and some solutions to the considered MILP problem.

2. Notation

The following notation is used throughout the paper.

2.1. Indices

K	number of stages in the DN
I_k	number of actors in the kth stage
$S_k = \{n_{i_k}, n_{i_k+1}, \ldots, n_{i_k+I_k-1}\}$ with $k = 1, 2, \ldots, K$	generic kth stage of the DN including I_k actors
$i_k = \sum_{h=1}^{k-1} I_h$	index of the first actor belonging to the kth stage
$I = \sum_{k=1}^{K} I_k$	total number of DN actors
$\bigcup_{k=1}^{K} S_k = \{n_1, \ldots, n_I\}$	set of actors constituting the DN
$\Delta = \{d\colon d = 1, 2, \ldots, D\}$	products set of the DN
$\Delta_i \subset \Delta$	subset of products distributed by the ith actor n_i
$\Theta = \{t : t = 1, 2, \ldots, T\}$	DN transportation modes set
$\Theta_i \subset \Theta$	subset of transportation modes by the ith actor
Pre_i	set of actors providing products to the ith actor n_i
Post_i	set of actors receiving products from the ith actor n_i
$\Lambda = \{1, 2, \ldots, L\}$	DN performance set of generalized costs
$\xi_1, \ldots, \xi_8$	labels of structure, capacity, demand, and existence constraints of the DN

2.2. Decision variables

$x_{i,d} \in \mathbb{R}^+$	quantity of product d provided by the ith actor n_i (units/year)
$y_i \in \mathbb{R}^+$	overall quantity of products provided by the ith actor n_i (units/year)
$w_{i,j}^{t} \in \mathbb{R}^+$	quantity of product d leaving the ith actor n_i by the tth transportation mode (units/year)
$z_{i,j}^{d,t} \in \mathbb{R}^+$	quantity of product d provided by the ith actor n_i to the jth actor n_j by the tth transportation way (units/year)
$r_{i,d} \in \{0, 1\}$	binary variable modeling the fact that actor n_i supplies (does not supply) product d
$s_i \in \{0, 1\}$	binary variable modeling the presence or absence of actor n_i in the DN
$\upsilon_{i,j}^{d,t} \in \{0,1\}$	binary variable modeling the transportation (absence of transportation) of the dth product by the tth transportation mode from actor n_i to n_j

2.3. Parameters

$a_{i,d}^{l}$ average unit cost of distribution of product d by the jth actor n_i (e.g., summation of the purchase costs, the holding costs, the pollutant emissions for unit)
b_i^l average unit cost of a generic product distribution by the jth actor n_i (independently from which kind of product it is)
$c_{i,j}^{l,d,t}$ average unit cost of transportation of product d from the ith actor n_i to the jth actor n_j via the tth transportation mode
$d_{i,d}^{l}$ average cost of the assignment to generic supplier $n_i \in S_1$ of the distribution of product d
e_i^l average cost associated with the presence of the ith actor n_i in the DN
$f_{i,j}^{l,d,t}$ average cost associated with the presence of a transportation link from the ith actor n_i to the jth actor n_j for the flow of product d by transportation mode t
$C_{i,d}$ maximum production capacity for product $d \in \Delta_i$ of DN producer $i \in \{1, 2, \ldots, I_1\}$ (units/year)
C_i maximum warehouse processing capacity of generic actor $n_i \in S_k$ with $k \in \{2, \ldots, K-1\}$ (units/year)
$O_{i,d}$ average product demand by retailers $n_i \in S_K$ for the product $d \in \Delta_i$ (units/year)

3. The distribution network model

3.1. The two level digraph model

To model the DN and the connections among stages in the design time period (that we assume equal to one year), we introduce two digraphs describing the DN at different detail levels. More precisely, the FLD depicts the network structure with the actors (the nodes of the digraph) and their connections (the edges of the digraph). In addition, the SLD is a more detailed graph of the FLD, obtained by substituting each first level node by a sub-digraph describing the product types available at each actor and the different possible transportation means used by such an actor. Moreover, the edges of the FLD, representing the material flow between two actors, are substituted by multiple connections representing different products and modes of transportation. In the sequel we formally define the two digraphs.

We define the FLD by the pair $\mathbf{D_F} = (\mathbf{N_F}, \mathbf{E_F})$, where $\mathbf{N_F}$ is the set of nodes representing the DN actors and $\mathbf{E_F}$ is the edge set and each edge represents a material connection between two actors in different stages. For the sake of simplicity, the same symbols indicate nodes in $\mathbf{N_F}$ and actors in $\bigcup_{k=1}^{K} S_k$. More precisely, a generic actor $n_i \in S_k$ is connected with a downstream node $n_j \in S_{k'}$ with $k' > k$ by an edge directed from actor n_i to n_j if there exists at least a transportation means connecting n_i to the downstream actor n_j. Fig. 1 shows an example of a FLD representing a DN that exhibits I actors, K stages, and several edges connecting them.

To detail the product types and transportation means available at each actor, we define the SLD $\mathbf{D_S} = (\mathbf{N_S}, \mathbf{E_S})$, where $\mathbf{N_S}$ is the node set and $\mathbf{E_S}$ is the edge set. More precisely, in the SLD the generic actor n_i of the DN is further characterized representing it by the sub-digraph shown in Fig. 2: two nodes α_i and β_i are associated with the presence of the actor, a node $\delta_{i,d}$ is associated with each product type $d \in \Delta_i$, and a node $\tau_{i,d,t}$ is associated with each product $d \in \Delta_i$ and with each possible transportation mode $t \in \Theta_i$.

In the SLD the edges of the sub-digraph describing each actor $n_i \in S_k$ are of four types and a real variable with the same name

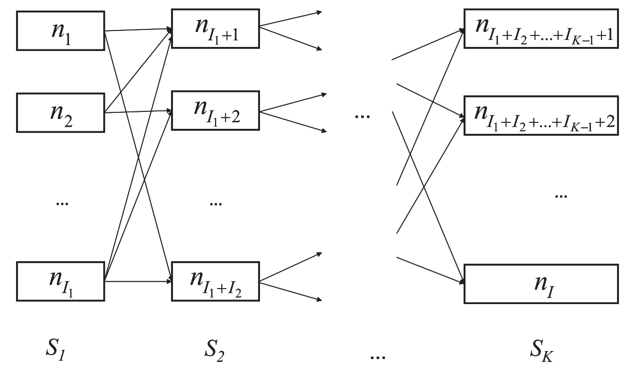

Fig. 1. The first level digraph describing the DN.

(see the notation in Section 2) is associated with each edge. In particular:

(1) arcs $x_{i,d}$ are from a node β_i to a node $\delta_{i,d}$ and the variable $x_{i,d} \in \mathbb{R}^+$ represents the quantity of product d provided by actor n_i per year;
(2) arcs y_i are from a node α_i to a node β_i and the variable $y_i \in \mathbb{R}^+$ expresses the overall quantity of products provided by actor n_i per year;
(3) arcs $w_{i,d}^{t}$ are from a node $\delta_{i,d}$ to a node $\tau_{i,d,t}$ and the variable $w_{i,d}^{t} \in \mathbb{R}^+$ represents the quantity of product d leaving actor n_i by the t transportation mode;
(4) arcs $z_{i,j}^{d,t}$ are from $\tau_{i,d,t}$ of actor $n_i \in S_k$ to node α_j of a downstream actor $n_j \in S_{k'}$ with $k' > k$ and the variable $z_{i,j}^{d,t} \in \mathbb{R}^+$ represents the quantity of product d provided by actor n_i to n_j per year by the tth transportation way.

All these variables are design variables, which are used in the following optimization procedure in order to determine the optimal DN configuration. Note that the presence or the absence of these arcs in the DN digraph affects its performance. This performance is evaluated in terms of costs (both monetary and nonmonetary) arising during the DN implementation and operation. The L performance measures of the DN in the set of generalized costs $\Lambda = \{1, 2, \ldots, L\}$ are used in this study to evaluate such an impact. In order to increase the general targeting of the optimization

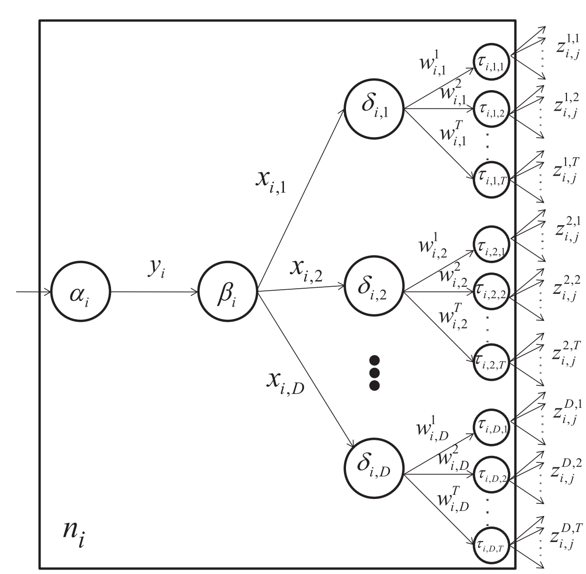

Fig. 2. The second level digraph describing a generic actor of the DN.

procedure, we introduce different kinds of generalized cost coefficients, as illustrated in Section 2.3. Moreover, also the quantities of products managed by a DN actor influence the performance, in a way which can either be independent on the type of products flowing in the multi-product DN (in this case the variables $y_i \in \mathbb{R}^+$ and the coefficients b_i^l can be used for performance assessment) or else can vary for each of the D products supplied in the multi-product DN (in this case the variables $x_{i,d}$ and the coefficients $a_{i,d}^l$ can be used for performance assessment). In addition, we highlight that, due to the strategic target of this study, although both monetary and nonmonetary costs can change in time and during different periods of the year, average cost coefficients are taken into account in this study for the sake of simplicity.

4. The proposed optimization procedure

This section introduces the two-step optimal design of the DN. The first step is based on the definition of a multi-objective MILP problem. The solution of such a problem provides a set of DN configurations forming a Pareto face (Ehrgott, 2000). In order to choose the best alternative among these solutions, a second level optimization procedure is applied, based on the use of the well-known AHP procedure that provides a ranking of the obtained DN configurations.

4.1. The first level optimization: objective function and constraints

The procedure starts from the definition of the FLD $\mathbf{D_F} = (\mathbf{N_F}, \mathbf{E_F})$ and the more detailed SLD $\mathbf{D_S} = (\mathbf{N_S}, \mathbf{E_S})$ that takes into account all the possible actors belonging to the DN and all the possible links that can connect them. Hence, the aim of the considered optimization technique is selecting a sub-digraph $\mathbf{D_S^*} = (\mathbf{N_S^*}, \mathbf{E_S^*})$ with $\mathbf{N_S^*} \subset \mathbf{N_S}$ and $\mathbf{E_S^*} \subset \mathbf{E_S}$ and the material flows flowing through it, defined by the variables $x_{i,d}$, y_i, $w_{i,d}^t, z_{i,j}^{d,t} \in \mathbb{R}^+$. Such a digraph corresponds to a DN configuration satisfying a set of constraints and exhibiting optimal or sub-optimal performance indices. More precisely, the objective of the model is to minimize a multi-objective function subject to the constraints that we characterize as structure, capacity, demand, and existence constraints.

To define the optimization problem, a triplet of binary variables is introduced for each actor n_i of the DN: $r_{i,d}$, s_i and $\upsilon_{i,j}^{d,t}$ (see Fig. 2). More in detail, variable $r_{i,d} \in \{0, 1\}$ is associated with edge $x_{i,d} \in \mathbf{E_S}$: $r_{i,d} = 1$ (=0) means that actor n_i supplies (does not supply) product d. In the same way, variable $s_i \in \{0, 1\}$ is associated with edge $y_i \in \mathbf{E_S}$ and its value indicates the presence ($s_i = 1$) or absence ($s_i = 0$) of edge y_i in $\mathbf{D_S}$. Similarly, $\upsilon_{i,j}^{d,t} \in 0,1$ is associated with edge $z_{i,j}^{d,t} \in \mathbf{E_S}$ and its value indicates the presence $\left(\upsilon_{i,j}^{d,t} = 1\right)$ or the absence $\left(\upsilon_{i,j}^{d,t} = 0\right)$ of edge $z_{i,j}^{d,t}$ in $\mathbf{D_S}$.

To define the objective function, we use the set $\Lambda = \{1, 2, \dots, L\}$ of L performance indices that are associated with the edges of $\mathbf{D_S}$. Such performance indices are generalized costs that can represent for example monetary, delay, and pollution costs. Moreover, for each index $l \in \Lambda$ we define six coefficients that denote the contribution of each edge to the overall value of the performance index l. The introduction of the coefficients derive from the assumptions that the arising of monetary or nonmonetary costs derive from six factors: the managing of the dth product by the i_kth actor and the managed amount, the existence of the i_kth actor and the managed amount of products (without distinction on type), the existence of a distribution flow of the dth product between actors i_k and $i_{k'}$ and the distributed quantity. These cost occurrences are respectively monitored through variables $r_{i,d}$, $x_{i,d}$, s_i, y_i, $\upsilon_{i,j}^{d,t}, z_{i,j}^{d,t}$ and the introduced six coefficients.

Single-Objective Optimization: Based on the introduced parameters, the following objective function F_{OPT}^l for each performance index $l \in \Lambda$ is defined:

$$\begin{aligned} F_{OPT}^l &= \min F^l(x,y,z,r,s,\upsilon) \\ &= \left(\sum_{i_k}\sum_d a_{i_k,d}^l \cdot x_{i_k,d} + \sum_{i_k} b_{i_k}^l \cdot y_{i_k} + \sum_{i_k}\sum_{i'_{k'}}\sum_d c_{i_k,i_{k'}}^{l,d,t} \cdot z_{i_k,i_{k'}}^{d,t} \right. \\ &\quad \left. + \sum_{i_k}\sum_d d_{i_k,d}^l \cdot r_{i_k,d} + \sum_{i_k} e_{i_k}^l \cdot s_{i_k} + \sum_{i_k}\sum_{i'_{k'}}\sum_d f_{i_k,i_{k'}}^{l,d,t} \cdot \upsilon_{i_k,i_{k'}}^{d,t} \right) \quad \text{s.t. } \xi_1,\dots,\xi_8, \ \text{with } l \in \Lambda. \end{aligned} \tag{1}$$

Hence, F_{OPT}^l is the objective function value for the optimal solution with respect to the lth criteria in Λ subject to 8 constraints $\xi_1, \dots, \xi_8$ that we define in the sequel and represent structure, capacity, demand, and existence constraints that the DN is required to fulfil.

Multi-Objective Optimization: Having defined the various single objective functions, we may define a multi-objective problem considering the optimization of the DN configuration according to the conflicting objectives collected in set Λ as follows:

$$\begin{aligned} &\min F(x,y,z,r,s,\upsilon) \\ &= \sum_{l\in\Lambda} \lambda_l \cdot \left(\frac{\sum_{i_k}\sum_d a_{i_k,d}^l \cdot x_{i_k,d} + \sum_{i_k} b_{i_k}^l \cdot y_{i_k} + \sum_{i_k}\sum_{i'_{k'}}\sum_d c_{i_k,i_{k'}}^{l,d,t} \cdot z_{i_k,i_{k'}}^{d,t}}{F_{OPT}^l} \right. \\ &\quad \left. + \frac{\sum_{i_k}\sum_d d_{i_k,d}^l \cdot r_{i_k,d} + \sum_{i_k} e_{i_k}^l \cdot s_{i_k} + \sum_{i_k}\sum_{i'_{k'}}\sum_d f_{i_k,i_{k'}}^{l,d,t} \cdot \upsilon_{i_k,i_{k'}}^{d,t}}{F_{OPT}^l} \right) \quad \text{s.t. } \xi_1,\dots,\xi_8, \end{aligned} \tag{2}$$

$$\text{with } \sum_{l\in\Lambda} \lambda_l = 1, \quad \lambda_l \in \mathbb{R}^+. \tag{3}$$

Coefficients λ_l in (2), (3) allow us to solve a multi-objective problem by means of a weighted sum scalarization (Ehrgott, 2000). In particular, in such a scalarization all combinations of such coefficients are considered with a fixed step so as to determine a Pareto solution set.

Hence, both the single-and multi-objective problems are defined with the following constraints $\xi_1, \dots, \xi_8$.

Structure Constraints: We impose that the quantity of product units entering each node of the DN has to be equal to that going out (except for source/sink nodes). Thus, we set:

$$\xi_1 : \begin{cases} \sum_{j\in Pre_i}\sum_{d\in\Delta_j}\sum_{t\in\Theta_j} z_{j,i}^{d,t} = y_i & \forall \alpha_i \in \mathbf{N_S} \quad \text{with } n_i \in S_k, \ k > 1 \\ y_i = \sum_{d\in\Delta_i} x_{i,d} & \forall \beta_i \in \mathbf{N_S} \\ x_{i,d} = \sum_{t\in\Theta_i} w_{i,d}^t & \forall \delta_{i,d} \in \mathbf{N_S} \\ w_{i,d}^t = \sum_{j\in Post_i} z_{i,j}^{d,t} & \forall \tau_{i,d,t} \in \mathbf{N_S} \quad \text{with } n_i \in S_k, \ k < K. \end{cases} \tag{4}$$

Hence, constraints (4) ensure the flow conservation. Moreover, it is necessary to guarantee that the quantity of product units of any type d arriving at an actor is equal to the amount of the same product type in its warehouse. Accordingly, the following constraints are also imposed:

$$\xi_2 : \sum_{j\in Pre_i}\sum_{t\in\Theta_j} z_{j,i}^{d,t} = x_{i,d} \quad \forall i \in \{I_1+1,\dots,I\}, \ d \in \Delta_i. \tag{5}$$

In addition to the above structure constraints that derive from the digraph configuration, the DN has to satisfy the following constraints.

Capacity Constraints: A manufacturer $n_i \in S_1$ can produce a set of products in quantities not superior to its productive capacity $C_{i,d}$ for each product d. Accordingly, we set:

$$\xi_3 : x_{i,d} \leqslant C_{i,d} \quad \forall i \in \{1,\ldots,I_1\}, \;\; d \in \Delta_i. \tag{6}$$

Similarly, we impose that the overall processing capacity of n_i in the considered time period is limited as follows:

$$\xi_4 : \sum_{d\in\Delta_i} x_{i,d} \leqslant C_i \quad \forall i \in \left\{I_1+1,\ldots,\sum_{k=1}^{K-1} I_k\right\}. \tag{7}$$

Demand Constraints: The last DN stage S_K is composed of retailers and each actor $n_i \in S_K$ requires $O_{i,d}$ products of type $d \in \Delta_i$. Hence, considering the upstream actors, we impose:

$$\xi_5 : \sum_{j\in Pre_i}\sum_{t\in\Theta_i} z_{j,i}^{d,t} = O_{i,d} \quad \forall i \in \left\{\sum_{k=1}^{K-1} I_k+1,\ldots,I\right\}, \;\; d \in \Delta_i. \tag{8}$$

Existence Constraints: If product $d \in \Delta_i$ flows towards actor n_i of the DN, this must be selected in the optimal solution ($s_i = 1$). Otherwise, if there is no flow towards n_i, then this actor does not belong to the digraph ($s_i = 0$). Hence, we impose:

$$\xi_6 : M \cdot s_i \geqslant y_i \quad \forall i \in \{1,\ldots,I\}, \tag{9}$$

where $M \in \mathbb{R}$ (with $M \gg 0$) is a design parameter bigger than the maximum product amount which can arrive at the ith actor.

In the same way, if the product $d \in \Delta_i$ is (not) provided by actor n_i, then $r_{i,d}$ has to be equal to 1 (0):

$$\xi_7 : M \cdot r_{i,d} \geqslant x_{i,d} \quad \forall i \in \{1,\ldots,I\}, \;\; d \in \Delta_i. \tag{10}$$

Analogously, if there exists (does not exist) a flow of product $d \in \Delta_i$ from actor $n_i \in S_k$ to a downstream actor n_j, then $v_{i,j}^{d,t}$ has to be equal to 1 (0). Hence, we impose:

$$\xi_8 : M \cdot v_{i,j}^{d,t} \geqslant z_{i,j}^{d,t} \quad \forall i \in \left\{1,\ldots,\sum_{k=1}^{K-1} I_k\right\}, \;\; j \in Post_i, \;\; d \in \Delta_i, \;\; t \in \Theta_i. \tag{11}$$

Solving (2), (3) subject to (4)–(11) for a given value set of λ produces a Pareto optimal point of the multiobjective optimization problem (Ehrgott, 2000). Moreover, different values for λ_l with $l \in \Lambda$ may produce different Pareto solutions and their number could be quite high. Hence, in order to single out the solution which best meets the decision maker requirements, a second level analysis is appropriate.

4.2. The second level optimization: the AHP method

The Analytic Hierarchy Process (AHP) is a multi-objective decision technique (Saaty, 2004; Saaty, 2008) for ranking a number of alternatives according to a set of conflicting criteria of various degrees of importance. In the second level optimization, the AHP procedure is selected to single out, among the Pareto solution digraphs determined at the first level of the procedure, the closest configuration to the requirements of the decision maker. AHP is chosen among the many available multi-objective decision making techniques because it relies on pairwise comparisons of the alternatives, thus exhibiting an enhanced accuracy with respect to other approaches. Nevertheless, setting up the pairwise comparison may be a difficult task, especially when the decision problem dimension includes an excessively large number of criteria, and in such cases (actually not so common in DN management) alternative decision making techniques may be selected. In addition, note that AHP, being based on a discrete comparison scale, may produce a stepwise ranking of the DN alternatives. The presence of two (or more) equally ranked best configurations can be avoided by further classifying them based on a predefined rule, for instance on the basis of one criterion only, e.g., cost.

The applied AHP technique consists of the following steps.

Step 1. Structuring the decision problem as a hierarchy. Fig. 3 shows the hierarchy of the AHP optimization. We select the first level of the hierarchical AHP structure as the overall goal "Effectiveness". Moreover, the second AHP level is composed of the h considered criteria contributing to the overall goal. In addition, the third AHP level is constituted by the m alternative DN configurations or SLD, belonging to the Pareto face determined in the previous optimization, that we wish to rank against the further criteria of the previous level.

Step 2. Constructing a set of pairwise comparison matrices. For each level of the AHP hierarchy (going from bottom to the top), the contribution of all the subsequent level elements to the current level has to be determined. To this aim, a pairwise comparison matrix $\mathbf{C}_{\mathbf{M}_0}$ of dimension $h \times h$ is first evaluated determining the importance of the h criteria of the second level in reaching the top objective. Second, h additional matrices $\mathbf{C}_{\mathbf{M}_i}$ of dimension mxm with $i = 1, \ldots, h$ are defined, each expressing how satisfactory every alternative in the third level is with respect to the ith criterion of the second level. More in detail, each element $c_{M_i}(j,k)$ of $\mathbf{C}_{\mathbf{M}_i}$ with $i = 0, \ldots, h$ represents the relative importance of the jth element of the AHP level compared to the kth one and it is determined interviewing the decision maker and associating such an importance an integer from 1 to 9 (see Table 1) (Saaty, 2004). If numerical performance values are available for all elements of a level of the AHP hierarchy, value $c_{M_i}(j,k)$ can be determined using the percentage difference between the performance values of the alternatives according to Table 2. More precisely, we compare the elements of the third level of the hierarchy in Fig. 3 as follows: for each couple of alternatives (j, k) with $j \geqslant k$ and $(j, k) \in \{1, 2, \ldots, m\}$ we define the ith criterion pairwise difference:

$$PD_i(j,k) = 100 \cdot \frac{\max(\varphi_i(j),\varphi_i(k)) - \min(\varphi_i(j),\varphi_i(k))}{\max(\varphi_i(j),\varphi_i(k))}, \quad \text{for} \;\; i = 1,\ldots,h, \tag{12}$$

where $\varphi_i(j)$ and $\varphi_i(k)$ are the performance values of the jth and kth alternatives, respectively, against the ith criterion. Hence, by Table 2 the corresponding AHP scale value $\sigma_i(j, k)$ is determined, and each element $c_{M_i}(j,k)$ is evaluated as follows:

$$c_{M_i}(j,k) = \begin{cases} \sigma_i(j,k) & \text{for } \varphi_i(j) > \varphi_i(k) \\ 1 & \text{for } \varphi_i(j) = \varphi_i(k), \\ \frac{1}{\sigma_i(j,k)} & \text{for } \varphi_i(j) < \varphi_i(k) \end{cases} \quad \text{for } j \geqslant k \text{ with } (j,k) \in \{1,2,\ldots,m\} \text{ and } i = 1,\ldots,h \tag{13}$$

$$c_{M_i}(j,k) = \frac{1}{c_{M_i}(k,j)}, \quad \text{for } j < k \text{ with } (j,k) \in \{1,2,\ldots,m\} \text{ and } i = 1,\ldots,h \tag{14}$$

Step 3. Determining priorities and normalized performances from comparisons. For each comparison matrix $\mathbf{C}_{\mathbf{M}_i}$ with $i = 0, \ldots, h$, the maximum eigenvalue and the corresponding eigenvector $\boldsymbol{v}_i$ with $i = 0, \ldots, h$ are determined with $\mathbf{v}_0 \in \mathbb{R}^h$ and $\mathbf{v}_i \in \mathbb{R}^m$ with $i = 1, \ldots, h$. The priority vector $\boldsymbol{P} = [p_1 \ldots p_h]^T$ is computed as follows:

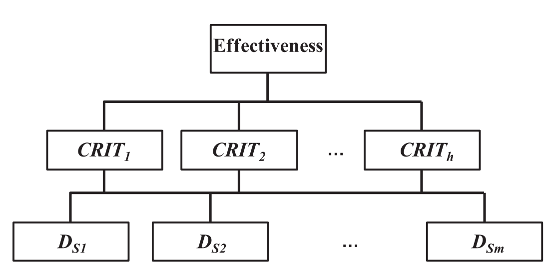

Fig. 3. The hierarchy of the AHP second level optimization.

Table 1
Saaty's AHP Scale of Comparison.

Intensity of importance	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	Intermediate values between the two adjacent judgments

$$\boldsymbol{P} = \frac{v_0}{\sum_{s=1}^{h} v_{0_s}}. \tag{15}$$

where each element p_i with $i = 1, \ldots, h$ represents the normalized importance degree of the ith criterion.

Similarly, the vector $\boldsymbol{CRIT}_i = [CRIT_{i_1} \ldots CRIT_{i_m}]^T$ of the normalized alternatives against the ith criterion are determined as follows:

$$\boldsymbol{CRIT}_i = \frac{v_i}{\sum_{t=1}^{m} v_{i_t}} \text{ with } i = 1, \ldots, h. \tag{16}$$

Step 4. Determining the relevance of alternatives. For each alternative j with $j = 1, \ldots, m$, its overall performance index is determined as follows:

$$PI_{j\_AHP} = \sum_{i=1}^{h} p_i CRIT_{i_j}. \tag{17}$$

Hence, PI_{j_AHP} expresses how satisfactory the jth alternative is with respect the criteria and their relevance.

Step 5. Ranking the alternatives. The DN digraphs are ranked according to the index PI_{j_AHP}. Obviously, the best configuration is the one showing the highest index PI_{j_AHP} obtained by (17).

It is well known that an issue in using AHP for ranking a number of alternatives according to a set of criteria is the consistency of judgments in pairwise comparison matrices. A comparison matrix $\mathbf{C}_{\mathbf{M}_i}$ with $i = 0, \ldots, h$ is said consistent if and only if it holds $\mathbf{C}_{\mathbf{M}_i}(j,l) = \mathbf{C}_{\mathbf{M}_i}(j,k) \cdot \mathbf{C}_{\mathbf{M}_i}(k,l) \forall (j,k,l) \in \{1,2,\ldots,\dim(\mathbf{C}_{\mathbf{M}_i})\}$ (Saaty, 2004), where $\dim(\mathbf{C}_{\mathbf{M}_i})$ is the dimension of square matrix $\mathbf{C}_{\mathbf{M}_i}$. In order to verify how much each comparison matrix respects this condition, that is, how consistent it is, Saaty suggested as indicators the Consistency Index $CI(\mathbf{C}_{\mathbf{M}_i})$ and the Consistency Ratio $CR(\mathbf{C}_{\mathbf{M}_i})$ of matrix $\mathbf{C}_{\mathbf{M}_i}$, with $i = 0, \ldots, h$, defined as follows:

$$CI(\mathbf{C}_{\mathbf{M}_i}) = \frac{\lambda_{\max,i} - \dim(\mathbf{C}_{\mathbf{M}_i})}{\dim(\mathbf{C}_{\mathbf{M}_i}) - 1} \tag{18}$$

$$CR(\mathbf{C}_{\mathbf{M}_i}) = \frac{CI(\mathbf{C}_{\mathbf{M}_i})}{RCI(\mathbf{C}_{\mathbf{M}_i})}, \tag{19}$$

where $\lambda_{\max,i}$ is the maximum eigenvalue of $\mathbf{C}_{\mathbf{M}_i}$. Moreover, $RCI(\mathbf{C}_{\mathbf{M}_i})$ is the so-called Random Consistency Index of a square matrix of the same dimension as $\mathbf{C}_{\mathbf{M}_i}$, generated with values belonging to set {1/9, 1/8, 1/7, ..., 1, ..., 7, 8, 9} according to Table 1. Each $\mathbf{C}_{\mathbf{M}_i}$ with $i = 0, \ldots, h$ is said consistent if and only if it holds $CR(\mathbf{C}_{\mathbf{M}_i}) < 0.1$.

Finally, we remark that the adoption of a second level AHP on the optimal solution set deriving from solving the first level MILP problem determines two further opportunities for the strategic management with respect to a single optimization design: (1) it introduces second level performance indicators – against which to optimize the solutions – by trading-off the main performance indicators considered in the first step; (2) it allows evaluating candidate solutions against nonlinear indicators (which are assessed only for the solutions deriving from the first level linear optimization) that cannot be taken into account in the first optimization by the introduced MILP procedure.

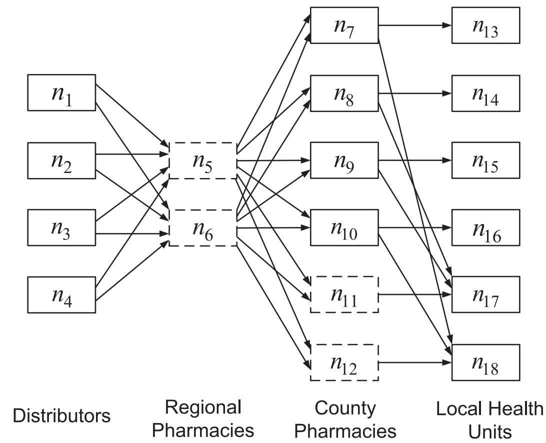

Fig. 4. A scheme of the first level description of the Apulia region HDDN (dashed lines indicate potential partners not currently included in the healthcare DN).

Table 3
Performance of minimum cost, minimum CO_2 emissions and minimum lateness HDDN digraphs.

HDDN configuration	F_{COST} (mln €)	F_{CO2} ($kgCO_2$)	F_{LATE} (units)
$\mathbf{D_{S1}}$ (minimum cost)	**109.85**	42002.59	322,500
$\mathbf{D_{S2}}$ (minimum CO_2)	124.62	**7889.99**	304,200
$\mathbf{D_{S3}}$ (minimum lateness)	121.22	12538.96	256,100

Bold values indicate minimum performance values.

5. The DN case study

This section considers a case study that refers to the Healthcare Drug Distribution Network (HDDN) of Apulia, a region of southern Italy. The HDDN, schematized in Fig. 4, is constituted by $K = 4$ stages S_1, S_2, S_3, and S_4 and $I = 18$ actors that distribute the product set $\Delta = \{1, 2, 3, 4\}$ and can use $T = 3$ modes of transportations: truck (1), rail (2) and air (3), so that $\Theta = \{1, 2, 3\}$.

The strategic design of the HDDN is aimed at the optimal re-configuration of the existing health care DN (currently formed by four distributors, four county pharmacies and six Local Health Units or LHU), with the possible inclusion of four novel potential actors, i.e., two regional pharmacies and two county pharmacies, which are highlighted in Fig. 4 by dashed lines. The current configuration of the HDDN relies on the idea of using county pharmacies only in the largest counties, as an intermediate level between drug suppliers and final consumers (i.e., the LHU). The present study aims at verifying whether the introduction of a further intermediate regional pharmacy level and of county pharmacies also for smaller counties can produce benefits for the overall HDDN performance.

Table 2
Saaty's AHP scale of comparisons for measurable alternatives.

Pairwise difference $PD_i(j,k)$	0–5	5–15	15–25	25–35	35–45	45–55	55–65	65–75	>75
AHP scale $\sigma_i(j,k)$	1	2	3	4	5	6	7	8	9

More in detail, the first stage $S_1 = \{n_1, \ldots, n_4\}$ is composed of $I_1 = 4$ distributors: distributor n_1 is located in Apulia and provides the set of drug families $\Delta_1 = \{1, 2\}$ with $\Theta_1 = \{1\}$; distributor n_2 is in a different region in southern Italy and provides the drug set $\Delta_2 = \{1, 3, 4\}$ with $\Theta_2 = \{1\}$; distributor n_3 is located in a foreign country and provides the drug set $\Delta_3 = \{2, 3, 4\}$ with $\Theta_3 = \{1, 2, 3\}$; distributor n_4 is in northern Italy and provides $\Delta_4 = \{3, 4\}$ with $\Theta_4 = \{1, 2\}$. The second stage $S_2 = \{n_5, n_6\}$ collects $I_2 = 2$ *potential* regional pharmacies: in particular, pharmacy n_5 is located in the central zone of the region, while pharmacy n_6 is in the south of the region. Moreover, the subsequent stage $S_3 = \{n_7, \ldots, n_{12}\}$ collects $I_3 = 6$ pharmacies, divided into four existing county or provincial pharmacies (n_7–n_{10}) and two additional *potential* county pharmacies: in particular, pharmacy n_7 is located in Bari; n_8 is in Lecce; n_9 is in Taranto; n_{10} is in Foggia; potential pharmacies n_{11} and n_{12} are located in Brindisi and in the BAT province, respectively. Finally, the last stage $S_4 = \{n_{13}, \ldots, n_{18}\}$ collects $I_4 = 6$ LHU: LHU n_{13} is located in Bari; n_{14} is in Lecce; n_{15} is in Taranto; n_{16} is in Foggia; n_{17} is in Brindisi; n_{18} is in the BAT province. In addition, due to the limited distance from regional pharmacies to

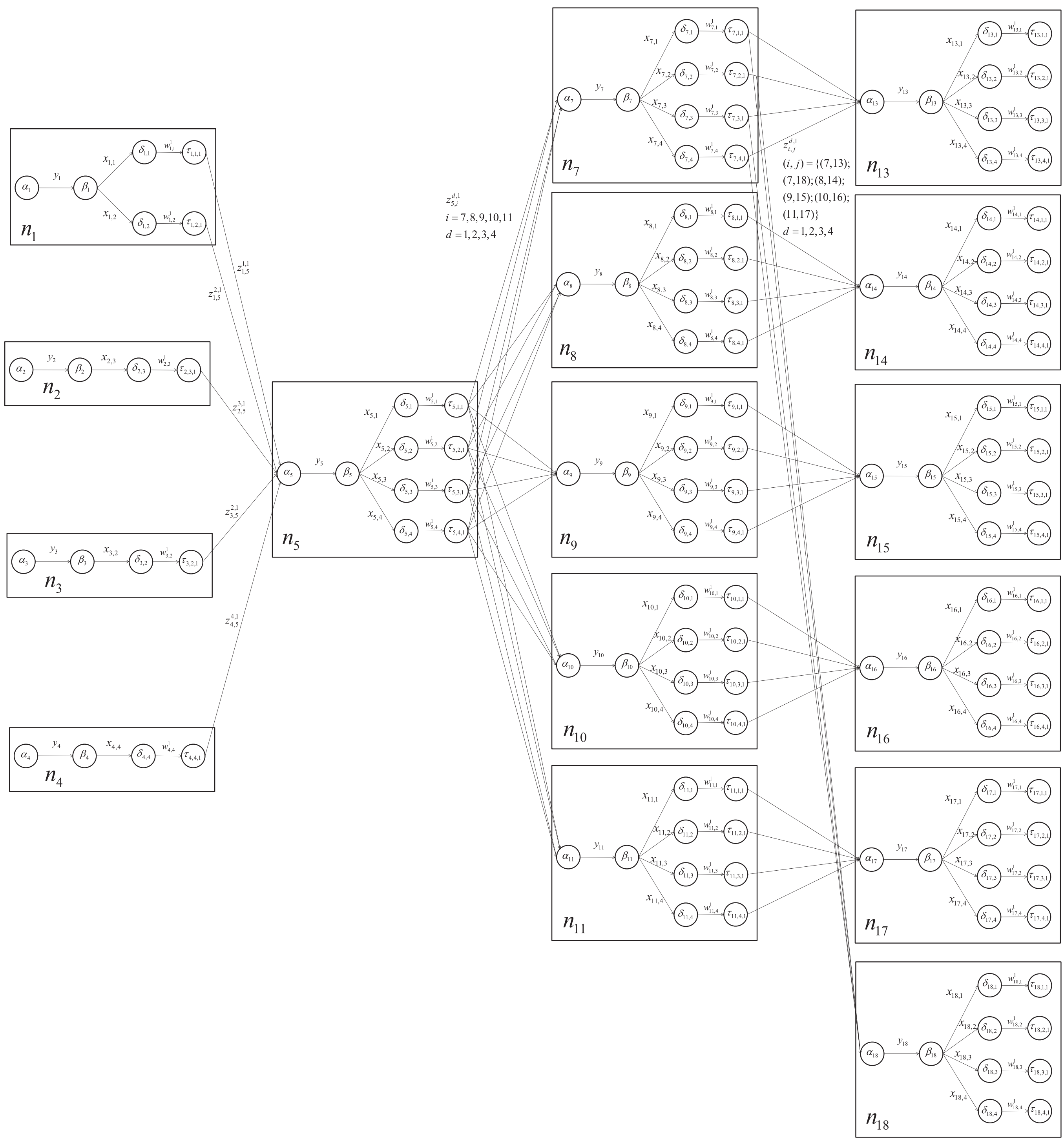

Fig. 5. The minimum cost HDDN digraph $\mathbf{D_{S1}}$.

the subsequent stages, all drug transportations starting from the second stage downstream can be carried out only by truck, so that it holds $\Theta_i = \{1\}$ for each $i = 5, \ldots, 18$. The description of the DN in Fig. 4 is completed by the definition of the connections between the DN actors, as follows: $Pre_i = \emptyset$ and $Post_i = \{5, 6\}$ for $i = 1, \ldots, 4$; $Pre_i = \{1, 2, 3, 4\}$ and $Post_i = \{7, 8, 9, 10, 11, 12\}$ for $i = 5, 6$; $Pre_i = \{5, 6\}$ for $i = 7, \ldots, 10$; $Post_7 = \{13, 18\}$; $Post_8 = \{14, 17\}$; $Post_9 = \{15, 17\}$; $Post_{10} = \{16, 18\}$; $Post_{11} = \{17\}$; $Post_{12} = \{18\}$; $Pre_{13} = \{7\}$; $Pre_{14} = \{8\}$; $Pre_{15} = \{9\}$; $Pre_{16} = \{10\}$; $Pre_{17} = \{8, 9, 11\}$; $Pre_{18} = \{7, 10, 12\}$; $Post_i = \emptyset$ for $i = 13, \ldots, 18$.

5.1. The first level optimization results

The first level optimization is carried out using the DN optimization model presented in Section 3A. In particular, $L = 3$ performance indices are considered in this phase: (1) the total DN costs (COST), that are the summation of fixed costs (depreciation costs of the facilities), variable costs (purchasing and management of raw materials, components and products), and transportation costs; (2) the CO_2 emissions during the drug transportation (CO_2); (3) the number of drug units supplied behind schedule

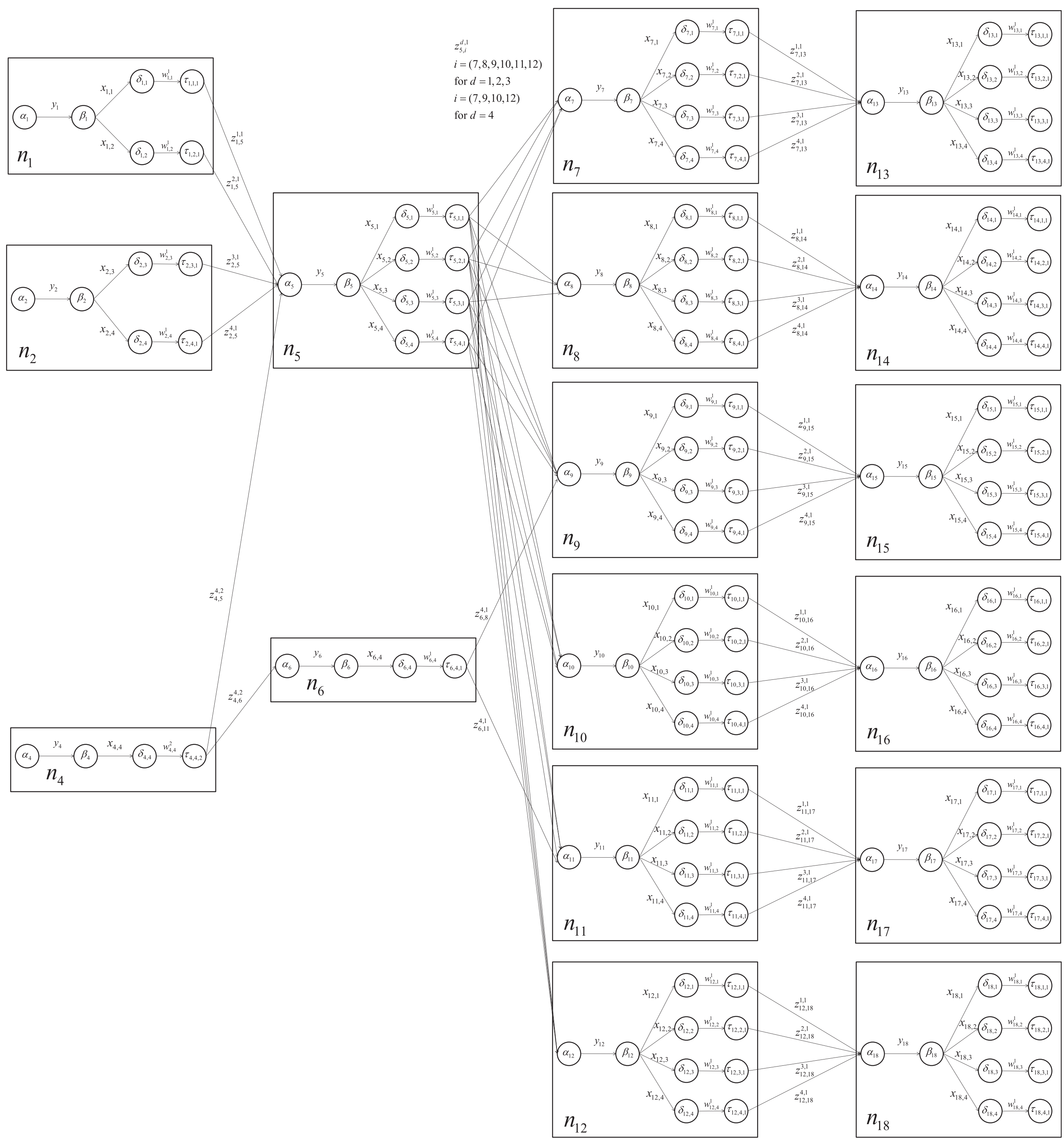

Fig. 6. The minimum emissions HDDN digraph $\mathbf{D_{S2}}$.

(LATE). As a consequence, we set $\Lambda = \{1, 2, 3\}$, where 1 = COST, 2 = CO_2, 3 = LATE.

The case study data are collected in Tables IA–VA in the Appendix. The data about monetary costs and percentage of product delivered out of due date derive from assessment of operating costs of existing structures and estimation of costs for structures whose implementation is considered. Instead, the emission contributions have been determined on the basis of the distances between DN actors and equivalent CO_2 emission coefficients (Luo, Zhou, & Caudill, 2001). In particular, Table IIIA reports the fixed costs of the DN actors and Table IVA reports the production capacities of the distributors and the warehouse capacities of the regional and county pharmacies in the considered time period (the year). In addition, Table IA shows transportation costs and CO_2 emissions for each product between each couple of DN actors. Moreover, Table IIA reports the variable costs and lateness percentages of the HDDN actors. Table IVA shows the purchasing costs from the actors of stage 1, the holding costs for downstream actors and percentages of late delivered product units for each actor and each drug. All these data are coefficients of the objective function

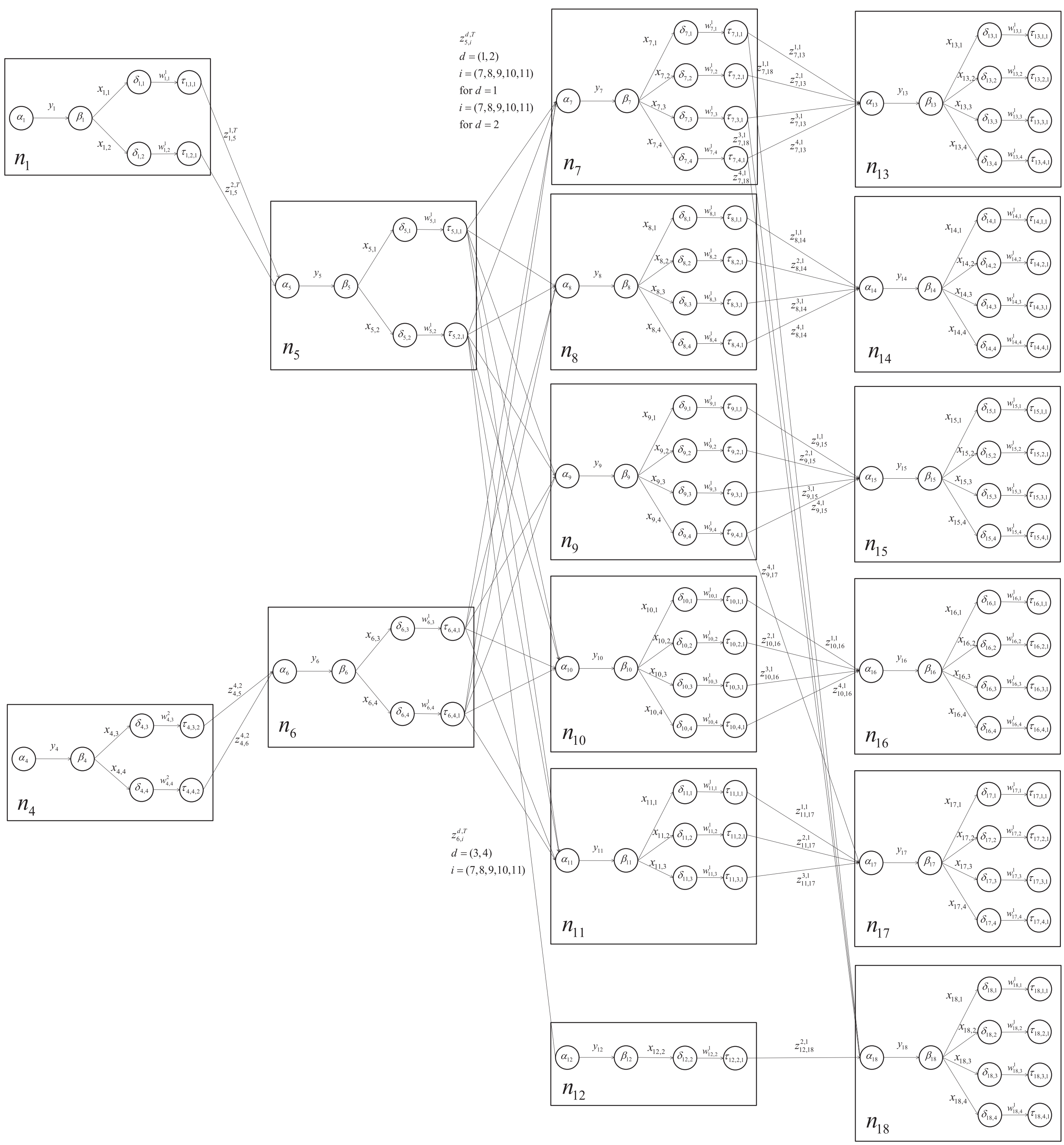

Fig. 7. The minimum lateness HDDN digraph $\mathbf{D_{S3}}$.

Table 4
Performance of the solution HDDN digraphs.

HDDN digraph	F_{COST} (mln €)	F_{CO2} ($kgCO_2$)	F_{LATE} (units)
$\mathbf{D_{S1}}$ (minimum cost)	**109.85**	42002.59	322,500
$\mathbf{D_{S2}}$ (minimum CO_2)	124.62	**7889.99**	304,200
$\mathbf{D_{S3}}$ (minimum lateness)	121.22	12538.96	**256,100**
$\mathbf{D_{S4}}$	127.48	8684.45	282,780
$\mathbf{D_{S5}}$	126.42	8152.08	289,580
$\mathbf{D_{S6}}$	125.58	7950.73	295,060
$\mathbf{D_{S7}}$	125.54	7937.85	295,700
$\mathbf{D_{S8}}$	125.51	7924.74	296,460
$\mathbf{D_{S9}}$	125.50	7921.64	297,000
$\mathbf{D_{S10}}$	111.60	13468.36	299,100
$\mathbf{D_{S11}}$	112.18	8563.36	299,100
$\mathbf{D_{S12}}$	112.15	8550.25	299,860
$\mathbf{D_{S13}}$	113.06	8330.60	299,660
$\mathbf{D_{S14}}$	113.04	8327.49	300,200
$\mathbf{D_{S15}}$	109.86	42014.10	321,500
$\mathbf{D_{S16}}$	112.10	8535.64	301,400
$\mathbf{D_{S17}}$	112.05	8577.85	301,500
$\mathbf{D_{S18}}$	112.03	8566.35	302,500
$\mathbf{D_{S19}}$	111.01	14597.60	322,500
$\mathbf{D_{S20}}$	110.44	19502.60	322,500

Bold values indicate minimum performance values.

Table 5
ASLT values of optimal HDDN digraphs.

HDDN configuration	*ASLT* (h)
$\mathbf{D_{S1}}$ (minimum cost)	11.33
$\mathbf{D_{S2}}$ (minimum CO_2)	8.85
$\mathbf{D_{S3}}$ (minimum lateness)	9.27
$\mathbf{D_{S4}}$	9.00
$\mathbf{D_{S5}}$	9.30
$\mathbf{D_{S6}}$	8.89
$\mathbf{D_{S7}}$	8.72
$\mathbf{D_{S8}}$	8.72
$\mathbf{D_{S9}}$	8.85
$\mathbf{D_{S10}}$	9.30
$\mathbf{D_{S11}}$	9.06
$\mathbf{D_{S12}}$	8.40
$\mathbf{D_{S13}}$	8.40
$\mathbf{D_{S14}}$	7.69
$\mathbf{D_{S15}}$	7.86
$\mathbf{D_{S16}}$	9.17
$\mathbf{D_{S17}}$	8.50
$\mathbf{D_{S18}}$	8.40
$\mathbf{D_{S19}}$	10.33
$\mathbf{D_{S20}}$	10.83

Table 6
Consistency indices and consistency ratio for pairwise comparison matrices $\mathbf{C_{M_i}}$.

Index *i*	$\lambda_{\max,i}$	$CI(\mathbf{C_{M_i}})$	$CR(\mathbf{C_{M_i}})$
0	3.000	0	0
1	20.000	0	0
2	21.000	0.053	0.032
3	20.152	0.008	0.005
4	20.364	0.019	0.011

(2) and all parameters of (2) not reported in Tables IA–IVA are equal to zero. Moreover, Table VA collects the demand for each drug at each stage of the HDDN.

The minimum cost, the minimum emission and the minimum lateness values solutions of the MILP problem are determined using the GLPKMEX algorithm (Gnu Linear Programming Kit, 2012) in the well-known MATLAB software environment and are shown in Table 3.

Moreover, Figs. 5–7 show the corresponding SLD digraphs $\mathbf{D_{S1}}$, $\mathbf{D_{S2}}$ and $\mathbf{D_{S3}}$, respectively, and Tables VIA–VIIIA in the Appendix report the drug quantities of the SLD edges. Quantities flowing in edges y_i and $w_{i,d}^t$ can easily be determined from the data in the tables by applying (4). Note that Figs. 5–7 report the SLD of the determined configurations with rectangles indicating the HDDN different actors, so that the FLD and corresponding HDDN configuration can be easily deduced.

We remark that the minimum cost digraph $\mathbf{D_{S1}}$ in Fig. 5 includes all the four candidate suppliers, each of them providing only a drug, except for supplier n_1 providing also drug 2 in order to fully satisfy the demand that supplier n_3 cannot satisfy due to the limitations in its production capacity. This configuration is characterized by the inclusion in the healthcare chain of the new regional pharmacy n_5 and of the provincial pharmacy n_{11} supplying the Brindisi LHU (n_{17}), while the BAT LHU (n_{18}) is supplied by the Bari provincial pharmacy (n_7). All transportations in this configuration are made by truck, which is the less expensive transportation mode.

The minimum CO_2 emissions digraph $\mathbf{D_{S2}}$ in Fig. 6 differs from $\mathbf{D_{S1}}$ in Fig. 5 for the absence of supplier n_3 and for the presence of two suppliers providing drug 4 each to a different regional pharmacy (in this case both n_5 and n_6 are present, each of them receiving a different subset of drugs). In this configuration, the focus on emissions determines the choice of both candidate provincial pharmacies: each LHU is linked only with the nearest provincial site. In addition, supplier n_4 uses the most environmental-friendly transportation mode, i.e., rail, among the ones it can adopt, while the other two suppliers adopt the truck transportation mode that is the only one they have.

As regards the minimum lateness digraph $\mathbf{D_{S3}}$ in Fig. 7, it is characterized by the presence of all regional and provincial candidate pharmacies and by only two suppliers n_1 and n_4. This is due to the fact that this optimization aims at choosing the most responsive supplying channels, without minimizing the total number of actors in the HDDN.

In addition, the tri-criteria optimization provides a Pareto face (Ehrgott, 2000) composed of 20 DN digraphs (see Table 4), obviously including the three single objective configurations listed in Table 3 and represented in Figs. 5–7 and Tables VIA–VIIIA. We remark that these 20 solutions are obtained by a scalarization considering all combinations of coefficients λ_l in (1) with a fixed step equal to 0.01 so as to determine a Pareto solution set. Such a solution required a computational time of 232 s on a Intel 2.13 GHz processor PC.

Table 7
AHP scores of optimal HDDN digraphs.

HDDN configuration	AHP score
$\mathbf{D_{S13}}$	0.0798
$\mathbf{D_{S14}}$	0.0773
$\mathbf{D_{S11}}$	0.0609
$\mathbf{D_{S12}}$	0.0609
$\mathbf{D_{S17}}$	0.0608
$\mathbf{D_{S18}}$	0.0586
$\mathbf{D_{S16}}$	0.0572
$\mathbf{D_{S7}}$	0.0539
$\mathbf{D_{S8}}$	0.0539
$\mathbf{D_{S1}}$	0.0497
$\mathbf{D_{S9}}$	0.0492
$\mathbf{D_{S6}}$	0.0485
$\mathbf{D_{S4}}$	0.0468
$\mathbf{D_{S3}}$	0.0447
$\mathbf{D_{S5}}$	0.0428
$\mathbf{D_{S10}}$	0.0418
$\mathbf{D_{S15}}$	0.0358
$\mathbf{D_{S19}}$	0.0281
$\mathbf{D_{S20}}$	0.0256
$\mathbf{D_{S2}}$	0.0237

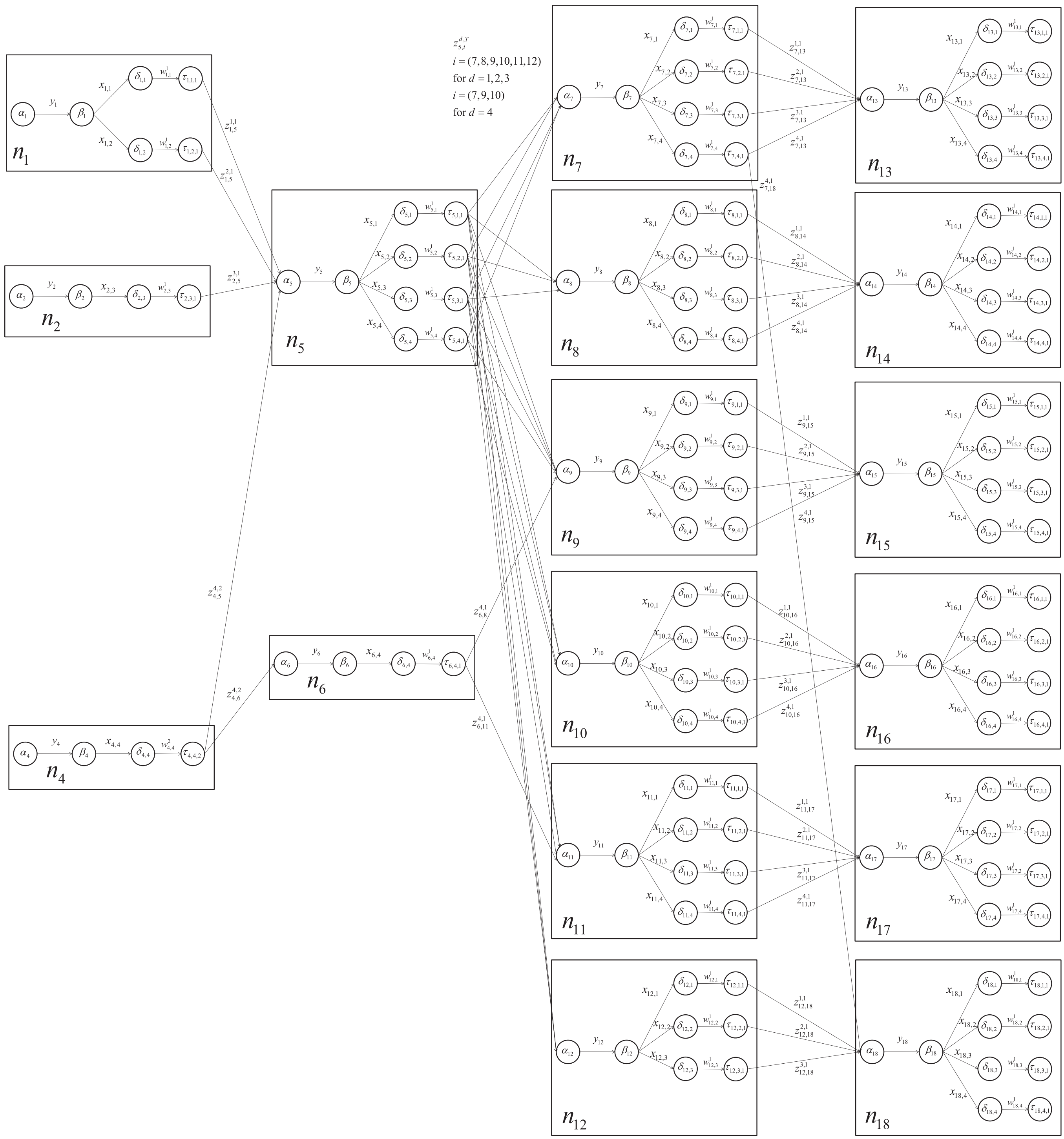

Fig. 8. The best compromise HDDN digraph $\mathbf{D_{S13}}$.

Table 8
Computational effort for single-objective DN design problems.

Case study	Total number of variables	Number of integer variables	Number of constraints	Solution time (s)
Present paper	282	18	246	4
Costantino, Falagario, Mangini, & Ukovich, 2010a	238	83	201	12
Costantino, Falagario, Mangini, and Ukovich (2010b)	244	88	218	14

Table IA
Costs, CO_2 emissions and duration of transportations among the HDDN Actors.

$z_{i,j}^{d,t}$	$c_{i,j}^{COST,d,t}$ (€/unit)	$c_{i,j}^{CO2,d,t}$ (gCO_2/u)	$f_{i,j}^{COST,d,t}$ (h)	$z_{i,j}^{d,t}$	$c_{i,j}^{COST,d,t}$ (€/unit)	$c_{i,j}^{CO2,d,t}$ (gCO_2/u)	$f_{i,j}^{COST,d,t}$ (h)	$z_{i,j}^{d,t}$	$c_{i,j}^{COST,d,t}$ (€/unit)	$c_{i,j}^{CO2,d,t}$ (gCO_2/u)	$f_{i,j}^{COST,d,t}$ (h)	$z_{i,j}^{d,t}$	$c_{i,j}^{COST,d,t}$ (€/unit)	$c_{i,j}^{CO2,d,t}$ (gCO_2/u)	$f_{i,j}^{COST,d,t}$ (h)
$z_{1,5}^{1,1}$	0.75	0.22	2.00	$z_{4,6}^{4,1}$	3.40	14.38	12.00	$z_{6,9}^{1,1}$	1.00	1.58	2.00	$z_{8,17}^{1,1}$	0.50	0.93	2.50
$z_{1,6}^{1,1}$	0.35	0.22	2.50	$z_{4,5}^{3,2}$	2.40	3.13	8.00	$z_{6,10}^{1,1}$	2.80	4.11	5.50	$z_{8,14}^{2,1}$	0.30	0.58	1.50
$z_{1,5}^{2,1}$	0.82	0.22	2.00	$z_{4,6}^{3,2}$	2.80	3.13	10.00	$z_{6,11}^{1,1}$	0.40	0.58	1.00	$z_{8,17}^{2,1}$	0.50	0.93	2.50
$z_{1,6}^{2,1}$	0.38	0.22	2.50	$z_{4,6}^{3,2}$	4.00	3.13	8.00	$z_{6,12}^{1,1}$	2.20	3.11	4.00	$z_{8,14}^{3,1}$	0.30	0.58	1.50
$z_{2,5}^{1,1}$	1.50	0.94	6.00	$z_{4,6}^{4,2}$	5.10	3.13	10.00	$z_{6,7}^{2,1}$	1.80	2.20	3.50	$z_{8,17}^{3,1}$	0.50	0.93	2.50
$z_{2,6}^{1,1}$	0.55	0.94	8.00	$z_{5,7}^{1,1}$	0.10	0.14	0.50	$z_{6,8}^{2,1}$	0.10	0.14	0.50	$z_{8,14}^{4,1}$	0.30	0.58	1.50
$z_{2,5}^{3,1}$	0.75	0.94	6.00	$z_{5,8}^{1,1}$	1.80	2.20	3.50	$z_{6,9}^{2,1}$	1.00	1.58	2.00	$z_{8,17}^{4,1}$	0.50	0.93	2.50
$z_{2,6}^{3,1}$	0.95	0.94	8.00	$z_{5,9}^{1,1}$	1.20	1.38	1.50	$z_{6,10}^{2,1}$	2.80	4.11	5.50	$z_{9,15}^{1,1}$	0.60	0.43	1.00
$z_{2,5}^{4,1}$	1.90	0.94	6.00	$z_{5,10}^{1,1}$	1.30	1.93	2.00	$z_{6,11}^{2,1}$	0.40	0.58	1.00	$z_{9,17}^{1,1}$	0.60	1.08	1.50
$z_{2,6}^{4,1}$	2.40	0.94	8.00	$z_{5,11}^{1,1}$	1.00	1.67	1.50	$z_{6,12}^{2,1}$	2.20	3.11	4.00	$z_{9,15}^{2,1}$	0.60	0.43	1.00
$z_{3,5}^{2,3}$	3.60	1005.00	3.00	$z_{5,12}^{1,1}$	0.50	0.92	1.00	$z_{6,7}^{3,1}$	1.80	2.20	3.50	$z_{9,17}^{2,1}$	0.60	1.08	1.50
$z_{3,6}^{2,3}$	5.40	1005.00	5.00	$z_{5,7}^{2,1}$	0.10	0.14	0.50	$z_{6,8}^{3,1}$	0.10	0.14	0.50	$z_{9,15}^{3,1}$	0.60	0.43	1.00
$z_{3,5}^{3,3}$	6.60	1005.00	3.00	$z_{5,8}^{2,1}$	1.80	2.20	3.50	$z_{6,9}^{3,1}$	1.00	1.58	2.00	$z_{9,17}^{3,1}$	0.60	1.08	1.50
$z_{3,6}^{3,3}$	8.40	1005.00	5.00	$z_{5,9}^{2,1}$	1.20	1.38	1.50	$z_{6,10}^{3,1}$	2.80	4.11	5.50	$z_{9,15}^{4,1}$	0.60	0.43	1.00
$z_{3,5}^{4,3}$	13.50	1005.00	3.00	$z_{5,10}^{2,1}$	1.30	1.93	2.00	$z_{6,11}^{3,1}$	0.40	0.58	1.00	$z_{9,17}^{4,1}$	0.60	1.08	1.50
$z_{3,6}^{4,3}$	17.40	1005.00	5.00	$z_{5,11}^{2,1}$	1.00	1.67	1.50	$z_{6,12}^{3,1}$	2.20	3.11	4.00	$z_{10,16}^{1,1}$	0.60	0.43	2.00
$z_{3,5}^{2,1}$	1.20	28.75	15.00	$z_{5,12}^{2,1}$	0.50	0.92	1.00	$z_{6,7}^{4,1}$	1.80	2.20	3.50	$z_{10,18}^{1,1}$	0.60	1.08	2.50
$z_{3,6}^{2,1}$	1.80	28.75	17.00	$z_{5,7}^{3,1}$	0.10	0.14	0.50	$z_{6,8}^{4,1}$	0.10	0.14	0.50	$z_{10,16}^{2,1}$	0.60	0.43	2.00
$z_{3,5}^{3,1}$	2.20	28.75	15.00	$z_{5,8}^{3,1}$	1.80	2.20	3.50	$z_{6,9}^{4,1}$	1.00	1.58	2.00	$z_{10,18}^{2,1}$	0.60	1.08	2.50
$z_{3,6}^{3,1}$	2.80	28.75	17.00	$z_{5,9}^{3,1}$	1.20	1.38	1.50	$z_{6,10}^{4,1}$	2.80	4.11	5.50	$z_{10,16}^{3,1}$	0.60	0.43	2.00
$z_{3,5}^{4,1}$	4.40	28.75	15.00	$z_{5,10}^{3,1}$	1.30	1.93	2.00	$z_{6,11}^{4,1}$	0.40	0.58	1.00	$z_{10,18}^{3,1}$	0.60	1.08	2.50
$z_{3,6}^{4,1}$	5.80	28.75	17.00	$z_{5,11}^{3,1}$	1.00	1.67	1.50	$z_{6,12}^{4,1}$	2.20	3.11	4.00	$z_{10,16}^{4,1}$	0.60	0.43	2.00
$z_{3,5}^{2,2}$	1.80	6.25	13.00	$z_{5,12}^{3,1}$	0.50	0.92	1.00	$z_{7,13}^{1,1}$	0.60	0.36	1.50	$z_{10,18}^{4,1}$	0.60	1.08	2.50
$z_{3,6}^{2,2}$	2.70	6.25	15.00	$z_{5,7}^{4,1}$	0.10	0.14	0.50	$z_{7,18}^{1,1}$	0.70	1.01	2.00	$z_{11,17}^{1,1}$	0.20	0.36	1.00
$z_{3,5}^{3,2}$	3.30	6.25	13.00	$z_{5,8}^{4,1}$	1.80	2.20	3.50	$z_{7,13}^{2,1}$	0.60	0.36	1.50	$z_{11,17}^{2,1}$	0.20	0.36	1.00
$z_{3,6}^{3,2}$	4.20	6.25	15.00	$z_{5,9}^{4,1}$	1.20	1.38	1.50	$z_{7,18}^{2,1}$	0.70	1.01	2.00	$z_{11,17}^{3,1}$	0.20	0.36	1.00
$z_{3,5}^{4,2}$	6.60	6.25	13.00	$z_{5,10}^{4,1}$	1.30	1.93	2.00	$z_{7,13}^{3,1}$	0.60	0.36	1.50	$z_{11,17}^{4,1}$	0.20	0.36	1.00
$z_{3,6}^{4,2}$	8.70	6.25	15.00	$z_{5,11}^{4,1}$	1.00	1.67	1.50	$z_{7,18}^{3,1}$	0.70	1.01	2.00	$z_{12,18}^{1,1}$	0.30	0.14	2.00
$z_{4,5}^{3,1}$	1.60	14.38	10.00	$z_{5,12}^{4,1}$	0.50	0.92	1.00	$z_{7,13}^{4,1}$	0.60	0.36	1.50	$z_{12,18}^{2,1}$	0.30	0.14	2.00
$z_{4,6}^{3,1}$	1.90	14.38	12.00	$z_{6,7}^{1,1}$	1.80	2.20	3.50	$z_{7,18}^{4,1}$	0.70	1.01	2.00	$z_{12,18}^{3,1}$	0.30	0.14	2.00
$z_{4,5}^{4,1}$	2.70	14.38	10.00	$z_{6,8}^{1,1}$	0.10	0.14	0.50	$z_{8,14}^{1,1}$	0.30	0.58	1.50	$z_{12,18}^{4,1}$	0.30	0.14	2.00

Table IIA
Variable costs and lateness percentages of the HDDN actors.

$x_{i,d}$	$a_{i,d}^{COST}$ (€/u)	$a_{i,d}^{LATE}$	$x_{i,d}$	$a_{i,d}^{COST}$ (€/u)	$a_{i,d}^{LATE}$	$x_{i,d}$	$a_{i,d}^{COST}$ (€/u)	$a_{i,d}^{LATE}$	$x_{i,d}$	$a_{i,d}^{COST}$ (€/u)	$a_{i,d}^{LATE}$	$x_{i,d}$	$a_{i,d}^{COST}$ (€/u)	$a_{i,d}^{LATE}$
$x_{1,1}$	40.00	0.030	$x_{5,4}$	1.30	0.030	$x_{9,1}$	0.65	0.030	$x_{13,2}$	0.00	0.00	$x_{16,3}$	0.00	0.00
$x_{1,2}$	15.00	0.040	$x_{6,1}$	1.50	0.040	$x_{9,2}$	0.90	0.010	$x_{13,3}$	0.00	0.00	$x_{16,4}$	0.00	0.00
$x_{2,1}$	50.00	0.050	$x_{6,2}$	2.00	0.040	$x_{9,3}$	1.30	0.200	$x_{13,4}$	0.00	0.00	$x_{17,1}$	0.00	0.00
$x_{2,3}$	4.50	0.060	$x_{6,3}$	2.80	0.010	$x_{9,4}$	1.00	0.005	$x_{14,1}$	0.00	0.00	$x_{17,2}$	0.00	0.00
$x_{2,4}$	180.00	0.030	$x_{6,4}$	1.00	0.020	$x_{10,1}$	1.00	0.010	$x_{14,2}$	0.00	0.00	$x_{17,3}$	0.00	0.00
$x_{3,2}$	13.00	0.060	$x_{7,1}$	1.00	0.010	$x_{10,2}$	1.10	0.025	$x_{14,3}$	0.00	0.00	$x_{17,4}$	0.00	0.00
$x_{3,3}$	6.00	0.045	$x_{7,2}$	1.00	0.025	$x_{10,3}$	1.20	0.030	$x_{14,4}$	0.00	0.00	$x_{18,1}$	0.00	0.00
$x_{3,4}$	145.00	0.020	$x_{7,3}$	1.20	0.010	$x_{10,4}$	0.90	0.010	$x_{15,1}$	0.00	0.00	$x_{18,2}$	0.00	0.00
$x_{4,3}$	7.00	0.040	$x_{7,4}$	1.10	0.005	$x_{11,1}$	0.90	0.005	$x_{15,2}$	0.00	0.00	$x_{18,3}$	0.00	0.00
$x_{4,4}$	120.00	0.010	$x_{8,1}$	0.80	0.015	$x_{12,2}$	0.85	0.010	$x_{15,3}$	0.00	0.00	$x_{18,4}$	0.00	0.00
$x_{5,1}$	2.00	0.010	$x_{8,2}$	0.60	0.020	$x_{12,3}$	1.30	0.005	$x_{15,4}$	0.00	0.00			
$x_{5,2}$	2.00	0.030	$x_{8,3}$	1.80	0.010	$x_{12,4}$	1.00	0.030	$x_{16,1}$	0.00	0.00			
$x_{5,3}$	2.00	0.020	$x_{8,4}$	0.95	0.025	$x_{13,1}$	0.60	0.010	$x_{16,2}$	0.00	0.00			

5.2. The second level optimization results

To rank the obtained Pareto face solutions listed in Table 4, we consider the second level AHP optimization. For this purpose, a new DN performance measure is used in addition to the previously employed performance indices, i.e., the Average Supply Lead Time (ASLT), measuring the average time required by a drug to arrive from distributors in the first stage to LHU in the last stage. More precisely, to determine the ASLT performance value of each Pareto face alternative, we define the set Π_j of paths π going from the first to the last stage of the FLD describing the corresponding jth DN configuration $\mathbf{D_{Sj}}$ with $j = 1, \ldots, m$. Obviously, each path in Π_j is made only by edges connecting actors belonging to subsequent stages, from the first to the last one; consequently, each $\pi \in \Pi_j$ is made by $K - 1$ edges. We recall that $f_{i,i'}^{TIME,d,t}$ is the transportation time of a drug d by means of the tth transportation mode from

Table IIIA
Fixed costs of the HDDN actors.

s_i	e_i^{COST} (€)	s_i	e_i^{COST} (€)	s_i	e_i^{COST} (€)	s_i	e_i^{COST} (€)
s_5	1,000,000	s_7	300,000	s_9	200,000	s_{11}	100,000
s_6	1,000,000	s_8	230,000	s_{10}	180,000	s_{12}	150,000

Table IVA
Production and warehouse capacities of the HDDN actors.

Distributors production capacity $C_{i,d}$ (units/yr)				
Product d	$i = 1$	$i = 2$	$i = 3$	$i = 4$
1	1,200,000	2,600,000	–	–
2	1,400,000	–	2,200,000	200,000
3	–	1,000,000	1,000,000	1,400,000
4	–	–	2,400,000	1,200,000
Regional and county pharmacies warehouse capacity C_i (units/yr)				
Product d	$i = 5$	$i = 6$	$i = 7$	$i = 8$
1, 2, 3, 4	4,000,000	4,000,000	2,400,000	1,800,000
Product d	$i = 9$	$i = 10$	$i = 11$	$i = 12$
1, 2, 3, 4	1,600,000	1,600,000	1,000,000	1,200,000

Table VA
Demand of HDDN LHU.

Demand $O_{i_k,d}$ (unit/yr)						
Product d	$i = 13$	$i = 14$	$i = 15$	$i = 16$	$i = 17$	$i = 18$
1	96,000	80,000	68,000	80,000	56,000	48,000
2	240,000	200,000	160,000	224,000	160,000	120,000
3	280,000	240,000	200,000	240,000	176,000	152,000
4	120,000	80,000	64,000	96,000	40,000	36,000

Table VIA
Data of the minimum Cost HDDN digraph $\mathbf{D_{S1}}$ in Fig. 5.

Edge	Drug quantity	Edge	Drug quantity	Edge	Drug quantity
$x_{1,1}$	428,000	$x_{14.2}$	200,000	$z^{3,1}_{5,7}$	432,000
$x_{1,2}$	104,000	$x_{14.3}$	240,000	$z^{3,1}_{5,8}$	240,000
$x_{2,3}$	1,288,000	$x_{14.4}$	80,000	$z^{3,1}_{5,9}$	200,000
$x_{3,2}$	1,000,000	$x_{15.1}$	68,000	$z^{3,1}_{5,10}$	240,000
$x_{4,4}$	436,000	$x_{15.2}$	160,000	$z^{3,1}_{5,11}$	176,000
$x_{5,1}$	428,000	$x_{15.3}$	200,000	$z^{4,1}_{5,7}$	156,000
$x_{5,2}$	1,104,000	$x_{15.4}$	64,000	$z^{4,1}_{5,8}$	80,000
$x_{5,3}$	1,288,000	$x_{16.1}$	80,000	$z^{4,1}_{5,9}$	64,000
$x_{5,4}$	436,000	$x_{16.2}$	224,000	$z^{4,1}_{5,10}$	96,000
$x_{7,1}$	144,000	$x_{16.3}$	240,000	$z^{4,1}_{5,11}$	40,000
$x_{7,2}$	360,000	$x_{16.4}$	96,000	$z^{1,1}_{7,13}$	96,000
$x_{7,3}$	432,000	$x_{17.1}$	56,000	$z^{1,1}_{7,18}$	48,000
$x_{7,4}$	156,000	$x_{17.2}$	160,000	$z^{2,1}_{7,13}$	240,000
$x_{8.1}$	80,000	$x_{17.3}$	176,000	$z^{2,1}_{7,18}$	120,000
$x_{8.2}$	200,000	$x_{17.4}$	40,000	$z^{3,1}_{7,13}$	280,000
$x_{8.3}$	240,000	$x_{18.1}$	48,000	$z^{3,1}_{7,18}$	152,000
$x_{8.4}$	80,000	$x_{18.2}$	120,000	$z^{4,1}_{7,13}$	120,000
$x_{9.1}$	68,000	$x_{18.3}$	152,000	$z^{4,1}_{7,18}$	36,000
$x_{9.2}$	160,000	$x_{18.4}$	36,000	$z^{1,1}_{8,14}$	80,000
$x_{9.3}$	200,000	$z^{1,1}_{1,5}$	428,000	$z^{2,1}_{8,14}$	200,000
$x_{9.4}$	64,000	$z^{2,1}_{1,5}$	104,000	$z^{3,1}_{8,14}$	240,000
$x_{10.1}$	80,000	$z^{3,1}_{2,5}$	1,288,000	$z^{4,1}_{8,14}$	80,000
$x_{10.2}$	224,000	$z^{2,1}_{3,5}$	1,000,000	$z^{1,1}_{9,15}$	68,000
$x_{10.3}$	240,000	$z^{4,1}_{4,5}$	436,000	$z^{2,1}_{9,15}$	160,000
$x_{10.4}$	96,000	$z^{1,1}_{5,7}$	144,000	$z^{3,1}_{9,15}$	200,000
$x_{11.1}$	56,000	$z^{1,1}_{5,8}$	80,000	$z^{4,1}_{9,15}$	64,000
$x_{11.2}$	160,000	$z^{1,1}_{5,9}$	68,000	$z^{1,1}_{10,16}$	80,000
$x_{11.3}$	176,000	$z^{1,1}_{5,10}$	80,000	$z^{2,1}_{10,16}$	224,000
$x_{11.4}$	40,000	$z^{1,1}_{5,11}$	56,000	$z^{3,1}_{10,16}$	240,000
$x_{13.1}$	96,000	$z^{2,1}_{5,7}$	360,000	$z^{4,1}_{10,16}$	96,000
$x_{13.2}$	240,000	$z^{2,1}_{5,8}$	200,000	$z^{1,1}_{11,17}$	56,000
$x_{13.3}$	280,000	$z^{2,1}_{5,9}$	160,000	$z^{2,1}_{11,17}$	160,000
$x_{13.4}$	120,000	$z^{2,1}_{5,10}$	224,000	$z^{3,1}_{11,17}$	176,000
$x_{14.1}$	80,000	$z^{2,1}_{5,11}$	160,000	$z^{4,1}_{11,17}$	40,000

actor n_i to actor $n_{i'}$ of the generic element $\pi \in \Pi_j$. Hence, assuming that $f^{TIME,d,t}_{i,i'}$ does not vary with d in our case study, and that t is the selected transportation mode in the generic $\mathbf{D_{Sj}}$ alternative, we call F^{TIME}_{π} the summation of the transportation times from the first to the last actor of π. Consequently, the ASLT performance value of the jth alternative digraph can be defined as follows:

$$ASLT(\mathbf{D_{Sj}}) = \frac{\sum_{\pi \in \Pi_j} F^{TIME}_{\pi}}{|\Pi_j|}, \tag{20}$$

where $|\cdot|$ is the operator determining the dimension of a set.

Table 5 reports the ASLT for the Pareto face configurations in Table 4.

Hence, we apply the AHP procedure in Fig. 3 with $n = 4$ criteria (cost, CO_2 emissions, lateness, ASLT) against which we rank the $m = 20$ alternative HDDN digraphs in Table 4.

The pairwise comparisons matrix between criteria for ranking alternatives is defined assigning the same importance (equal to 1) to cost, CO_2 emissions and lateness and higher importance intensity (equal to 3) to ASLT with respect to the other three criteria. Consequently, the following criteria pairwise comparison matrix is used:

$$\mathbf{C_{M_0}} = \begin{bmatrix} 1 & 1 & 1 & 1/3 \\ 1 & 1 & 1 & 1/3 \\ 1 & 1 & 1 & 1/3 \\ 3 & 3 & 3 & 1 \end{bmatrix}. \tag{21}$$

The first line (or column) in the criteria comparison matrix corresponds to cost, the second one regards CO_2 emissions, the third one is about the lateness, and the fourth regards ASLT. The relative intensity of the performance index of the alternatives is calculated defining the percentage difference (12) of all indices for each couple of alternatives and using the Saaty scale in Table 2. The four comparison matrices $\mathbf{C_{M_i}}$ with $i = 1, \ldots, 4$ that compare each couple of the 20 digraphs with regard to criteria cost ($i = 1$), CO_2 emissions ($i = 2$), lateness ($i = 3$), and ASLT ($i = 4$) are hence determined by (13) and (14).

Table 6 shows that all the determined comparison matrices can be considered consistent. Indeed, the table reports for each row the indicators of the consistency of each comparison matrix $\mathbf{C_{M_i}}$ as follows: the first column reports the matrix indices $i = 0, \ldots, 4$, the subsequent one collects the maximum eigenvalues, the second last column reports the consistency indices, and the last one collects the consistency ratios, which are all inferior to the limit value 0.1. Note that these indices are calculated by (18) and (19) using the values of $RCI(\mathbf{C_{M_i}})$ proposed by Stein and Mizzi (2007), i.e., $RCI_4 = 0.882$ and $RCI_{20} = 1.630$.

Applying the AHP procedure, we obtain the scores in Table 7, showing that the best compromise HDDN is $\mathbf{D_{S13}}$ of Table 4. This configuration, represented in Fig. 8 and in Table IXA, is close to the minimum emission digraph $\mathbf{D_{S2}}$ in Fig. 6, with few differences: drug 4 is exclusively supplied by n_4 (by truck only) and arrives to the BAT LHU n_{18} from the Bari provincial pharmacy n_7, allowing an improvement in the ASLT performance and hence in the overall score.

Table VIIA
Data of the minimum emissions HDDN digraph $\mathbf{D_{S2}}$ in Fig. 6.

Edge	Drug quantity	Edge	Drug quantity	Edge	Drug quantity
$x_{1,1}$	428,000			$z^{3,1}_{5,7}$	280,000
$x_{1,2}$	1,104,000	$x_{14,2}$	200,000	$z^{3,1}_{5,8}$	240,000
$x_{2,3}$	1,288,000	$x_{14,3}$	240,000	$z^{3,1}_{5,9}$	200,000
$x_{2,4}$	200,000	$x_{14,4}$	80,000	$z^{3,1}_{5,10}$	240,000
$x_{4,4}$	236,000	$x_{15,1}$	68,000	$z^{3,1}_{5,11}$	176,000
$x_{5,1}$	428,000	$x_{15,2}$	160,000	$z^{3,1}_{5,12}$	152,000
$x_{5,2}$	1,104,000	$x_{15,3}$	200,000	$z^{4,1}_{5,7}$	120,000
$x_{5,3}$	1,288,000	$x_{15,4}$	64,000	$z^{4,1}_{5,9}$	64,000
$x_{5,4}$	316,000	$x_{16,1}$	80,000	$z^{4,1}_{5,10}$	96,000
$x_{6,4}$	120,000	$x_{16,2}$	224,000	$z^{4,1}_{5,12}$	36,000
$x_{7,1}$	96,000	$x_{16,3}$	240,000	$z^{4,1}_{6,8}$	80,000
$x_{7,2}$	240,000	$x_{16,4}$	96,000	$z^{4,1}_{6,11}$	40,000
$x_{7,3}$	280,000	$x_{17,1}$	56,000	$z^{1,1}_{7,13}$	96,000
$x_{7,4}$	120,000	$x_{17,2}$	160,000	$z^{2,1}_{7,13}$	240,000
$x_{8,1}$	80,000	$x_{17,3}$	176,000	$z^{3,1}_{7,13}$	280,000
$x_{8,2}$	200,000	$x_{17,4}$	40,000	$z^{4,1}_{7,13}$	120,000
$x_{8,3}$	240,000	$x_{18,1}$	48,000	$z^{1,1}_{8,14}$	80,000
$x_{8,4}$	80,000	$x_{18,2}$	120,000	$z^{2,1}_{8,14}$	200,000
$x_{9,1}$	68,000	$x_{18,3}$	152,000	$z^{3,1}_{8,14}$	240,000
$x_{9,2}$	160,000	$x_{18,4}$	36,000	$z^{4,1}_{8,14}$	80,000
$x_{9,3}$	200,000	$z^{1,1}_{1,5}$	428,000	$z^{1,1}_{9,15}$	68,000
$x_{9,4}$	64,000	$z^{2,1}_{1,5}$	1,104,000	$z^{2,1}_{9,15}$	160,000
$x_{10,1}$	80,000	$z^{3,1}_{2,5}$	1,288,000	$z^{3,1}_{9,15}$	200,000
$x_{10,2}$	224,000	$z^{4,1}_{2,5}$	200,000	$z^{4,1}_{9,15}$	64,000
$x_{10,3}$	120,000	$z^{4,2}_{4,5}$	116,000	$z^{1,1}_{10,16}$	80,000
$x_{10,4}$	96,000	$z^{4,2}_{4,6}$	120,000	$z^{2,1}_{10,16}$	224,000
$x_{11,1}$	56,000	$z^{1,1}_{5,7}$	96,000	$z^{3,1}_{10,16}$	240,000
$x_{11,2}$	160,000	$z^{1,1}_{5,8}$	80,000	$z^{4,1}_{10,16}$	96,000
$x_{11,3}$	176,000	$z^{1,1}_{5,9}$	68,000	$z^{1,1}_{11,17}$	56,000
$x_{11,4}$	40,000	$z^{1,1}_{5,10}$	80,000	$z^{2,1}_{11,17}$	160,000
$x_{12,1}$	48,000	$z^{1,1}_{5,11}$	56,000	$z^{3,1}_{11,17}$	176,000
$x_{12,2}$	120,000	$z^{1,1}_{5,12}$	48,000	$z^{4,1}_{11,17}$	40,000
$x_{12,3}$	152,000	$z^{2,1}_{5,7}$	240,000	$z^{1,1}_{12,18}$	48,000
$x_{12,4}$	36,000	$z^{2,1}_{5,8}$	200,000	$z^{2,1}_{12,18}$	120,000
$x_{13,1}$	96,000	$z^{2,1}_{5,9}$	160,000	$z^{3,1}_{12,18}$	152,000
$x_{13,2}$	240,000	$z^{2,1}_{5,10}$	224,000	$z^{4,1}_{12,18}$	36,000
$x_{13,3}$	280,000	$z^{2,1}_{5,11}$	160,000		
$x_{13,4}$	120,000	$z^{2,1}_{5,12}$	120,000		

5.3. Discussion and comparison with the related literature

Applying the proposed model to the case study shows that it exhibits several advantages compared to the contributions in the related literature. First, thanks to the focus on the distribution part of the SC, we reduce the complexity of the existing approaches addressing the complete chain, like the ones by Jang et al. (2002), Ambrosino and Scutellà (2005), and Miranda et al. (2009), and offer a generic and effective model which answers the need of distribution managers for simultaneous optimization tools of multiple linear performance indices.

Second, by a hierarchical approach to decisions, we address the DN strategic configuration by disregarding the time variable and avoiding the difficulty of the related literature that analyzes simultaneously also tactical and operational issues (as, for instance, Ambrosino and Scutellà (2005)).

Table VIIIA
Data of the minimum lateness HDDN digraph $\mathbf{D_{S3}}$ in Fig. 7.

Edge	Drug quantity	Edge	Drug quantity	Edge	Drug quantity
$x_{1,1}$	428,000	$x_{14,3}$	240,000	$z^{3,1}_{6,8}$	240,000
$x_{1,2}$	1,104,000	$x_{14,4}$	80,000	$z^{3,1}_{6,9}$	200,000
$x_{4,3}$	1,288,000	$x_{15,1}$	68,000	$z^{3,1}_{6,10}$	240,000
$x_{4,4}$	436,000	$x_{15,2}$	160,000	$z^{3,1}_{6,11}$	176,000
$x_{5,1}$	428,000	$x_{15,3}$	200,000	$z^{4,1}_{6,7}$	156,000
$x_{5,2}$	1,104,000	$x_{15,4}$	64,000	$z^{4,1}_{6,8}$	80,000
$x_{6,3}$	1,288,000	$x_{16,1}$	80,000	$z^{4,1}_{6,9}$	104,000
$x_{6,4}$	436,000	$x_{16,2}$	224,000	$z^{4,1}_{6,10}$	96,000
$x_{7,1}$	144,000	$x_{16,3}$	240,000	$z^{1,1}_{7,13}$	96,000
$x_{7,2}$	240,000	$x_{16,4}$	96,000	$z^{1,1}_{7,18}$	48,000
$x_{7,3}$	432,000	$x_{17,1}$	56,000	$z^{2,1}_{7,13}$	240,000
$x_{7,4}$	156,000	$x_{17,2}$	160,000	$z^{3,1}_{7,13}$	280,000
$x_{8,1}$	80,000	$x_{17,3}$	176,000	$z^{3,1}_{7,18}$	152,000
$x_{8,2}$	200,000	$x_{17,4}$	40,000	$z^{4,1}_{7,13}$	120,000
$x_{8,3}$	240,000	$x_{18,1}$	48,000	$z^{4,1}_{7,18}$	36,000
$x_{8,4}$	80,000	$x_{18,2}$	120,000	$z^{1,1}_{8,14}$	80,000
$x_{9,1}$	68,000	$x_{18,3}$	152,000	$z^{2,1}_{8,14}$	200,000
$x_{9,2}$	160,000	$x_{18,4}$	36,000	$z^{3,1}_{8,14}$	240,000
$x_{9,3}$	200,000	$z^{1,1}_{1,5}$	428,000	$z^{4,1}_{8,14}$	80,000
$x_{9,4}$	104,000	$z^{2,1}_{1,5}$	1,104,000	$z^{1,1}_{9,15}$	68,000
$x_{10,1}$	80,000	$z^{4,1}_{4,5}$	1,288,000	$z^{2,1}_{9,15}$	160,000
$x_{10,2}$	224,000	$z^{4,1}_{4,6}$	436,000	$z^{3,1}_{9,15}$	200,000
$x_{10,3}$	240,000	$z^{1,1}_{5,7}$	144,000	$z^{4,1}_{9,15}$	64,000
$x_{10,4}$	96,000	$z^{1,1}_{5,8}$	80,000	$z^{4,1}_{9,17}$	40,000
$x_{11,1}$	56,000	$z^{1,1}_{5,9}$	68,000	$z^{1,1}_{10,16}$	80,000
$x_{11,2}$	160,000	$z^{1,1}_{5,10}$	80,000	$z^{2,1}_{10,16}$	224,000
$x_{11,3}$	176,000	$z^{1,1}_{5,11}$	56,000	$z^{3,1}_{10,16}$	240,000
$x_{12,2}$	120,000	$z^{2,1}_{5,7}$	240,000	$z^{4,1}_{10,16}$	96,000
$x_{13,1}$	96,000	$z^{2,1}_{5,8}$	200,000	$z^{1,1}_{11,17}$	56,000
$x_{13,2}$	240,000	$z^{2,1}_{5,9}$	160,000	$z^{2,1}_{11,17}$	160,000
$x_{13,3}$	280,000	$z^{2,1}_{5,10}$	224,000	$z^{3,1}_{11,17}$	176,000
$x_{13,4}$	120,000	$z^{2,1}_{5,11}$	160,000	$z^{2,1}_{12,18}$	120,000
$x_{14,1}$	80,000	$z^{2,1}_{5,12}$	120,000		
$x_{14,2}$	200,000	$z^{3,1}_{6,7}$	432,000		

Third, we consider aggregate product flows, product families, demand and performance and propose a modular model allowing a systematic and straightforward MILP formulation.

In addition to the above, we remark that previously published approaches to DN strategic design and optimization generally determine the minimum-cost configuration and hardly ever take into consideration also other factors like, for instance, the summation of backorders and unsold products, the dependencies among retailers or the customer satisfaction (Afshari et al., 2010; Nunkaew & Phruksaphanrat, 2009; Zanjirani Farahani & Elahipanaha, 2008). On the contrary, we formulate a multi-criteria objective problem that is able to consider many different issues, according to the will of the manager, e.g., the delivery lead-time, pollutant emissions, on-time delivery, etc.

As a result, the presented model may be used as a decision support tool by DN managers allowing the improvement of the DN flexibility and performance.

Finally, we remark that the proposed single-objective procedure is characterized by an acceptable computational effort, thanks to the low number of integer variables, as shown in Table 8. In this table we report a comparison with other DN design cases solved with an alternative approach (Costantino et al., 2010a and

Table IXA
Data of the HDDN digraph $\mathbf{D_{S13}}$ in Fig. 8.

Edge	Drug quantity	Edge	Drug quantity	Edge	Drug quantity
$x_{1,1}$	428,000	$x_{14,2}$	200,000	$z^{3,1}_{5,8}$	240,000
$x_{1,2}$	1,104,000	$x_{14,3}$	240,000	$z^{3,1}_{5,9}$	200,000
$x_{2,3}$	1,288,000	$x_{14,4}$	80,000	$z^{3,1}_{5,10}$	240,000
$x_{4,4}$	236,000	$x_{15,1}$	68,000	$z^{3,1}_{5,11}$	176,000
$x_{5,1}$	428,000	$x_{15,2}$	160,000	$z^{3,1}_{5,12}$	152,000
$x_{5,2}$	1,104,000	$x_{15,3}$	200,000	$z^{4,1}_{5,7}$	156,000
$x_{5,3}$	1,288,000	$x_{15,4}$	64,000	$z^{4,1}_{5,9}$	64,000
$x_{5,4}$	316,000	$x_{16,1}$	80,000	$z^{4,1}_{5,10}$	96,000
$x_{6,4}$	120,000	$x_{16,3}$	240,000	$z^{4,1}_{6,8}$	80,000
$x_{7,2}$	240,000	$x_{16,4}$	96,000	$z^{4,1}_{6,11}$	40,000
$x_{7,3}$	280,000	$x_{17,1}$	56,000	$z^{1,1}_{7,13}$	96,000
$x_{7,4}$	156,000	$x_{17,2}$	160,000	$z^{2,1}_{7,13}$	240,000
$x_{8,1}$	80,000	$x_{17,3}$	176,000	$z^{3,1}_{7,13}$	280,000
$x_{8,2}$	200,000	$x_{17,4}$	40,000	$z^{4,1}_{7,13}$	120,000
$x_{8,3}$	240,000	$x_{18,1}$	48,000	$z^{4,1}_{7,18}$	36,000
$x_{8,4}$	80,000	$x_{18,2}$	120,000	$z^{1,1}_{8,14}$	80,000
$x_{9,1}$	68,000	$x_{18,3}$	152,000	$z^{2,1}_{8,14}$	200,000
$x_{9,2}$	160,000	$x_{18,4}$	36,000	$z^{3,1}_{8,14}$	240,000
$x_{9,3}$	200,000	$z^{1,1}_{1,5}$	428,000	$z^{4,1}_{8,14}$	80,000
$x_{9,4}$	64,000	$z^{2,1}_{1,5}$	1,104,000	$z^{1,1}_{9,15}$	68,000
$x_{10,1}$	80,000	$z^{3,1}_{2,5}$	1,288,000	$z^{2,1}_{9,15}$	160,000
$x_{10,2}$	224,000	$z^{4,2}_{4,5}$	316,000	$z^{3,1}_{9,15}$	200,000
$x_{10,3}$	240,000	$z^{4,2}_{4,6}$	120,000	$z^{4,1}_{9,15}$	64,000
$x_{10,4}$	96,000	$z^{1,1}_{5,7}$	96,000	$z^{1,1}_{10,16}$	80,000
$x_{11,1}$	56,000	$z^{1,1}_{5,8}$	80,000	$z^{2,1}_{10,16}$	224,000
$x_{11,2}$	160,000	$z^{1,1}_{5,9}$	68,000	$z^{3,1}_{10,16}$	240,000
$x_{11,3}$	176,000	$z^{1,1}_{5,10}$	80,000	$z^{4,1}_{10,16}$	96,000
$x_{11,4}$	40,000	$z^{1,1}_{5,11}$	56,000	$z^{1,1}_{11,17}$	56,000
$x_{12,1}$	48,000	$z^{1,1}_{5,12}$	48,000	$z^{2,1}_{11,17}$	160,000
$x_{12,2}$	120,000	$z^{2,1}_{5,7}$	240,000	$z^{3,1}_{11,17}$	176,000
$x_{12,3}$	152,000	$z^{2,1}_{5,8}$	200,000	$z^{4,1}_{11,17}$	40,000
$x_{13,1}$	96,000	$z^{2,1}_{5,9}$	160,000	$z^{1,1}_{12,18}$	48,000
$x_{13,2}$	240,000	$z^{2,1}_{5,10}$	224,000	$z^{2,1}_{12,18}$	120,000
$x_{13,3}$	280,000	$z^{2,1}_{5,11}$	160,000	$z^{3,1}_{12,18}$	152,000
$x_{13,4}$	120,000	$z^{2,1}_{5,12}$	120,000		
$x_{14,1}$	80,000	$z^{3,1}_{5,7}$	280,000		

Costantino et al., 2010b) and characterized by a comparable numbers of variables and constraints, but a higher number of integer variables. The table clearly shows that the presented approach well fits the case of the DN design with a reduced number of integer variables.

6. Conclusion

This paper faces the problem of the strategic choice of the actors of a Distribution Network (DN), a specific supply chain that does not perform any assembly or transformation processes. More precisely, a DN is devoted to the storage and the distribution of goods. In this paper the DN is described by two direct graphs (digraphs) that model the stage actors (nodes) and the material flow connecting them (edges). A two level DN optimization procedure is proposed in order to determine an optimal DN configuration according to a set of performance indices. In the first level optimization, a procedure is presented to define the constraints and the multi-criteria objective function so that the optimization problem is defined on the basis of the digraph knowledge. In the second level, the resulting Pareto face solutions of the first level optimization are ranked using the well-known analytic hierarchy process.

The DN design methodology has several distinctive features with respect to the related literature. First, the model exhibits a reduced complexity with respect to alternative existing approaches. Second, the proposed technique allows a systematic, flexible and straightforward formulation of the DN optimization problem. Third, using a hierarchical approach, the procedure allows ranking and selecting the DN configurations on the basis of two multi-criteria strategies in order to obtain the solution that best meets the decision maker requirements. In addition, the methodology is flexible in building the optimization constraints, improving agility, performance and re-configurability in the DN design. For instance, it is possible to add or substitute constraints representing the presence or absence of a link and to select different performance indices. In order to show the effectiveness of the proposed strategy, the technique is applied to a case study modeling an Italian drug regional distribution chain.

Future research aims at enhancing the model taking into account uncertainties in the DN, e.g., fluctuations of the demand, costs, as well as processing and transportation times. In addition, new constraints could be taken into account, as those related to transportation capacity.

Appendix A

In the appendix we report the tables with the data describing the case study of Section 4(Tables IA–VA) and the SLD solutions (Tables VIA–IXA).

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