Distribution network design under uncertain demand

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Abstract

This paper is focused on the optimised design of a distribution network taking into account the variability of the final customer demand. In particular we study the design of a one-to-many distribution system, considering the product flows from the hub to the different transit points, as well as the reverse flows. The optimization procedure consists of two main steps: the first step is the determination of the total number of the transit points and the second step is the positioning, within the considered regions, of the different transit points with respect to the position of the main hub. The fluctuating demand over the different regions modifies the optimal solution at the different evaluation times. The goal is the definition of the network configuration that minimizes the total costs considering the uncertainty of the customer demand. We have identified two possible strategies to face such uncertainty: a robust and a stable, where the former produces the minimum expected total cost while the latter determines the minimum variability of the different cost components over the different scenarios. The problem has been inspired by a real industrial case in the food distribution sector that has been reported to show the applicability of the proposed model.

Keywords: Logistics, Distribution network, robustness, uncertain demand.

1.   Introduction

In general, Supply chain management involves decisions concerning locations (where to produce), mix (what is to be produced), and volumes (e.g., quantities to be produced at each site, levels of goods to hold in inventory at each stage of the process). Additional decisions concern IT (e.g., how to share information among parties in the process) and, finally, facilities location (where to locate plants and distribution centres). The location decisions are often the most critical and most difficult within the set of decisions required by an efficient supply chain [1].

Over the different location decision problems that can be generalised with the facility location decisions, the present paper deals with the Distribution Network Design problem.

Distribution Network Design looks at the strategies finalised to the efficient distribution of finished products to customers at the lowest cost. In particular, in this paper we look at the design of the initial configuration of a distribution network as a complex task which may exert a relevant impact on the medium-long time horizon and which determines a decision difficult to be reversed after the implementation . The decision questions investigated are:

- How many different levels should be studied?
- How many Main Hubs should be planned?
- How many DCs (Distribution Centres) should be planned?
- Where should they be located?
- Which group of customers should be served by each DC?
- Which transportation methods should be used?

The main factors influencing distribution network design can be divided into the following two main groups [2]. The first one concerns the costs incurred and the second one deals with the service level offered to the customer:

- Costs affected by the network structure:
  - Inventories
  - Transportation
  - Facilities and handling
  - Information

- Elements of the customer service influenced by the network structure:
  - Response time
  - Product variety
  - Product availability
  - Customer experience
  - Order visibility
  - Returnability

During the time period over which the design decisions are effective, each one of the problem parameters (costs, product demands, distances) may fluctuate widely. Parameter estimations may also be inaccurate due to poor measurements or because of the tasks inherent in the modelling process. Thus in this paper we propose a framework for Distribution Network Design in uncertain environment that may help managers to take decisions explicitly taking into account this variability.

The paper is organized as follows, in the next section a literature review on the network design under demand uncertainty problem is presented; then, starting from the basis of previous works, an explicit definition of the key performance measures used (i.e. robustness and stability) is offered. Afterwards, the model developed, the case study and related results will be given. Finally, the conclusion will summarize the proposed approach to face the uncertainty and the applicability in a real context of the model outlined.

2.   Literature review

Since supply chain design involves decisions at the strategic level, it is desirable to keep the supply chain configuration unchanged over a relatively long period of time once it is determined. Uncertainty is one of the most challenging and important aspects of supply chain management. How to model uncertainty in the supply chain design context remains an important and yet unresolved problem [3].

This is a key reason why the literature on distribution network design under uncertainty consistently grew up in the last decade.

According to a recent literature review [4], half of the more than 150 papers cited were published in the past 10 years and roughly a third were published in the past five years. The growing attention paid to these problems is due to the increased awareness of the uncertainties faced by the gratest part of the firms, as well as to the improvements in both optimization technology and computing power.

It has to be observed that the distribution network design problem has some similarity to the facility location problem and to the facility layout problem. Hence, attention will be paid to to previous studies already published on this topic for uncertain demand environments.

One of the first reviews on the stochastic facility location problems is provided in [5].

In [6] demands are stochastic and price-sensitive, and plants are uncapacitated. The Authors used a heuristic to select facilities to be opened and the allocation of clients to facilities. The quantities to be transported from plants to customers are optimized separately for each plant-customer combination in view of the random demand of each customer to each plant.

In [7] it is possible to find a stochastic uncapacitated facility location problem in which demands, variable production and transportation costs as well as selling prices can be random, uncertainty of the random variables is captured and appreciated by the discussion of different scenarios.

A class of production-distribution planning problems with non-stochastic uncertain demand is presented in [8]. The study models the system as a dynamic game between two players who control the flows on a network with node and arc capacity constraints.

A survey on strategic aspects of facility location, including problems under uncertainty, is offered in [9].

In [10] a method, which uses simulation to develop risk profiles based on uncertain values of various parameters, is proposed. One of the approaches proposed aims at finding the decision policy that yields the most stable outcome, i.e. with low variability of the key performance measures (such as service level or total supply chain inventory). Another approach tries to find a policy able of reducing the total number of changes to the plan over the time horizon, while keeping the key performance measures fixed at their target level. The outcome is a planning process for tactical demand chain planning.

The study [11] proposed a multi-period single-sourcing problem (MPSSP) for the logistics network design evaluation in a dynamic environment. The Authors consider a dynamic demand pattern as well as inventory policies. So as to solve the problem, a class of heuristic solution approaches are presented.

Finally, the study [12] indicates that when developing the network a careful consideration has to be given to reliably estimating the inventory holding costs and the mechanism for determining the capital holding charge. The model designed shown that optimum design is most at risk due to the uncertainties associated with stock holding costs and delivery frequencies rather than customer volume changes and transport tariffs.

3.   Robustness and stability definition

There are a variety of performance measures that can be used for the distribution network design under uncertain: some of them are discussed in [3] and in [4].

Ideally, we would like to design a distribution network that has the lowest total cost (or highest total profit) under the whole set of the possible demand scenarios. However, this is usually unachievable.

A distribution network configuration that has the lowest total cost (or highest total profit) for some demand scenarios may not perform well for other profiles.

Firstly, the concept of *robust design* was introduced by Genuchi Taguchi in the 1960s, and it was subsequently accepted and used in the field of experimental design and quality control. The basic idea of robust design is to make a manufacturing process insensitive to noise factors.

Starting from this concept, a set of studies proposed the application to the design of supply chains, namely *robust supply chain design.*

The literature review [4] illustrates a rich variety of approaches to the optimization under uncertainty that appeared in the literature and their application to facility location problems. In particular, the paper discusses the different "robustness" performance addressed by different authors and it compares the methods adopted to achieve the solution.

Looking at the layout problem, as proposed in the literature review section, from such a point of view some similarities exist with the distribution network design, where the strategic decision of location uncertainty plays an important role. Under this kind of problems, the study [13] and the following [14] proposed a robustness-oriented approach to the facility layout problem under stochastic demand scenarios: the property of layout robustness can be regarded as the ability to minimize the total expected costs.

The subsequent contribution [15] proposes an alternative approach, named stability. The concept of layout stability significantly differs from the concept of robustness: stability aims at reducing the variability in the performance of a given layout, which is a consequence of the exogenous instability of the system.

Hence, coming back to the similarity with the layout problem, we explicitly define the following performance measures for the distribution network design problem:

- ***robustness:*** *property of a distribution network configuration which is able to guarantee the lowest expected cost in the long-run, over the potential scenarios determined by the changes in the external context;*

- *__stability:__ property of a distribution network configuration to show a limited sensitivity to demand variability i.e. a configuration which, regardless of the changes in the external context, will always perform similarly to the levels given in the planning phase.*

Given the two previous definitions, it is also possible to define:

- *the robust distribution network* as the configuration that minimizes the total expected costs over the different scenarios
- *the stable distribution network* as the configuration that minimizes the variability of the different cost components over the different scenarios.

Considering the robustness performance measure, the explanation is straightforward. Viceversa, when considering the stability performance measure, it is possible to observe how variance is usually considered as a standard measure of risk. For companies that are risk adverse, the optimal supply chain design which incorporates attitudes prone to risk may be different than the design approach adopted by those companies which adopt expected costs as the main decision criterion [3]. Moreover, the minimisation of the sensitivity to demand variability may lead to a set of important benefits:

- Reduced need for rearrangement of transit point and central distribution capacities.
- Reduced need for transport fleet rearrangement.

However, it is also opportune to assess a comparison between the stable configuration and the robust solutions. This is a reasonable approach, because the choice of the stable solution may imply a poor performance of the whole network, in terms of expected log-run costs, making the choice made affected by a low profitability. On the other hand, the choice of the robust configuration may lead to a significant variability of the performance itself. In the case of a variability level close to the one offered by the stable configuration, a significant saving in the average total costs may be detected. Therefore, when a stable configuration is preferred to the choice of the robust one, it is also opportune to appreciate some additional performance indicators, such as the following parameters:

- the deterioration of the solution performance in terms of increase in the expected long run costs;
- the improvement of the performance of the solution, which may be appreciated by the decrease in variability of the cost components.

These calculations should be performed to allow the analyst appreciate the level of risk associated with the deteriorated performance of the distribution network configuration.

Moreover, some comments are needed to underline how the expected result is that the stable configuration should be more centralised than the robust one, due to the risk pooling effect. Anyway, it has to be claimed that due to the fact that risk pooling effect decreases as the correlation between demands from the markets becomes more positively correlated, the benefits, deriving from risk pooling, to have a more centralised stable configuration (compared to the robust one) decrease while the market demands become more positively correlated.

4.   Problem definition

We formulate a two-stage distribution network problem considering three different kinds of location: the Distribution Centres (in brief, DCs), Transit Points (in brief, TPs) and Sale Points (in brief, SPs). At each DC, there is the opportunity of shipping products both to the TPs or directly to the SPs. At the TPs, products are shipped to the SPs and, therefore, there is the responsibility for managing the product flows from the DCs to the SPs. Finally, the SPs are the places where products are sold to the customers.

We consider a network with limited capacity for both the DC's and the TP's. In addition, some distinctive features of the problem are considered:

- products distributed are perishable
- products may return from the customers.

As far as the limited shelf life of the products distributed is concerned, an industrial case observed (as explained in the next sections, too) inspired the model proposed below. In particular, the reference case belongs to the sector of fresh food distribution and, therefore, this specific feature was to be accurately included and detailed in the problem definition, giving adequate relevance to both return flows and shelf life ends.

As far as the return option is concerned, due to some regulation restrictions in the transport operation, it was considered that only the DCs may receive the returned products, directly from the SPs, while the TPs cannot receive the returned products. Basically, returned products are defined as those products that cannot be sold at the SPs, because they are defective or because the their shelf life is already expired. In some cases, these products are also affected by an end-of-life cost and they may be subjected to specific regulations concerning their disposal.

The structure of the distribution network considered is shown in figure 1, where the dashed lines represent the returned product flows.
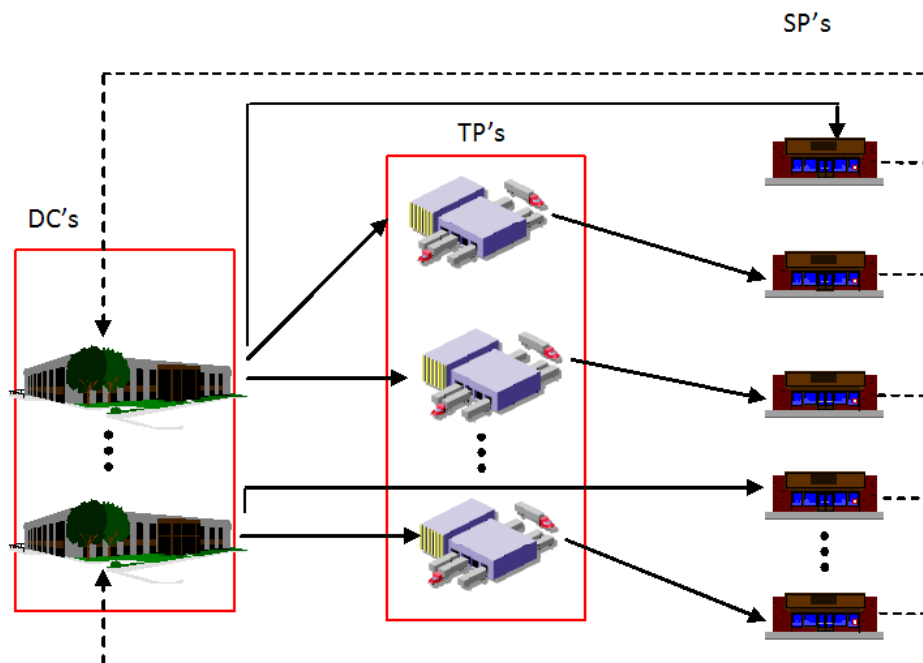

Figure 1. The distribution network structure

It is also opportune to highlight some of the hypotheses introduced, as the reference case implied their assumption.

1. The problem definition refers to a "green field" situation, so there isn't any solution to consider as starting point for the optimisation.
2. Demand uncertainty is captured and modelled using different scenarios over time: demand may vary, from a period to another, up to the end of the time horizon set at the preliminary stage. Thus the optimisation can be carried out by a multi period Mixed Integer Programming, comparing the performance over different scenarios.
3. A preliminary hypothesis was that no modification could be introduced in the network configuration during the evolution of the market demand. In other terms, the optimisation is carried out in long-run terms appreciated over a mix of possible demand scenarios. Consequently, it is assumed that, once adopted the configuration of the

network, it will not be modified up to the end of the time horizon assumed. This is necessary as the network performance is evaluated in long-run terms.

5. Model design

For the formulation of the model, the following notation was introduced:

Indices

$i \in \{1,2...I\}$: index of the potential location sites for Distribution Centres (DCs)

$j \in \{1,2...J\}$: index of the potential location sites for Transit Points (TPs)

$k \in \{1,2...K\}$: index of the Sale Points (SPs)

$t \in \{1,2...T\}$: number of periods considered

$d \in \{1,2...D\}$: number of different shipment drop, where a drop is the specific weight of the delivery (it is used to define a table for shipment tariffs)

Parameters:

cp_{ij}: transportation cost for shipments between the i-th DC and the j-th TP, considering fully loaded truck [€/(ton*km)];

cs_{ikd}: transportation cost for shipments between the i-th DC and the k-th SP, for the specific shipment drop d [€/(ton*km)];

cs_{jkd}: transportation cost for shipments between the j-th TP and the k-th SP, for the specific shipment drop d [€/(ton*km)];

cr_{kid}: transportation cost for reverse shipments between the k-th SP and the i-th DC, for the specific shipment drop d [€/(ton*km)];

ds_{ij}: travel distance between the potential i-th DC and the potential j-th TP [km]

ds_{ik}: travel distance between the potential i-th DC and the k-th SP [km]

ds_{jk}: travel distance between the potential j-th TP and the k-th SP [km]

g: fixed cost of setting up a DC [€]

f: fixed cost of setting up a TP [€]

o: operation activity costs (includes: receiving, handling, picking and shipping activities) at the TPs [€/ton]

e: operation cost for shipping products from DC to SP (includes additional picking and shipping activities) [€/ton]

d_{kt}: products demand in k-th SP in the t-th period [ton]

p: maximum capacity of the DC [ton/period]

r: maximum capacity of the TP [ton/period]

vp: average transportation speed for the shipment between DC and TP and between DC and SP [km/h]

vs: average transportation speed for the shipment between TP and SP [km/h]

sl: maximum time of total transportation activities (from DC to SP) so as to guarantee the shelf life of the product [h]

top: time spent in operation activities (including: receiving, handling, picking and shipping activities) at the DC or at the TP to prepare the shipment for the SP [h]

α: percentage of the returned products [%]

Decision variables

q_{ijt}: quantity shipped from the i-th DC to the j-th TP during the t-th period [ton]

q_{ikt}: quantity shipped from the i-th DC to the k-th SP during the t-th period [ton]

q_{jkt}: quantity shipped from the j-th TP to the k-th SP during the t-th period [ton]

$x_i = 1$, if a DC is located and set up at potential site i, 0, otherwise

$y_j = 1$, if a TP is located and set up at potential site j, 0, otherwise

$w_{ji} = 1$, if the j-th TP is served by the i-th DC, 0, otherwise
$z_{kj} = 1$, if the k-th SP is served by the j-th TP, 0, otherwise
$u_{ki} = 1$, if the k-th SP is served by the i-th DC, 0 otherwise
$b_{ik} = 1$, if the returned products of the k-th SP is shipped to the i-th DC, 0 otherwise

Robust solution
The model for obtaining the robust configuration (i.e. the configuration with the lowest expected total cost) can be formulate as a multi period MIP:

$$\min\left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} q_{ijt}\cdot(cp_{ij}+o) + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} q_{jkt}\cdot cs_{jk}^{d} + \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{t=1}^{T} q_{ikt}\cdot(cs_{ik}^{d}+e) + \sum_{i=1}^{I} g\cdot T\cdot x_i + \right.$$

$$\left. + \sum_{j=1}^{J} f\cdot T\cdot y_j + \sum_{k=1}^{K}\sum_{i=1}^{I}\sum_{t=1}^{T} \alpha\cdot d_{kt}\cdot cr_{ki}^{d}\cdot b_{ik} \right)$$

s.t.

$$\sum_{i} q_{ikt} + \sum_{j} q_{jkt} = d_{kt} \qquad \forall k,t ; \qquad (1)$$

$$q_{ikt} = u_{ki}\cdot d_{kt} \qquad \forall i,k,t ; \qquad (2)$$

$$q_{jkt} = z_{kj}\cdot d_{kt} \qquad \forall j,k,t ; \qquad (3)$$

$$u_{ki} \leq a_i \qquad \forall i,k ; \qquad (4)$$

$$w_{ji} \leq a_i \qquad \forall i,j ; \qquad (5)$$

$$\sum_{j} w_{ji} + \sum_{k} u_{ki} \geq x_i \qquad \forall i ; \qquad (6)$$

$$\sum_{i} w_{ji} = y_j \qquad \forall j ; \qquad (7)$$

$$z_{kj} \leq y_j \qquad \forall k,j ; \qquad (8)$$

$$\sum_{i} q_{ijt} = \sum_{k} q_{jkt} \qquad \forall j,t ; \qquad (9)$$

$$b_{ik} \leq x_i \qquad \forall i,k ; \qquad (10)$$

$$\sum_{k}\sum_{i} b_{ik} = \sum_{j}\sum_{k} z_{kj} + \sum_{i}\sum_{k} u_{ki} \qquad \forall i,k,t ; \qquad (11)$$

$$\frac{ds_{ij}}{vp}\cdot w_{ji} + \frac{ds_{jk}}{vs}\cdot z_{kj} + top \leq sl \qquad \forall\, i,j,k ; \qquad (12)$$

$$\frac{ds_{ik}}{vp}\cdot u_{ki} + top \leq sl \qquad \forall\, i,k ; \qquad (13)$$

$$\sum_{i} x_i\cdot p \geq \sum_{k} d_{kt} \qquad \forall t ; \qquad (14)$$

$$q_{ikt} \leq u_{ki}\cdot p \qquad \forall i,k,t ; \qquad (15)$$

$$q_{ijt} \leq w_{ji}\cdot r \qquad \forall i,j,t ; \qquad (16)$$

$$\sum_{k} q_{ikt} + \sum_{j} q_{ijt} \leq x_i\cdot p \qquad \forall i,t ; \qquad (17)$$

$$\sum_{k} q_{jkt} \leq y_j\cdot r \qquad \forall j,t . \qquad (18)$$

The solution of the model proposed will allow the user to decide the locations of the two types of facilities (i.e., the DCs and the TPs), while considering simultaneously the forward and the reverse flows, together with their correlation, the limited capacity of the facilities and the constraints on the maximum time for transportation (so as to guarantee the shelf life of the products). The objective of the model is to minimize the total costs of the system, which include both the fixed costs and the variable ones.

This model has been coded using Xpress® (Dash Optimization Xpress-MP) and, assessing several experimental tests, it was possible to observe how the optimal solution may be efficiently solved up to 50 facilities to locate and 10 time-periods to capture the different scenarios describing the uncertainty of the demand.

Stable solution

Demand at each SP varies from each period to each period, the variability of these demand streams induce the fluctuations of the different flows, having defined the flow as the cost weighted transported quantity between two generic points of the network.

The variance of the flows between each facility has been taken into account as main source of variability.

Four different flow have been taken into account separately, named:

f_{ijt}: flow from the i-th DC to the j-th TP during the t-th period [ton]
f_{ikt}: flow from the i-th DC to the k-th SP during the t-th period [ton]
f_{jkt}: flow from the j-th TP to the k-th SP during the t-th period [ton]
f_{kit}: flow of reverse shipments from the k-th SP to the the i-th DC [ton];

The variance of the flows are computed as follows:

$$\sigma_1^2 = \sum_{i,j} \sigma_{f_{ij}}^2$$

$$\sigma_2^2 = \sum_{j,k} \sigma_{f_{jk}}^2$$

$$\sigma_3^2 = \sum_{i,k} \sigma_{f_{ik}}^2$$

$$\sigma_4^2 = \sum_{i,k} \sigma_{(f_{ik})}^2$$

So as to calculate the stable distribution network, according to the definition given the network configuration, which is able to originate the lowest variation of the different cost components, over the horizon of demand uncertainty set, among different variability dimensions we chose the total variance of the flows as the key performance indicator.

Therefore the stable network configuration is the configuration that minimizes the following relationship:

$$\min\left(\sigma_{sys}^2 = \sum_{f=1}^{4} \sigma_f^2 \right)$$

6. Model application and results

The proposed model was applied to a producer and distributor of fresh food in the milk sector Italy. The network design problem in this context is particularly complex, mainly because of the constraint introduced by the need for a specific transport time, from the DC to the SP (both direct or via TP), which should be less than 24 hours, so as to guarantee the appropriate shelf life of the product at the SP. Such a constraint increases the total costs of the network because, in general, it is necessary to have a higher number of TPs with respect to other types of networks. Moreover, it is necessary to adopt particular vehicles and warehouses, so as to maintain the products at the right temperature. We consider the situation in which the given

SP number is 50 and their location is defined. For each SP, the demand is known and it is defined as a distribution, described by a mean and a coefficient of variation, that may vary from a region to another. Moreover a correlation matrix of the demand between the different regions is given. Based on these distributions, yearly demands were sampled for each region for an horizon of 10 scenarios (corresponding to 10 years), so as to apply the multi period MIP model. In the following table, the most relevant parameters of the industrial case are offered, as implemented in the model.

Parameter	Value
g	250 [k€]
f	180 [k€]
e	33 [€/ton]
o	37 [€/ton]
p	90.000 [ton/year]
r	7.000 [ton/year]
v_p	80 [km/h]
v_s	50 [Km/h]
top	5 [h]
α	3%

Table 1. Parameters of the industrial case

Applying the MIP model for the optimisation of the robust solution within the set of parameters given, a solution with 2 Distribution Centres and 9 Transit Points was found. The application of the heuristic, developed for the stable configuration, lead to a solution with 2 Distribution Centres and 25 Transit Points. As expected at a preliminary evaluation, while comparing the two solutions, the stable exhibited a total expected cost greater than the robust one (with a limited difference, equal to the 1.5%). On the contrary, the decrease in the variability of the different cost components was equal to 10.6%.

Robust configuration   Stable configuration

9
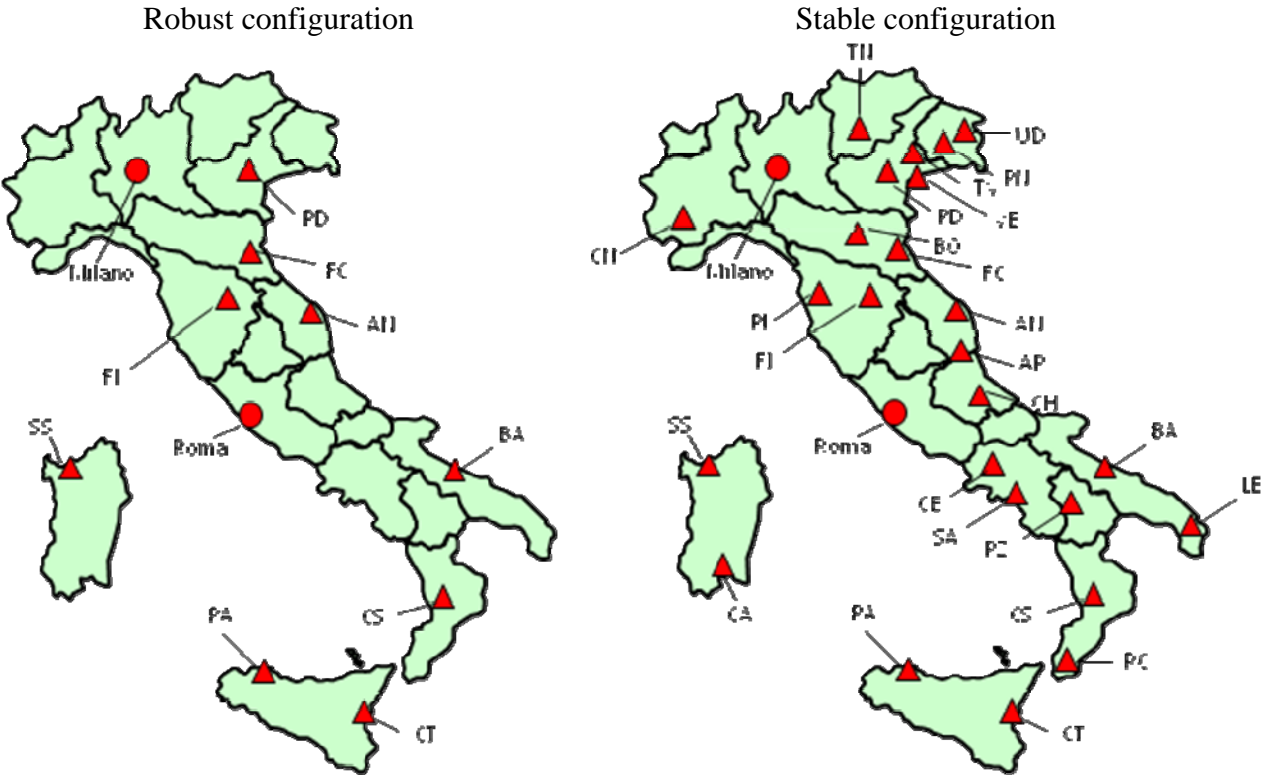
▲ = Transit Point   ● = Distribution Center

Number of DC = 2	Number of DC = 2
Number of TP = 9	Number of TP = 25

Figure 2. Distribution network robust and stable configuration

7.   Conclusions

The distribution network design is a critical step within the assessment of strategic decisions for a supply chain management. In particular, this step which exerts a significant influence on the system performance, especially when demand is uncertain and variable over time. In order to take this fact into account, two alternative strategies were identified and discussed, i.e. the identification of a robust or a stable distribution network configuration. The present paper formally defined and discussed the properties of the two strategies which may be founded on the adoption of a stable configuration or a robust one. In particular, the discussion made also reference to previous studies by the authors themselves, which were published on the features of layout flexibility.

The study proposed was motivated by the real problem observed and faced in a fresh food company in Italy. In particular, the company produces a number of product types in the milk sector, starting from different factories located in Italy, and distributing them all over the country through a multi level distribution network. So as to find the solution, a model was presented and the results obtained helped the company managers to proceed to take the decision about the best network configuration.

A further development of the present study is to consider as source of risk not only the customer demand changes but also risk due to the uncertainties associated with stock holding costs and delivery frequencies changes as proposed by [12].

An additional further development of interest is to look for a performance indicator taking into account the reliability of the network itself, as firstly introduced in [16], the aim of which is to minimize costs taking into account, together with the expected transportation costs, the possible failures at the facilities.

8.   Acknowledgements

9.   References

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