Distribution network design in Large-Scale Retail Trade industry with K-means approach

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Abstract: The facility location problem, which aims to identify the best location to maximize or minimize a specific objective function, is among the most studied problem in the operations and logistics research literature. In the large-scale retail trade (LSRT) industry, the distribution centres (DCs) location choice represents one of the most critical decision to design an efficient distribution network; indeed, this strategic decision has significant effects on logistic costs as well as on the effectiveness of distribution activities. In this paper we present a method for solving the facility location problem in the LSRT industry using a combined k-means clustering cascaded with a local search algorithm, finding the optimal balance between distribution costs on primary and secondary routes through 3 DCs. The approach has been validated on the real case of a LSRT company operating on the entire Italian territory.

Keywords: Large Scale Retail Trade; Facility location problem; K-means algorithm

1.Introduction

The facility location problem (FLP) has been addressed several times either in the operations research and in the operations management literature. It aims at identifying the best positioning of facilities in order to maximize or minimize a determined objective function. Among the various problem instances, the location of distribution centres (DCs) serving a retailer network, with the aim of minimizing the overall logistics costs, is of major importance in the large-scale retail trade (LSRT) industry.

A DC is a facility plant acting as a buffer within a distribution network, between product sources (production facilities or central warehouses) and points of sales. Here, several processes are carried out, among which receiving, storing, handling, picking, sorting, grouping, labelling, packaging, preparing for shipment. As to the choice of a DC location, besides the considerations related to fixed costs variability (e.g. rental fees vary with the geographical position), this shall minimize the total costs either in primary distribution routes (from sources to the DC) and secondary distribution routes (from the DC to the points of sale), i.e. on a two-echelon (2E) distribution network.

A two-echelon logistics distribution network has been widely adopted in supply-chain and transportation systems (Lin and Lei, (2009), Nguyen et al., (2012), Wang, Ma, Lao, Wang, (2014)). It is composed of a small number of source points (eventually one), several distribution centres and a large number of customers (Wang, Xiaolei Ma, et al. 2015).

In this paper we present a practical heuristic for solving the two-echelon facility location problem (2E-FLP) in the LSRT industry: the heuristic aims to identify the optimal position of three local DCs receiving good originating in a single source point, i.e. a central warehouse, using a combined k-means clustering cascaded with a local search algorithm, finding the optimal balance between distribution costs on primary and secondary distribution routes. A representation of the two-echelon logistic network is shown in Figure 1 below.

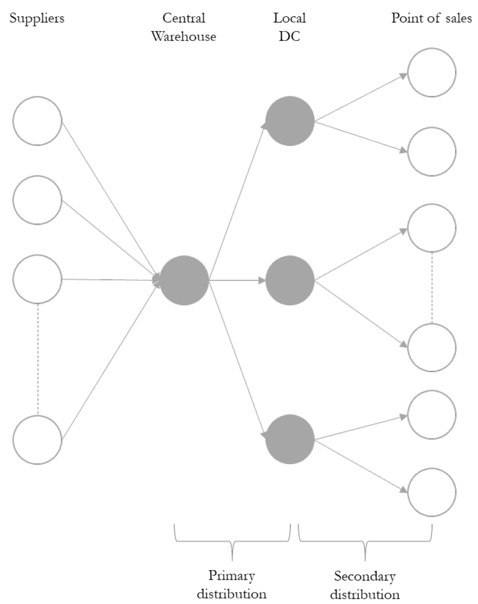

Figure 1: two-echelon logistic network

Differently from the several approaches in literature, the proposed methodology only focuses on the 2E facility location, without taking into account combined routing or inventory management optimizations. As a result, the mathematical approach is straightforward and results to be easy to implement on a simple spreadsheet, avoiding the hurdles which come along with complex multicriteria models. Thus, we provide supply chain managers and people from LSRT industry with a practical tool to solve the problem in real cases.

Indeed, the paper presents a case study as well: the proposed method has been validated on a distribution network composed by 429 geo-localized points of sale in Italy, along with their sales volumes, and a central warehouse The analysed company intended to set-up 3 DCs and succeeded in choosing their optimal position to minimize the overall distribution costs following the procedure here described.

The method follows a 2-stage approach: first, only the secondary distribution is considered, i.e. the objective is to minimize the weighted distance between the DCs and the point of sales. Here, the k-means clustering algorithm is used. Secondarily, the primary distribution is also considered, i.e. the objective function includes the weighted distance between the central warehouse and the DCs, and a local-search algorithm is used to find the final solution. Weights are computed according to point of sales distribution volumes, which are considered to be proportional to their turnover. As said, both the steps have been implemented on a simple MS-Excel spreadsheet.

2. Literature review

The facility location problem was originally formalized by Weber in his "Theory of the Location of Industries" (Weber 1929) where the aim was to determine the point to locate a factory in order to minimize transportation and labour costs. Later, this theme was treated by numerous researchers among which Cooper, who defined the "Location-Allocation Problem" (Cooper, 1963, 1967), where the destination locations and shipping costs are given and where the aim is determining the optimal position of a fixed number of sources as well as their allocation to destinations, to minimize the total costs. The generalized facility location problem is intended as finding the position of a source point in the two dimensions space such that the distance is minimal for any number of predefined destinations.

The generalized facility location problem complexity strongly depends on the number of DCs and the chosen distance measurement model. Indeed, the case with a single DC and linear (Euclidean) distances is considered quite easy to approach with many exact algorithms able to solve it in polynomial time. With more than one DCs, usually heuristic approaches are chosen. As to the distance measurement model, precise travel information data (e.g. road distances or timings) are seldom used and more simplistic approaches are preferred, such as those based on coordinates systems references and distance computed with Euclidean or "Manhattan" metrics. Cooper in 1968 assumed transportation cost as proportional to the distance raised to some power.

Facility location problem is usually treated in conjunction with other supply chain problems, such as customer clustering problems (Hu and Sheu, (2003), Miranda et al., (2009), distribution region partitioning problem, Vehicle Routing Problem (Chepuri and Mello, (2010), Sheu and Lin, (2012), Wang et al., (2013), Wang, Ma, Lao, Yu et al., (2014) or inventory management (Federgruen, Prastacos e Zipkin 2019). In (1998), Min et al. published a comprehensive literature review on combined location-routing problem (LRP): the Two-Echelon Location Routing Problem (LRP-2E) was proposed to take into account the relationship between logistics and distribution centres in the two-echelon logistics distribution network. Jacobsen and Madsen (1980) as well as Madsen (1983) studied the two-level location routing problem to distribute newspapers and their studies are considered the forerunners of LRP-2E. Later on, notable is the work of Nguyen et al. (2012) who studied the two-echelon location routing problem with a single central depot (already located) and a set of potential satellites using a greedy randomized adaptive search procedure complemented by a learning process and path relinking. Indeed, the LRP-2E is recognized to be a complex problem to solve: Barreto, Ferreira, Paixão, and Santos (2007) presented a cluster analysis procedure based on hierarchical and non-hierarchical clustering techniques with several proximity measures to gain the heuristic versions, followed by a sequential heuristic algorithm with clustering techniques to address the LRP. Lin and Lei (2009) studied two-echelon location routing problem considering two-level routing, where number of distribution centres and their locations are taken into account into model formulation. To solve this problem, a hybrid genetic algorithm with a routing heuristic is proposed to achieve a near-optimal solution. Derbel, Jarboui, Hanafi, and Chabchoub (2012) proposed a hybrid approach to combine a Genetic Algorithm with an Iterative Local Search. An extensive review on solving approaches to the LRP-2E can be found in Wang et Al. (2015).

To sum up, the greatest part of the authors aiming at solving the integrated location-routing problem proposed quite complicated solutions, which require complex mathematical approaches most of time outside the competence sphere of industrial supply chain managers or software designer.

Indeed, also combining the facility location problem with inventory management theory results in intricated models: for multiple retailers, multiple supplier distribution networks a near optimal inventory policy was presented by (Ganeshan 1999) while Nozick and Turnquist (2001)proposed Lagrangian-based scheme to solve an incapacitated facility location problem with a linear safety stock function. On the similar line, a DC location model was introduced by Daskin, Coullard, and Shen (2002) that incorporates safety stock and working inventory cost at the DCs. (Firoozi, et al. 2014) have formulated the problem as a mixed integer nonlinear mathematical model that integrates inventory control and facility location decisions solving with a memetic algorithm. Drezner and Scott (2013) presented a model that combines inventory and location decisions considering a single distribution centre location that serves a finite number of sales outlets for a perishable product in order to minimize the transportation costs from the distribution centre to the sales outlets and the inventory related costs at the sales outlets. Perishability is also treated in Chen & Zhong (2013) who described an improved genetic algorithm for solving location problem of logistic distribution centres for perishable products when restrictive area exists. The model considers the impact of the perishability as part of the overall distribution cost, and a heuristic approach on sub distribution areas and feasible routes is combined with genetic algorithm to solve the problem.

Again, as it happens with the LRP, integration of inventory, safety stock, allocation decisions etc., into FLPs makes these non-linear and complex (Aaron Guerrero Campanur, et al. 2018). The resulting mathematical approaches are difficult and problematic and increase the separation between model and reality. Indeed, there is the risk that the numerous variations of Weber's original problem were inspired more from literature rather than from industrial cases, and the evidence of influence on supply chain practice is questionable.

To our knowledge, there is little or no evidence of works essentially focusing on two-echelon facility location problem and proposing simple approaches that can be straightforwardly translated in industrial practice. Besides neglecting to simultaneously determine the optimal routes, the optimal inventory level, the optimal region partitioning, in this work we aimed at finding a good trade-off between complexity of the approach and solution effectiveness.

3. Modelling of the analysed problem

The problem is here defined as finding the optimal position of a set of distribution centres that receive goods from a single source and distributes to different points of sales, evaluating transportation cost linearly proportional to distance and volume flows. In turn, volume flows are assumed proportional to turnovers. That is: flows on secondary distribution are assumed to be proportional to the turnover of each point of sale; primary distribution flows reflect the number of destinations associated with each DC, with their relative turnovers.

Area is not modelled in the continuous space but as a discrete grid and distances are computed with the Euclidean metric. We are aware these assumptions may lead to a sub-optimal solution, as Ballou stated in 1973, but the complexity is lowered so much that a simple spreadsheet can manage the problem, allowing industrial managers to approach and solve this strategic and complex decision-making issue.

The total distribution cost results from the sum of two components:
i) the primary distribution cost, related to the flows from the single central warehouse to the distribution centres; this depend on the distance between the source and each distribution centre, weighted with the turnover of the associated destinations.

ii) the secondary distribution cost related to the flows from each distribution centre to the associated destinations; this depends on the weighted distance between the distribution centre and the associated destinations.

3.1 Minimizing the secondary distribution costs

The problem is here first approached with a clustering algorithm to minimize the secondary distribution cost *(ii)*. The k-means algorithm (MacQueen 1967) is one of the simplest methods to solve the clustering problem. Here it is applied as follows:

1. the procedure starts with a random location of k centroids;
2. each destination point is assigned to the nearest centroid;
3. the location of each centroid is recalculated choosing the central position among the assigned set of destination points;
4. Iterate from step 2 until the centroid position remains unchanged on the grid.
5. The final location for each centroid is chosen, according to the k-means algorithm.

Distances are always weighted with the point of sale turnovers.

This algorithm is well-known thanks to its simplicity and the speed of convergence to a local minimum. The grid resolution may influence the algorithm convergence: with a very narrow grid there is no guarantee that the algorithm will find a stable solution. In these cases, a time limit on the algorithm execution time may be adopted. Another drawback is related to its sensitivity to the initial position of the centroids: as in the cited other approaches on large-scale data, the quality of the final solution depends on the goodness of the initial instance. Indeed, as reported by (Oliveira e do Carmo Nicoletti 2018) in their research article, the performance of the k-Means is highly dependent on a 'good' initialization of the k group centroids as well as of the value assigned to the number of groups the final clustering should have.

The following figures exemplifies two steps of the algorithm behaviour in a case with five destination points and two clusters (i.e. two DCs).

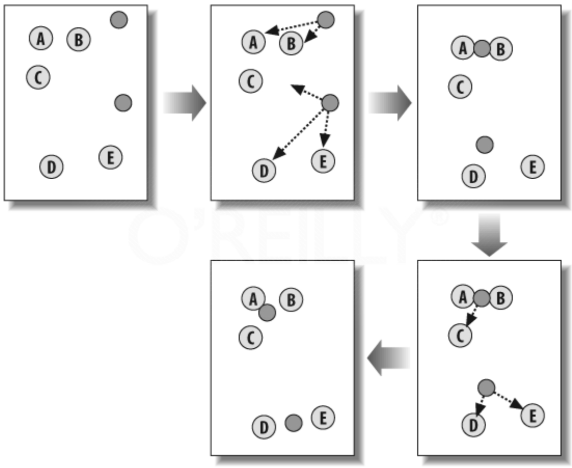

Figure 2: example of K-means algorithm execution

3.2 Minimizing the total distribution costs

To minimize the total distribution costs - considering primary distribution *(i)* as well - and find the final solution, a local-search approach has been used in cascade to the k-means result. The local search finds the optimal position of the distribution centres iteratively searching in the neighbourhood of the final positions provided by the k-means algorithm. It evaluates the total cost for each possible position of the DC in any of the associated destination point.

Here it is applied as follows:

6. Take in input the final centroid location provided by the k-means algorithm;
7. Compute the total distribution costs summing the secondary distribution cost and the primary distribution cost;
8. Change the DC location among one of the positions on a geographical discrete grid;
9. Iterate from step 7 until all the associated point of sales positions have been evaluated for each DC;

The final location for each centroid is chosen as that which yields the minimum total distribution cost.

To consider the cost differences between primary and secondary distribution, a multiplication factor has been introduced: indeed, in primary distribution maximum load factors of high capacity truck are reached while in secondary distribution lower load factors and smaller trucks are used. Using exemplificatory values, the ratio between the transportation cost of a given number of pallets onto 16-plt trucks with a 90% load factor and the transportation cost of the same number of pallets onto 33-plt trucks with 95% load factor represent a multiplication factor to convert the cost of primary distribution flows into secondary distribution flow. In the specific case, the multiplication factor has been defined and shared with the company logistic manager.

4. Validation on the case of a LSRT company in Italy

The large-scale retail trade is the modern retail sales system implemented through a network of supermarkets. In the large-scale retail trade industry, the distribution centres location choice represents one of the most critical decision to design an efficient distribution network; indeed, this strategic decision has significant effects on logistic costs as well as on the effectiveness of distribution activities.

The proposed method has been applied to solve the problem in a large Italian company in the LSRT industry, operating in almost the entire country territory with 429 stores, mostly "cash & carry" (C&C) positioned as shown in Figure 3 below, along with the LAT-LONG scale.

The size of the bubble indicates the point of sale turnover.

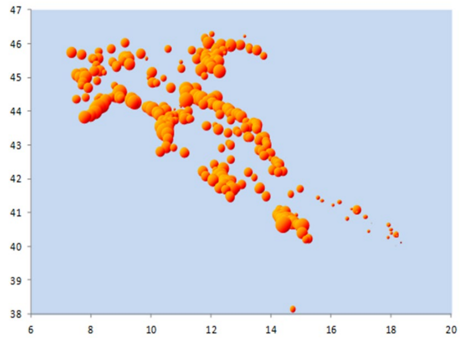

Figure 3: points of sale positions and turnovers

The algorithm has been implemented on Microsoft Excel in VBA. The k-means computation time was always around 2-3 seconds on a standard laptop, regardless of the number of clusters to be found. On the other hand, local search computation time was heavily dependent on the number of clusters and location alternatives and quite slow, ranging from 25 to 45 minutes each run. The final solution required 3 clusters due to the fact that the analysed company requested to locate 3 DCs only.

The possible alternatives for locating the DCs have been selected within the set of the point of sales. Besides the need of performing the local search onto a small number of alternatives, the choice of evaluating the overlap of a DC and a store originates, most at all, onto the strategic consideration that transforming a cash and carry (C&C) in a distribution centre is – where possible – by far much more convenient than building an ex-novo DC at a limited distance. On top of this, the choice of the location of a DC is affected by several other variables which are not considered in this model (such as, for example, road accessibility or land and building cost) and thus the company was looking for an approximate indication.

The first-stage k-means algorithm yielded the solution depicted in the following Figure 4.

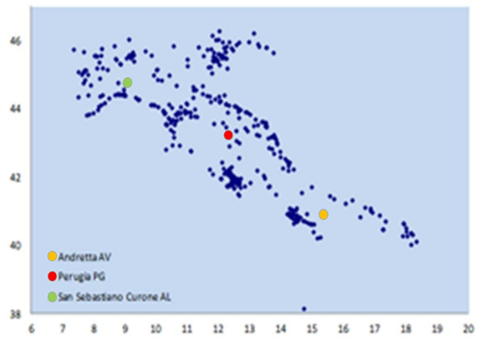

Figure 4: K-means solution with three DC

The k-means solution went in input to the local search algorithm for the second-stage of the procedure, which yielded the solution depicted in Figure 5 below.

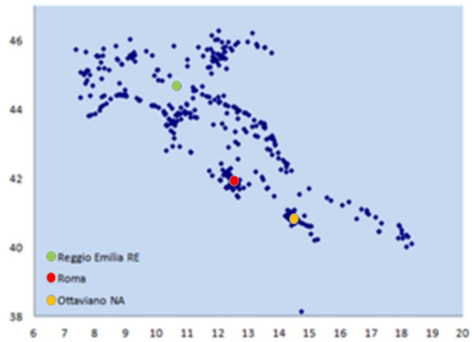

Figure 5: Local search solution with three DC

Is it possible to note that the centre-Italy distribution centre (red dot) moved from Perugia to Rome; analogously, the southern-Italy DC (yellow dot) moved north from Avellino to Naples province and the northern-Italy DC (green dot) moved east from Alessandria to Reggio Emilia province. This was the result of the local-search algorithm which also considered the primary distribution flows, from the unique source and the 3 DCs. The reader may not be surprised to acknowledge that the unique source point was in Rome city, and this clearly acted as an attraction point.

The analysed case took inspiration from the selected company logistic problem, which required to locate 3 DCs; indeed, interesting insights may come from analysing the problem varying the number of DCs: because the possible number of DCs to be possibly located may range within a very narrow interval, a simple approach is to compute the optimal location respectively for 2, 3, 4.. up to n DCs.

The following Figure 6 shown the distribution cost variation increasing the number of DCs, also evidencing the effect of local search procedure onto the k-means algorithm solution.

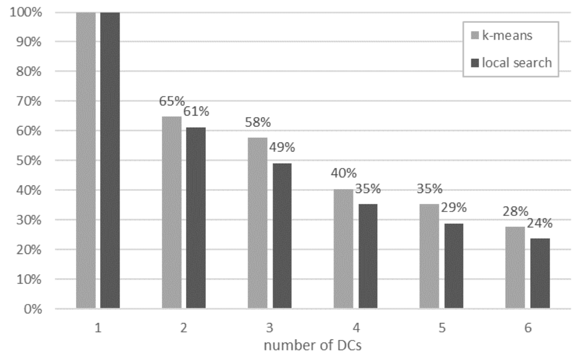

Figure 6: distribution costs variation with the DC number

It is evident that the local search procedure has always improved the original solution obtained through the k-means algorithm, except that in the single DC case. Regarding the distribution cost, this clearly decreases as the number of DC increases: this originates from the multiplication factor, which makes the primary distribution more convenient than secondary distribution. Thus, as a general rule, the greater the number of DCs on the territory, the lower the distribution cost. Only considering distribution costs, however, is not sufficient to determine the optimal number of DCs, because capitalized and operative expenditures for setting up and managing the DCs must be estimated and added.

5. Limitations of the approach

Is to be noted that many aspects do exist that separate a theoretical model from a real case: changes of the volume flows may lead to different solutions over years; certain geographical areas may be inaccessible, e.g. due to the presence of lakes or mountains; Euclidean metric usually do not replicate real road distances; transportation costs may not linearly vary with distance and flows (Rushton, Croucher e Baker 2006), e.g. in road transport, cost varies with truck capacities and load factor. Administrative aspects related to strategical position choice (differences in legal conditions, taxes, etc. see Randawa and West, 1995) are not contemplated here mainly because the considered area falls entirely within a unique country with fairly homogeneous regions. Lastly, significant differences among the product assortment in the point of sales may lead to misalignment between volumes and turnovers (e.g. fruit and vegetables have a lower price with respect to cold cuts and cheese).

6.Conclusions

The proposed approach managed to effectively solve a localization problem for three distribution centres (DCs) sourcing from a unique point and serving 429 destinations, using a combined k-means and local search approach.

The k-means algorithm proved to be efficient and to converge very quickly. Despite these practical advantages, generally speaking the k-means algorithm may suffer from potential flaws: first of all, if the number of items to be classified is small, the initial instance significantly influences the final solution. If using an initial random assignment, the k-means may not always yield the same final solution.

Finally, if the item distribution is heavily uneven, the algorithm could be trapped in a local optimum, therefore not being able to find an overall global optimum. Nevertheless, its simplicity allowed to solve a relatively large instance (429 items and 3 clusters) on a simple spreadsheet, computing the solution of minimal cost for the secondary distribution (from the DCs to the point of sales) in few seconds.

On the other side, the cascaded local search algorithm, beyond being very simple and intuitive, works fairly well regardless of the initial input. Therefore, not suffering the same flaws of the k-means algorithm, it can be used as a further step to refine the solution found by the former. On the other hand, it turned out to be quite slow, and with larger data set its use may not be convenient. However, for a LSRT company, a number of points of sales greater than 500 in an unique geographical area (thus served from a single central warehouse) is an infrequent condition; as a consequence, the local search algorithm efficiency shall not negatively influence the approach practicality. Indeed, here, the local search has been used to include the primary distribution cost (from the unique source to the DCs) in the final solution.

Finally, modelling assumptions such as the metric chosen to measure distances or the criteria behind the choice of the weights of the distribution flows are considered not to be significant in influencing the proposal approach effectiveness. On the contrary, further research on the method should include a sensitivity analysis on the algorithm performances varying the multiplication factor value and the network characteristics, which will be the topic of future works.

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