Abstract

The ever-increasing complexity of the advanced manufacturing environments together with the global competition, dictate the investigation of new approaches for manufacturing networks design and configuration. In addition to that, the newcomer concept of frugal innovation is moving towards a new business model by adapting local market requirements and providing cost-efficient and high customer-value solutions. Towards that end, a methodology for manufacturing networks design via a smart search algorithm is proposed, targeting the adoption of frugal innovation in a new manufacturing network. The proposed methodology is validated using data from an industrial case study.

Keywords: Design; Manufacturing Networks; Frugal; Manufacturing.

1. Introduction

The contemporary manufacturing industry is characterised by immense competition, divergent regional markets, high demand volatility, and heterogeneity. Towards that end, manufacturing global supply chains are shaped into regional blocks, i.e. European, Asian and North-American [1]. This leads to regional characterisation of customer demands and product requirements. This combination of global production and distributed customer networks forms the basis of frugal innovation, which aims at exploiting the concept of intelligent use of resources, turning the related constraints into advantages and a driving force towards product innovation [2]. To address these challenges, the Original Equipment Manufacturers (OEMs) are searching for better approaches to create well-structured manufacturing networks with higher efficiency, moving towards a more close-to-customer approach. Thus, properly configured and easily adaptable manufacturing networks are needed, which would be capable of handling the complexity and enormity of the supply chain structures. The selection of optimum manufacturing network configurations that satisfy these challenging objectives however, is a proven data-intensive problem [3]. To support the decision process, this research work proposes a method for the design and operation of highly efficient modern manufacturing networks operating under demand fluctuations, economic and environmental constraints. In addition to that, a multi-criteria ranking method is utilized to rank the suitable suppliers and support the design of the manufacturing networks.

2. State of the art

The manufacturing environment is characterized by dynamic changes and ever-increasing complexity due to the fact that globalization and customer demand impose new requirements to industries [4], while states are creating legislation for a more socially and environmentally responsible production. Adding to this, the rising logistics costs, mass customization and regionalism are all trends pushing towards distributed manufacturing in order to achieve greater efficiency and sustainability [5]. Distributed manufacturing is going to play an important role in niche markets, where products created by local suppliers are more favourable to the public. Regionalism also affects production design, as adapting to local market requirements is of high importance for companies. This is a part of a bigger paradigm which is emerging, called Frugal innovation. Frugal products are low- to mid-end products or services sold mainly in emerging markets. They can be defined in terms of the attributes: Functional, Robust, User-friendly, Growing, Affordable and Local, and can be found in most industries [6]. Globalization and rising incomes in developing countries may also instigate frugal innovation. Such services and products...
need not be of inferior quality, but must be provided at a low and affordable price [7].

Distributed manufacturing can be defined as a system of autonomous agents; mutually dependent on each other, but at the same time are characterised by geographical dispersion [8]. These agents are companies that create a distributed manufacturing network (DMN), which is complex to design, plan and operate.

The configuration of a production network system follows the same logic in decision making and coordination of manufacturing activities on a global basis, as production systems in the development of production as well as in functions of production in plants or in plant areas (micro level)[9]. Decentralized manufacturing systems, also called as distributed manufacturing systems, have already shown many of their benefits. As shown in [10] and [11], the decentralized systems can handle unexpected market requests more efficiently, and therefore are better suited for DMNs. There have been many frameworks for manufacturing networks design, namely the game theoretic approach [12], the agent-based where a survey can be found in [13] and an architecture for outsourcing SMEs in [14], the holonic [15] and a multi-criteria method for network design[16], among others.

The main challenge during manufacturing networks design is to select the optimum suppliers based on their suitability and availability. Therefore, there is a need for multi-criteria supplier ranking and selection methods so that the chosen suppliers can be the most suitable for each circumstance. The multi-criteria ranking will give the opportunity to consider multiple and conflicting criteria that will support the supplier selection based on any new product configuration. There has been a large number of methods for dealing with this problem, which are further analysed in [17]. A commonly used method is the Analytic hierarchy process (AHP) [18], where the method provides a means of decomposing the problem into a hierarchy of sub-problems so that they are subjectively evaluated. The subjective evaluations are converted into numerical values and are processed to rank each alternative on a numerical scale. Another approach is the ELECTRE III [19], which is based on pairwise comparisons between alternatives characterised by outranking relations, that is then distilled by two antagonist procedures one ascending and one descending.

Addressing the aforementioned challenges of frugal innovation and the data-intensive problem of manufacturing networks configuration and design, the proposed methodology will aim at generating optimum manufacturing network configuration. The usage of a multi-criteria smart search algorithm supported by a multi-criteria supplier ranking and selection algorithm will reduce the solution space of the generated alternatives and will lead to high-performance manufacturing networks, addressing challenges of the existing literature review that have not yet been adequately tackled. Moreover, the proposed approach will increase the proportion of multiple and regional suppliers selecting the optimum ones and targeting frugality’s main objectives of optimum cost and time.

3. Design and configuration of manufacturing networks

3.1 Description of methodology

This paper proposes a framework for manufacturing networks design and configuration, aiming at reducing the solution space of the network configuration problem and generating optimum alternatives. The proposed method consists of two main steps. The first one is the multi-criteria supplier ranking and selection algorithm. The second one is a multi-criteria smart search algorithm (SSA) for the design and planning of the manufacturing networks.

The new product configuration is based on the regional customer demands and requirements, which trigger the algorithm of multi-criteria supplier ranking and selection. New regional and frugal components of the product are
considered for the dusting of the product configuration, and various suppliers should be considered in order to address customer needs. Multiple and different suppliers are considered in different markets. Through this algorithm the system ranks the suitable suppliers based on the defined criteria, and the optimum are selected to be considered in the design process of the manufacturing network. Once the optimum suppliers are selected based on the method, they are inserted as input in the decision-making algorithm for the design and configuration of the manufacturing network. The decision-making procedure used for the identification of optimum manufacturing network configurations is based on resource-task assignment decisions. The process is based on 6 steps: (i) formation of alternatives, (ii) determination of criteria to satisfy objectives, (iii) definition of criteria weights, (iv) calculation and normalisation of criteria values, (v) calculation of utility value, and (vi) selection of an alternative with the highest utility value [20]. A manufacturing network configuration alternative is defined as a set of partner-task assignments, capable of manufacturing a frugal product within a manufacturing network structure. The combination of the supplier ranking method with the smart search algorithm for the design of the manufacturing network will reduce the solution space and will generate alternative networks with higher performance, targeting best solutions (Fig. 1).

3.2 Multi-criteria ranking method for supplier selection

The multi-criteria ranking method that is employed is called ELECTRE III, and relies on the construction and the exploitation of the outranking relations [19]. These two distinct phases are the main phases of this method. In the phase of the construction of the outranking relation, the alternatives are pairwise compared (A, B). Each pairwise comparison is characterised by an outranking relation. To say that “alternative A outranks alternative B” means that “A is at least as good as B”.

Fig. 2 Workflow of the proposed ranking method [19]

During the phase of the exploitation of the outranking relation, two pre-rankings are then constructed with two antagonist procedures (ascending and descending distillation). The combination of the two pre-rankings yields the final ranking (Fig. 2). Practically, the end user defines the criteria that will be considered in the pairwise comparison. Once the criteria are defined, the weights of the criteria should be provided. The weights of the criteria are user-defined based on the needs and the nature of the problem. Moreover, the indifference q and the preference p thresholds are defined based on the values of the provided data in order to support the building of the outranking relations. The proposed method was selected instead of the AHP due to the fact that enables the fine-tuning of the outranking relations by using the indifference, preference and veto thresholds.

3.3 Network design and operation algorithm

The decision-making procedure is supported by the Smart search algorithm (SSA). The SSA generates a subset of the Total Number of Alternative (TNA) manufacturing network configurations through 3 adjustable control parameters (Fig. 1). The control parameters are: the Selected Number of Alternatives (SNA) which defines the breadth of the search, the Decision Horizon (DH) which controls the depth of the search, and the Sampling Rate (SR) which guides the search towards the high quality branches of the tree of alternatives. The required number of experiments (obtained through a suitable orthogonal array), the optimum values for these three factors, as well as their influence on the utility value, are obtained through a Statistical Design of Experiments (SDoE) [21] and were identified at SNA = 100, DH = 3 and SR = 10. The workflow of the method is depicted in Fig. 3.

Fig. 3 Workflow of the proposed smart search algorithm

The criteria that were used to determine the results for each configuration were the following:

1. Production and Transportation Cost (PTC): Superposition of the sum of the production cost (PC) for the manufacturing network partner (MNP) i to perform task k, and of sum of the transportation cost (TC) from partner i to partner j, where i, j, k P n, i = 0, 1 ... I, j = 0, 1 ... J and k = 0, 1 ... K [10]:
\[ \text{PTC} = \sum_{i} \sum_{k} P_{C_{ik}} + \sum_{i} \sum_{j} T_{C_{ij}}(€) \]  

(1)

(2) CO2 Emissions (CO): The emitted grams of CO2 for the transportation (CE) required from partner i to partner j (km) [20], [22], [23]:

\[ \text{CO} = \sum_{i} \sum_{j} \text{CE}_{ij}(g \text{ of CO2}) \]  

(2)

(3) Energy Consumption (EC): Superposition of the sum of energy consumption (EP) for partner i to perform task k, and of the sum of the transportation energy (ET) required from partner i to partner j [20], [23]:

\[ \text{EC} = \sum_{i} \sum_{k} \text{EP}_{ik} + \sum_{i} \sum_{j} \text{ET}_{ij}(J) \]  

(3)

(4) Lead time (LT): The lead time is calculated from the point that an order is placed to the point that it is actually available to satisfy customer demand [24]. Lead time is calculated as the superposition of the sum of processing and set-up time (PT) for partner i to perform task k, and the sum of the transportation time (TT) from partner i to partner j.

\[ \text{LT} = \sum_{i} \sum_{k} \text{PT}_{ik} + \sum_{i} \sum_{j} \text{TT}_{ij} \text{(hours)} \]  

(4)

(5) Quality (QL) is calculated as the average of the qualities of the supply chain partners that are selected in an alternative configuration [20]. The values for the qualities are obtained from the ODM of the case study, based on empirical and historic data:

\[ \text{QL} = \frac{\sum_{k} QL_{ik}}{K} \]  

where QL_{ik} is the quality of the supplier performs task k.

Once the criteria are calculated and normalized, the utility value of each alternative is calculated. The alternative with the highest utility value is selected.

4. Frugal Innovation in Manufacturing networks

Among the main directions for frugal innovation, which means to develop product for specific market with optimal costs and quality, is the development of new products for local centers, the design and re-design the manufacturing networks by increasing the consideration of local suppliers, as well as the adjustment of the current strategies or operations in order to reduce cost and time. Through the proposed methodology, once new frugal modules or parts of a product are configured based on the regional customer’s requirements, different suppliers are considered, giving focus on increasing the proportion of regional suppliers. The suppliers ranking method performs a first selection of the appropriate suppliers based on their capabilities and availability as well as on defined criteria. In addition to the above, the distance and the delivery cost between the customer and the suppliers or the assembly plants is considered during the network design and configuration. The proposed approach will empower the integration of the customer in the product development and in manufacturing networks design and planning. In this way and with the proposed methodology manufacturing networks will be capable of supporting new products configurations and support different markets. Finally, main objectives of frugal innovation like optimal cost and time of a new product will be achieved and as a result new markets will adapt easily and efficiently new products.

5. Industrial case study – Results and discussion

To test and validate the proposed methodology, a domestic appliance industry is considered that is moving towards frugal innovation in manufacturing and as a result, different product configurations are taken into consideration in different production facilities, in different counties. The industrial case study considers various partners, with characteristics and capabilities drawn from a real-life manufacturing network. Different operations are performed from different partners at varied cost, time, and quality. The product, which is a refrigerator, consists of certain main components Bill of Materials (BoM). The main processes; Bill of Processes (BoP); considered are forming, extrusion of plastics parts, assembly of subcomponents, as well as the final product assembly (Fig. 4). The door and the plastic components are parts that vary based on the regional customisation options. As a result, new suppliers and plants are considered from in order to address the demand and the customization options. In this case, four of the subcomponents shown in Fig. 4 are provided by a pool of suppliers. Some of the sub-components are manufactured by cooperating plants, and the final assembly is performed in the main plant of the company. The pool of suppliers is defined by the company and also local and regional suppliers are considered based on the customer’s requirements. As a result, the most appropriate suppliers should be considered that will fulfill the customer’s requirements. The proposed methodology and, specifically, the multi-criteria ranking method will assist the company to select the optimum suppliers based on certain defined criteria. In this case, four different criteria were considered, namely: quality, delivery time, cost as well as locality. The weight for each criterion were extracted from the industrial users and were configured to: 0.2, 0.25, 0.25, and 0.3 respectively. Quality is calculated as the overall quality of the component that a supplier can provide with range from 1 to 10. Delivery time is calculated as the production time and the transportation time (hours). Cost is calculated as sum of the production and the transportation cost (€). Finally, the frugal criterion, the locality, is calculated as the percentage of how close is a supplier to the targeted market where the product will be sold and is calculated with following equation:

\[ \text{LO} = \left(1 - \frac{\text{DS}_{i}}{\sum_{m} \text{DS}_{m}} \right) \times 100\% \]  

(6)

where LO is the % of supplier’s locality and the DSi is the distance between the supplier and the targeted market.
In addition to that, the indifference q and the preference p thresholds are defined based on the values of the provided data. The indifference q for each criterion is 1, 1, 10, 25 and the preference p is 2, 3, 25, and 55 respectively. The veto value has not been considered in this case. Four of the sub-components of the refrigerator are provided by suppliers; the compressor, the plastic components, the door gasket as well as the door foam. For each one of the aforementioned sub-components, a pool of suppliers was considered by the company, 9, 10, 6 and 7 respectively. Following the proposed methodology, the suppliers that are placed in the 0 and the 1 position are considered as input in the SSA and the ranking method, the suppliers that are placed in the 0 and the 1 position are considered as input in the SSA and the ranking method.

Table 1 below presents the results of the ranking method on the selected suppliers, based on the defined criteria.

Table 1 Ranking of suppliers

<table>
<thead>
<tr>
<th>Component</th>
<th>Supplier No</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor</td>
<td>Supplier 4</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Supplier 8</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Supplier 2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Supplier 3</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Supplier 9</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Supplier 5</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Supplier 6</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Supplier 7</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Supplier 1</td>
<td>4</td>
</tr>
<tr>
<td>Plastic Comp</td>
<td>Supplier 1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Supplier 3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Supplier 8</td>
<td>1</td>
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<tr>
<td></td>
<td>Supplier 2</td>
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<tr>
<td></td>
<td>Supplier 4</td>
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<td>Supplier 5</td>
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<td></td>
<td>Supplier 7</td>
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<tr>
<td></td>
<td>Supplier 10</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Supplier 6</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Supplier 9</td>
<td>3</td>
</tr>
<tr>
<td>Door Gasket</td>
<td>Supplier 4</td>
<td>0</td>
</tr>
</tbody>
</table>

The selected suppliers are considered as input in the SSA, multiple alternatives as well as the optimum alternative are generated, all of which constitute the optimum manufacturing network, which is graphically presented in Fig. 5 below. Considering an order of 100 products, the main results of the generated network considers a reliability of 90% and a total quality of the product of 72%, among others.

This combination of the two methods leads to solution space reduction and, simultaneously, to better and more accurate results. The optimum suppliers are selected based on the defined criteria, and only these are taken into account in the SSA, resulting to manufacturing networks with higher performance and efficiency. In addition to that, through the proposed methodology the design and operation of the manufacturing systems is moving towards frugal innovation. The proposed methodology exploits the concept of intelligent use of resources, as multiple suppliers can be considered with different characteristics and from different markets, with the purpose of addressing the customer’s regional requirements in the most suitable manner. As a result, through the proposed method, optimum manufacturing networks that turn the related constraints into advantages and driving forces towards product innovation are generated targeting the optimum cost and time.

6. Conclusions and outlook

The research work described a method for supporting the decision–making process of establishing high-performance manufacturing networks, which are capable of addressing the needs of frugal innovation. Multiple and conflicting criteria were considered by both the ranking and the SSA method, which encapsulated important manufacturing objectives of today’s landscape. By utilizing the multi-criteria decision making algorithm, a small subset of the solution space is examined. However, the nature of the algorithm and the parameter of sampling rate both yield a percentage of randomness. This percentage is being reduced through the implementation of the supplier ranking multi-criteria, and through the selection of the optimum one to be considered in the generalisation of the alternatives. Moreover, the combination of these two algorithms in the proposed methodology offers the opportunity to consider multiple suppliers, especially local, based on various product configurations, and rank them quickly and efficiently, thus reducing the effort and at the same time producing high performance networks through targeting the best ones.
In addition to the above, the proposed algorithm will shift the design and operation of manufacturing networks towards frugal innovation as different customer requirements, both regional and frugal, can be considered. Furthermore, through the intelligent use of resources and through the optimum network configuration, cost efficient and frugal products in general, will be further exploited. Targeting the meaning of Frugal the proposed methodology addresses the local, growing, as well as affordable perspective of the frugal innovation considering local customer requirements and low-cost manufacturing networks that will empower different markets.

Future work will be focused on testing the performance of the proposed methodology with other solutions, and also implementing additional criteria. Moreover, the re-configuration of the manufacturing networks will be examined based on the performance of the networks and the actual status and reliability of the partners that have been selected.

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