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A multi-criteria evaluation of centralized and decentralized production networks in a highly customer-driven environment

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Abstract: This paper presents an investigation on the performance and viability of centralized and decentralized production networks, under heavy product customization. Discrete-event simulation models of automotive manufacturing networks were developed, for evaluating their performance under highly diversified product demand. Multiple conflicting user-defined criteria were used for the evaluation, including lead time, final product cost, flexibility, annual production volume and environmental impact due to product transportation. An assessment of the examined approaches, with respect to their responsiveness and suitability for highly customer-driven environments is provided, and can be used as a guideline for the production network design.

Keywords: Distributed manufacturing, Manufacturing system, Customisation

1. Introduction and State of the Art

The landscape of the global market has changed over the last decades, and centralized mass production seems unable to cope with the emerging production requirements that globalization has imposed [1]. The export of finished goods to foreign markets has been the dominant theme in the international trade up to the 1990s, and gained even more attention during the last decade. Meanwhile, the transportation costs for the main intercontinental transport modes, air and sea, dropped significantly, leading to easier distribution of products at dispersed production plants, located at places with low human labour costs [2]. In the late 1980s, 'Mass Customization' [3] emerged as a new paradigm in response to consumer demands for higher product variety, and manufacturers started to offer larger numbers of product 'options' or variants of their standard product. The transition from mass production to mass customization in the automotive industry derives from the need towards higher customization options and more vehicle variants using fewer resources and materials [4]. Customers expressed the need for products that combine quality with short life-cycles and that are also available at low prices at the right time [5]. Mass customization is focused on achieving economy of scope through market segmentation, by designing variants according to a product family architecture and allowing customers to choose the design combinations [6]. The high product variety has been partly achieved in a cost-effective manner by designing a series of basic product options, and by allowing the customers to select the assembly combination that they prefer the most. Such an approach allows the manufacturer to achieve economy of scale at the component level, and use reconfigurable assembly systems in order to create high variety for the economy of scope of the final assembly [6]. At present though, most researches are concerned with the strategic impact of mass customization and do not address to specific implementation issues [7].

Chryssolouris stated: 'It is increasingly evident that the era of mass production is being replaced by the era of market niches. The key to creating products that can meet the demands of a diversified customer base, is a short development cycle yielding low cost and high quality goods in sufficient quantity to meet demand' [8]. Centralization has been replaced by decentralization, and top-down analytic methods by bottom-up synthesis [9]. The picture of a stand-alone company that is linked to its customers and suppliers only by delivery and procurement of products is no longer valid and cooperation between enterprises is of utmost importance [10] [11]. The facilities of a modern supply chain may be operated by the company, or by vendors, customers, third-party providers, or other firms with which the company has business arrangements [12].

Special focus needs to be given to the European automotive industry, which plays a major role in the global economy, currently holding a market share of 25.8% of the global automotive production volume [13]. In order for automotive manufacturers to survive in the current market landscape, they need to perform well in dimensions such as cost, quality, speed, environmental friendliness, and adaptability to demand variations [14]. A research conducted in the U.K. related to automotive products, revealed that 61% of the customers wanted their vehicle to be delivered within 14 days [15] [16]. Consumers from North America responded that they could wait no longer than 3 weeks for their car, even if it is custom built [15]. The complexity generated in the automotive manufacturing activities due to the exploding product variety, requires a holistic approach to be considered during the design, planning and operating of the entire manufacturing system [17]. In addition, the new type of life-cycles, the increasing number of product models, increased outsourcing, manufacturing at different sites, and the diverse cooperation in networks, increase the complexity of production processes [18]. The manufacturing activities in today's turbulent environment are characterized by uncertainty; however, the majority of the existing approaches for production planning assume that both information and environment are static factors [19]. Online customization features are already offered to customers, and truly unique products will be requested in the near future by users around the globe [20]. The apparent gap between mass production and mass customization is a challenging task that needs to be addressed. The aim of this paper is to determine optimal network configurations that are dedicated to the production of highly customized products, in a cost-effective, quick and accurate manner.

2. Decentralized and Centralized production networks model

The typical decentralized automotive manufacturing network comprises of geographically dispersed facilities of Original

Equipment Manufacturers (OEMs), Suppliers and Dealers, all cooperating in order to carry out orders from customers. The decentralized network in the presented case study is configured in such a way that assembly tasks and customization, e.g. the production of the hood variants, can also be performed at a supplier or a dealer site, whereas in the centralized approach, the OEM gathers all the product components, performs the assembly tasks and delivers the finished product to the dealers (Figure 1).

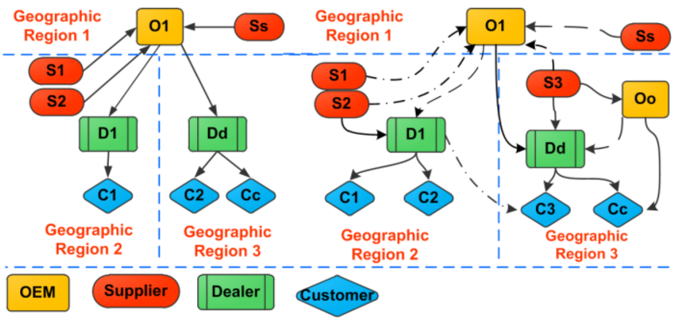

Figure 1. Models of centralized and decentralized production networks

2.1. Criteria

The quality of the production and transportation schemes is quantified by the means of the following criteria:

1 Cost (**C**): The cost is calculated as the sum of the production cost and the transportation cost:

$$C = \sum_{t=1}^{T} Pc_t + \sum_{r=1}^{R} Tr_{Cr}$$

where Pc: production cost (€), Tr_C: transportation cost (€), r: the number transportation roots (r = 1, 2,...R), t: the number of tasks for one job (t = 1, 2,...T).

2 Lead time (**L**): The lead time is the length of time between the time that an order is placed to the point that the order is actually available for satisfying customer demand [21]:

$$L = \sum_{t=1}^{T} Pt_t + \sum_{r=1}^{R} Tt_r + \sum_{t=1}^{T} St_t$$

where Pt: production time, Tt: transportation time, St: setup time.

3 Environmental Impact (**EI**): The environmental impact is calculated by a function that takes into consideration the distance travelled and the emission of CO_2 per kilometre (km):

$$EI = \sum_{r=1}^{R} \frac{D_r * G}{P}$$

where D: transportation distance (Km), G: CO_2 emissions/Km [22], P: number of products that one truck is carrying.

4 Annual Production Rate: The annual production rate (**AP**) is expressed as the mean value of annual production volumes over the complete simulation period. The calculated value depends on the resource characteristics (reliability, cycle time, etc.) and also on the demand scenario defined by the user [23].

$$AP = \frac{\sum_{i=1}^{n_y} AP_i}{n_y}$$

where AP: the annual production rate of the alternative examined, n_y: the number of years (simulation period), AP_i: the annual production volume for the i^{th} year of simulation.

5 FLEXIMAC: This indicator provides a quantification of flexibility, using the processing and flow time of the parts produced. It is calculated by finding the system eigenvalues Ω_i and computing the amplitude Q_i on those Ω frequencies. It is then calculated as an average value of the ten largest Q_i [24].

$$FLEXIMAC = \frac{1}{10} \sum_{i=1}^{10} \frac{1}{2Q_i}$$

where Q_i: the eigenvalues of the system.

2.2. Aggregation of criteria values

The decision between the alternative manufacturing schemes requires a normalization of the values of each criterion as described in [25]. Afterwards, a decision matrix is used for the selection among the alternative schemes. The rows of the matrix represent the possible alternatives and the columns the evaluation criteria [25]. The matrix contents are the values of the criteria of each alternative. The cardinal preference (utility value) is calculated using a sum of weighted criteria normalized to the sum of one. The alternatives with the highest utility value are the most preferable (Figure 4).

3. Intelligent search algorithm

The algorithm for the evaluation and selection of the manufacturing scheme alternatives is described in [25]. The intelligent search algorithm uses three adjustable control parameters, namely the Maximum Number of Alternatives (MNA), the Decision Horizon (DH) and the Sampling Rate (SR), which guide the search through the solution space. The nodes R1, R2, R3 and R4, shown in Figure 2, represent decision points where a task is assigned to a resource. The red highlighted path represents an alternative production scheme (Figure 2). The steps of the algorithm are described below:

Step 1: Starting at the root, generate alternatives by randomly creating assignments for all DH layers, until MNA is reached.
Step 2: For each branch (Step 1), create SR random alternatives (samples) until all the nodes in the branch are searched.
Step 3: Calculate the criteria scores for all the samples belonging to the same alternative of Step 1.
Step 4: Calculate the score of the branch as the average of the scores achieved by its samples.
Step 5: Calculate the utility values of each alternative/branch.
Step 6: Select the alternative with the highest utility value.
Step 7: Repeat Steps 1 to 6 until an assignment has been done for all the nodes of the selected branch.

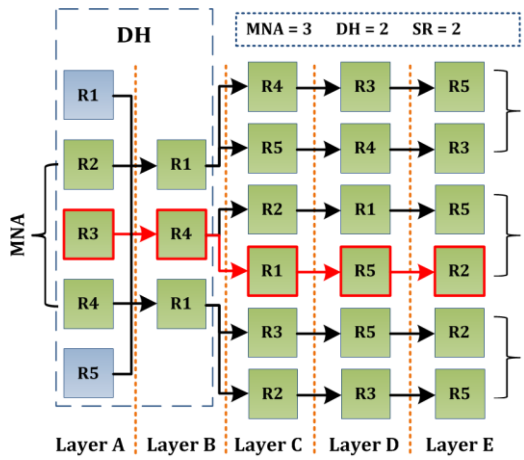

Figure 2. Intelligent search algorithm example

The MNA controls the breadth of the search and DH the depth, whereas SR directs the search path towards branches that can provide higher quality solutions. The selection of these search parameters is described in [25]. The quality of the solutions identified increases as the MNA, DH and SR are properly tuned. The increase follows an almost negative exponential distribution, and levels off at the alternatives with the highest utility values. As a result, the proper selection of MNA, DH and SR allows the identification of a good solution by examining a limited portion of the search space, significantly reducing computational time [26].

4. Software tool implementation

In order to test the functionality and performance of the methodology, a prototype software tool has been designed using Unified Modelling Language Diagrams (UML) and has been implemented in an object-oriented programming language, using the .NET Framework™. The tool interface consists of user-friendly Graphical User Interfaces (GUIs) for performing the data entry, and for configuring the control parameters of the intelligent search algorithm (Figure 3). The tool is integrated to a web-based system, which is programmed using the JAVA™ Framework, and exchanges data via web services. To ensure fast data retrieval and respect data integrity constraints, a Relational Database Management System (RDBMS) has been implemented using the Oracle 9i Database. The experiments were performed on an Intel™ i7 3.4GHz powered computer, with 8GB of RAM.

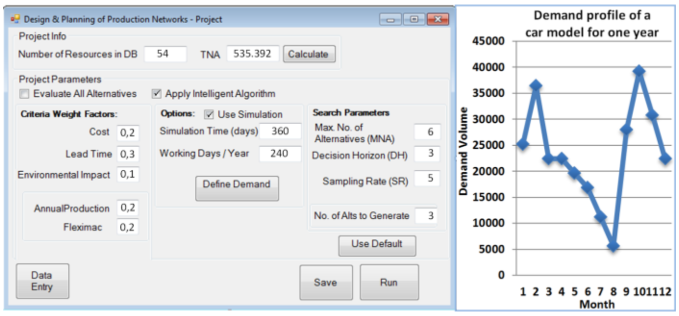

Figure 3. Search parameters, Criteria weights and Demand profile

The user is able to select between the exhaustive search and intelligent search algorithm functionalities, and define the search parameters. The tool generates upon request any number of alternatives and presents their performance in the form of charts. The resource assignments and operations designated for each product component and subassembly are stored in database tables. The tool is able to automatically generate discrete event simulation models via an integrated simulation software. The user can designate the demand profile, and then each alternative is evaluated against this profile. The runtime for each model, the performance characteristics, and the outcome of the experiments are presented and discussed in the case study results.

5. Industrial Case Study

A real-life scenario was used to demonstrate the functionality of the tool, utilizing data from a European automotive manufacturer. The scenario involves the production of a customized car hood subassembly, which comprises of 6 components that can be produced by 30 different supply chain partners, at different locations and costs (see Figure 4). The demand profile used for the case study utilizes real-life data coming from a European automotive manufacturer (Figure 3). The demand profile is $280x10^3$ cars, for a period of 12 months. At the real-life industrial case study described below, a portion of this demand profile includes orders for cars equipped with customized hood variants. The results from the experiments are shown below (Table 1). The results depicted in Table 1 indicate that a decentralized production network behaves more efficiently than a centralized network. The decentralized network shows 4.01% reduced cost, 19.87% reduced lead time and 10.7% less environmental impact, versus the centralized network for the manufacturing of the same customized product.

Table 1. Exhaustive Search Results

Method	Criteria	Decentralized	Centralized
Exhaustive search	Cost (€)	1,677.90	1,748.11
	Lead Time (hours)	22.29	27.82
	Environmental Impact (gr CO_2)	807.60	904.40

The Total Number of Alternatives (TNA) for the manufacturing of a customized hood subassembly is calculated at 535,392, for the decentralized manufacturing network, and at 10,368 for the centralized scenario. Furthermore, if the order contains two customized products, a combinatorial explosion occurs at the TNA that is calculated at 287x109 (Figure 5), thus prohibiting the use of an exhaustive search. The criteria scores for the decentralized manufacturing network as derived from the experiments performed with the intelligent search algorithm are included in Table 2.

Table 2. Intelligent Search Algorithm Results

Method	Criteria	Decentralized
Exhaustive search	Cost (€)	1,677.90
	Lead time (hours)	22.29
	Environmental Impact (gr CO_2)	807.60
Intelligent Algorithm	Cost (€)	3,104.34
	Lead time (hours)	45.73
	Environmental Impact (gr CO_2)	2,056.40

Following, the required computation time using the intelligent algorithm, is reduced from an average of 65 minutes to approximately 1 minute, and the solutions that derive are of high quality.

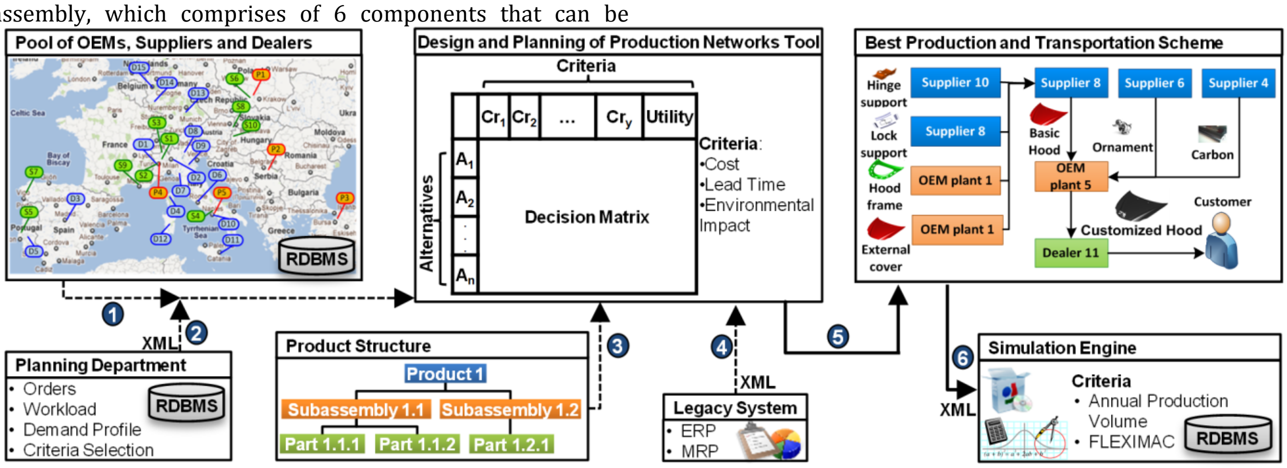

Figure 4. Design and Planning of Production Networks tool architecture

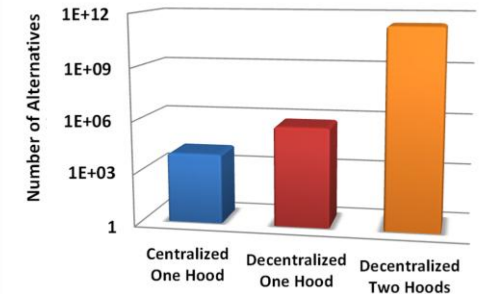

Figure 5. Number of alternatives for different scenarios

The areas in the pie charts (Figure 6) represent the percentage of alternatives provided by the exhaustive search that belong to the calculated value ranges for each criterion The solutions identified by the intelligent search algorithm belonged to the 8% of the best production schemes, with a cost under 3,300€, to the 8% with a lead time below 50 hours, and to the 11% with environmental impact below 2,300 grams of CO2.

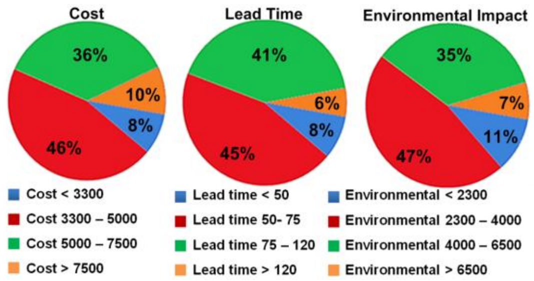

Figure 6. Distribution of criteria values

Finally, the best schemes deriving from the exhaustive search for the decentralized and centralized networks, were modelled in a simulation software in order to compare their performance under the same demand profile that consists of three car hood variants, two of which were highly customized. The results of the experiments (Table 3) indicate that the decentralized production network is more flexible than the centralized approach, and is capable of larger production volume at the same time.

Table 3 Simulation Results

Criteria	Decentralized	Centralized
Annual Production Volume	20,308 (9,500)*	16,857 (9,492)*
FLEXIMAC	$6.1675x10^{-6}$	$4.9586x10^{-6}$

* The number of the customized variants

6. Conclusions and outlook

The presented method and tool can be exploited for supporting the design of efficient manufacturing networks. The results obtained through the presented approach, seem promising. The decentralized manufacturing network displays significantly reduced cost, lead time and environmental impact values, and greater flexibility and productivity, against a centralized network for the production of the same customized product. The constraints in a centralized network allow assembly operations to be performed only at an OEM plant, thus leading to a limited number of alternative manufacturing and supply schemes. Some of the excluded schemes however, are of high quality with respect to cost, lead time and environmental impact, which are reduced due to different factors, among them the decreased transportation distance. Moreover, the intelligent search algorithm greatly reduced the computation time, generating high-quality alternatives. The intelligent method provided an efficient solution to identifying a high-quality scheme, when the number of alternatives was not feasible to be processed using an exhaustive search, due to the required computation time.

Future research will focus on extending the capabilities of the proposed method, in order to bridge the gap between mass customization and personalization, by engaging the customer in the initial design of the products and by realizing the manufacturing of these products in a novel, coordinated, and more efficient decentralized approach. Additional cost efficiency and environmental impact metrics will be used.

Acknowledgments

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