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Design and operation of manufacturing networks for mass customisation

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ABSTRACT

The mass customisation paradigm, in combination with the volatility of globalised heterogeneous markets, directly affects industries towards realising efficient manufacturing network configurations. This research work aims to support the design and operation of manufacturing networks based on a multi-objective decision-making and simulation approach. The alternative network designs are evaluated through a set of multiple conflicting criteria including dynamic complexity, reliability, cost, time, quality and environmental footprint. Moreover, the impact of demand volatility to the operational performance of these networks is investigated through simulation. The proposed approach is validated through a real life case acquired from the CNC machine building industry.

1. Introduction

Original Equipment Manufacturers (OEMs) operate in highly competitive, volatile markets, with fluctuating demand, increasing labour costs in developing countries, and new environmental regulations [1]. Driven by the ever increasing need to reduce cost and delivery times, OEMs are called to efficiently overcome these issues by designing and operating sustainable and efficient manufacturing networks. The selection of optimum manufacturing network configurations that satisfy these challenging objectives however, is a proven data-intensive, NP-hard problem [2]. Therefore, strategic level decision-making cannot be accurately performed solely based on the experience and past knowledge of a supply chain manager [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.

2. State of the art

The manufacturing landscape is nowadays more complex and dynamic than ever, due to the consequences of globalisation and recent economic recession [4] among other. The design of the manufacturing network of cooperating companies and its operation are key decisions for companies in order to endure competition. The push-pull model followed by many modern industries in order to address the product personalisation requirements [1] has driven the development of postponement strategies [5]. Product and process variety has also been identified as an enabler towards improving the customer-perceived value [6]. Likewise, recent environmental directives consist of additional constraints when designing and managing supply chains [7]. Moreover, a large number of recent publications deals with the emerging aspects of increasing complexity of manufacturing activities and the dynamic nature of supply chains [8]. The importance of managing the complexity in supply chains is indicated in [9] as the study depicted that lower manufacturing network complexity is associated with reduced costs and overall network performance [10]. Thus, complexity should be considered as a cost criterion that has to be minimised. Complexity has been studied through approaches based on information theory, time series analysis, axiomatic theory, coding systems for machines and products, and through methods inspired by fluid dynamics [11].

In this landscape, the industrial sector of CNC machine building is facing challenges. As far as Europe is concerned, the CNC sector accounts for 158,000 jobs spread over 1474 companies with a worth of 17,512 billion €. Thus, it makes a key contribution to the economy and balance of payments [12].

For producing highly customised products, flexible and configurable machines are required for providing the capability to perform diversified manufacturing tasks in the concept of mass customisation. The proposed method aims to the timely identification of optimum or near optimum manufacturing network configurations for the production of heavily customised CNC machines. Both static and dynamic characteristics of the system under diversified market demands are captured, when examining the performance of different manufacturing network configurations. A complexity measure is incorporated in the decision-making process. Moreover, the network reliability is considered during the manufacturing network design, along with criteria of cost, time, quality and environmental footprint. Finally, the applicability of the approach is validated via a real life case study with data acquired from a CNC machine building industry.

3. Design and operation of manufacturing network method

3.1. Modelling of the manufacturing network

A modern manufacturing network is composed of cooperating OEM plants, suppliers and dealers that produce and deliver final products to the market. In this research work, Decentralised Manufacturing Network (DMN) and Centralised (CMN)

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configurations are modelled and their performance is compared. As opposed to traditional CMNs, a DMN is structured upon more flexible relations between these manufacturing entities. Assembly tasks in DMN can be performed by suppliers and dealers, in proximity to the final customer, thus leading to decreased transportation and environmental costs, as depicted in [13].

3.2. Description of the design and operation method

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 alternative with the highest utility value [19]. A manufacturing network configuration alternative is defined as a set of partner-task assignments, capable to manufacture a customised product within a manufacturing network structure.

Two methodologies are used in the decision-making process for the generation and evaluation of manufacturing network alternatives, namely the Exhaustive Search Algorithm (EXS) and the Intelligent Search Algorithm (ISA). The EXS is an enumerative method, whereas ISA generates a subset of the Total Number of Alternative (TNA) manufacturing network configurations through 3 adjustable control parameters (Fig. 1A) [13,14]. The control parameters are: the Selected Number of Alternatives (SNA) that defines the breadth of the search, the Decision Horizon (DH) that controls the depth of the search and the Sampling Rate (SR) that guides the search to high quality branches in 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) [15] and were identified at SNA = 100, DH = 3 and SR = 10. The workflow of the method is depicted in Fig. 1.

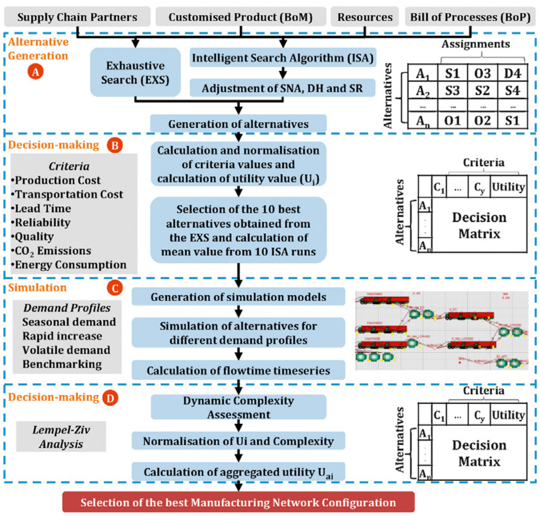

Fig. 1. Workflow of the proposed design and operation method.

The above procedure is followed for both the DMN and the CMN configurations. The 10 best identified alternatives from the EXS (based on their utility value U_i) (Fig. 1B) for these two manufacturing network types are automatically modelled and simulated against a set of demand profiles. Totally, 80 simulation experiments were conducted (20 alternative network configurations × 4 demand profiles) (Fig. 1C). The simulation period was one year and the profile used for the generation of the number of orders per week are: (i) seasonal demand (sinusoidal), (ii) rapid demand increase (parabolic), (iii) volatile demand (Gaussian) and (iv) benchmarking (uniform) (Fig. 2). The results of simulation are used for the calculation of dynamic complexity (Fig. 1D). It should

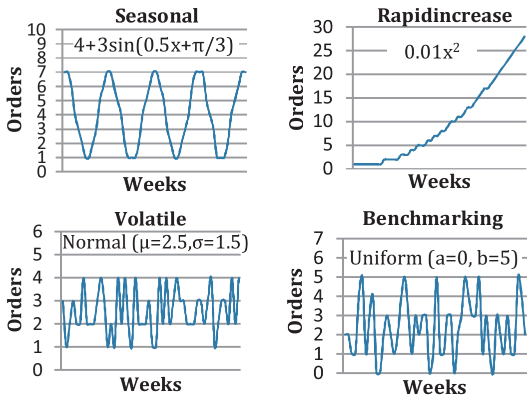

Fig. 2. Demand profiles used in the simulation experiments.

be noted here that the number of orders controlled by these statistical distributions respects the capabilities of the system. The ratio p = *demand requirements/system manufacturing capacity* is maintained below 1, in order not to lead the system to unstable behaviour [16].

3.3. Criteria of the multi-objective decision-making process

The criteria for determining the performance of an alternative manufacturing network configuration are the following:

Production and Transportation Cost (PTC): the sum of the production cost (PC) for manufacturing network partner i to perform task k and of the transportation cost (TC) from partner i to partner j, where $i, j, k \in \mathbb{N}$, $i = 0,1,\ldots,I$, $j = 0,1,\ldots,J$ and $k = 0,1,\ldots,K$ [13].

$$\mathrm{PTC} = \sum_{i}^{I}\sum_{k}^{K}\mathrm{PC}_{ik} + \sum_{i}^{I}\sum_{j}^{J}\mathrm{TC}_{ij} \quad (€)$$

Lead Time (LT): the sum of processing and setup time (PT) for partner i to perform task k and of the transportation time (TT) from partner i to partner j [17,20].

$$\mathrm{LT} = \sum_{i}^{I}\sum_{k}^{K}\mathrm{PT}_{ik} + \sum_{i}^{I}\sum_{j}^{J}\mathrm{TT}_{ij} \quad (\text{days})$$

Energy Consumption (EC): sum of energy consumption (EP) for partner i to perform task k and of the transportation energy (ET) required from partner i to partner j [18].

$$\mathrm{EC} = \sum_{i}^{I}\sum_{k}^{K}\mathrm{EP}_{ik} + \sum_{i}^{I}\sum_{j}^{J}\mathrm{ET}_{ij} \quad (\mathrm{J})$$

CO_2 emissions (CO): the emitted tonnes of CO_2 for the transportation (CE) required from partner i to partner j [18].

$$\mathrm{CO} = \sum_{i}^{I}\sum_{j}^{J}\mathrm{CE}_{ij} \quad (\text{tonnes } \mathrm{CO}_2)$$

Quality (Q): the mean quality of the partners of an alternative manufacturing network configuration [19].

$$Q = \frac{\sum_{i}^{I}\mathrm{QL}_i}{I}$$

Reliability (R): total reliability, where s represents a serial and p a parallel resource [20], $s,\ p \in \mathbb{N}$, $s = 0,1,\ldots,S$ and $p = 0,1,\ldots,P$.

$$R_{\mathrm{stot}} = \prod_{s}^{S} R_s, \quad \text{for serial resources}$$

$$R_{\mathrm{ptot}} = 1 - \prod_{r}^{R}(1 - R_p), \text{for serial resources}, \text{for parallel resources}$$

Dynamic Complexity (C_{LZ}): expressed as the unpredictability of the flowtime timeseries (Fig. 3A). C_{LZ} is calculated through a