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Technical Paper

# A toolbox for the design, planning and operation of manufacturing networks in a mass customisation environment

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ABSTRACT

The task of design, planning and operation of manufacturing networks is becoming more and more challenging for companies, as globalisation, mass customisation and the turbulent economic landscape create demand volatility, uncertainties and high complexity. In this context, this paper investigates the performance of decentralised manufacturing networks through a set of methods developed into a software framework in a toolbox approach. The Tabu Search and Simulated Annealing metaheuristic methods are used together with an Artificial Intelligence method, called Intelligent Search Algorithm. A multi-criteria decision making procedure is carried out for the evaluation of the quality of alternative manufacturing network configurations using multiple conflicting criteria including dynamic complexity, reliability, cost, time, quality and environmental footprint. A comparison of the performance of each method based on the quality of the solutions that it provided is carried out. The statistical design of experiments robust engineering technique is used for the calibration of the adjustable parameters of the methods. Moreover, the impact of demand fluctuation to the operational performance of the alternative networks, expressed thorough a dynamic complexity indicator, is investigated through simulation. The developed framework is validated through a real life case, with data coming from the CNC machine building industry.


## 1. Introduction and motivation

The contemporary manufacturing industry is characterised by immense competition, divergent regional markets, high demand volatility and heterogeneity. Moreover distinctive characteristics include the impact of strict environmental regulations and an increasing need for customised products throughout the globe [1]. Thus, properly configured and easily adaptable manufacturing networks are needed, which are capable of handling the complexity and enormity of the supply chain structures. These qualities are critical for companies in order to maintain their viability.

To support the strategic level decision making process, this research work describes a set of optimisation methods that have been developed and are integrated in a toolbox approach, for the design and operation of highly complex manufacturing networks. These networks operate under demand fluctuations, economic and environmental constraints [58,60]. The unpredictability of the operational performance of the networks is expressed through a dynamic complexity indicator [49]. The complexity of alternative network configurations is examined through discrete event simulation, where the demand profile is modelled so as to represent different stochastic product demands. The inter-arrival times and volume of orders is affected by changes in the profile representing seasonal, volatile, rapid increases and fully unpredictable demand scenarios. The differentiated demands are modelled through statistical distributions from which the simulator samples the inter-arrival times of the ordered batches.

The problem of the design of multi-stage, multi-product manufacturing networks under multiple pre and post-conditions and constraints is investigated. The problem is of NP-Hard computational complexity. To demonstrate that a problem is in the class of NP-Hard complexity, it is common practice to depict that it is at least as hard as another proven NP-hard problem [2]. To demonstrate the computational complexity of the inventory routing and scheduling problem, Liu and Chen, referred to the inventory routing problem, which is NP-Hard. By including in their method the scheduling of tasks, the problem becomes strongly NP-Hard [3]. Similarly, the fixed-charge capacitated network design problem was characterised in another study as NP-Hard as it extended, complexity-wise, the proven manufacturing network design problem [4]. The problem under investigation in the presented research work can be classified as a counterpart of the Simple Plant Location (SPL) multi-criteria assignment problem, which is NP-hard. In addition to the SPL problem, the proposed approach models a

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multiple tier multi-product supply chain and simultaneously considers multiple conflicting criteria in order to assess the quality alternatives. Therefore, it can be considered as NP-Hard [5]. Moreover, the identification of Pareto optimal solutions which is faced in the described approach is NP-Hard [5,6]. Indicatively, the feasible alternative solutions in the examined manufacturing network configuration decision-making problem are calculated at $4 \times 10^{17}$. It is evident that for this magnitude of search spaces, exhaustive enumerative techniques are rendered useless due to computational resource constraints. In addition, strategic level decision-making cannot be accurately performed based solely on the experience and past knowledge of a supply chain manager [7] due to the enormity and dynamic nature of the problem.

## 2. State of the art

The manufacturing landscape is nowadays more complex and dynamic than ever, due to rapid globalisation [8] and recent economic recession [1] among other reasons. The design of the manufacturing network of interacting companies and its operation are key strategic decisions for companies trying to endure competition. The less push and more pull business model followed by many modern industries in order to address the product personalisation requirements calls for immediate decisions. This is necessary even in a supply chain level, in order for companies to respond effectively to the ever-changing market needs [9]. Stable cooperation structures based on rigid alliances between companies are no longer viable due to various disruptions that can affect a supply chain [10]. Likewise, recent environmental directives and fluctuating gas prices consist of additional constraints when designing and managing supply chains [11].

The implications for the implementation of mass customisation are examined in [50,51]. Specifically, on a product level, a key enabler towards achieving customisation in production is product modularity and postponement strategies. The division of a product into separate modules/components, provides the means to achieve high product variety at low costs [52]. Modularity, as a variety enabler, can be achieved during different stages of product realisation from design to production, assembly, as well as during sales and usage. Two forms of postponement strategies can be found in the literature, namely form and time postponement. During the former, differentiation is moved downstream in the value chain and is performed on a component level by the suppliers, whereas in the latter, the production of commonly used components is performed normally, while customer specific features and components are added at the final stages of the production [51]. In order to address the introduced complexity due to high variety, the Generic Bill of Material Structures (GBOM) have been proposed for the representation of product families and all the varieties [53].

Moreover, the coordination between the independent enterprises that form the manufacturing network must be achieved in order to align their objectives towards a common goal and maintain global performance. Two main approaches have been proposed over the years for realising this coordination: centralised and decentralised planning methods and tools [58]. The latter are the most prominent, as centralised practices have often been criticised for their limited flexibility and restricted coordination efficiency. Coordinated decentralised planning has been acknowledged as a resolution towards cooperative responsive manufacturing enterprises [60]. The channels for achieving the coordination are generally: supply chain contracts, information technology, information sharing and joint decision-making.

A decentralised game theoretic framework is proposed in [57] using negotiation-based models and multi-agent systems. The results from a case study supported game theory as a promising methodology for coordination in distributed production planning. Another study proposed flexible coalition strategies and investigated the advantages of using integrated production planning and negotiation in e-marketplace bringing real advantages for both customers and suppliers [59]. An agent-based negotiation framework has been proposed in [61]. Utilising a branch-and-bound heuristic, the method handled the negotiations for allocating numerous orders to multiple members for supply chain formation. Another study depicted the advantages of information sharing [62]. Though simulation-based comparison, the supply chain costs were calculated for a model with full information sharing policy and were compared against a model with traditional information sharing policy, resulting in a maximum difference of 12.1% lower costs in favour of the first model. Finally, the SCOR model helps in evaluating and improving enterprise wide supply chain performance and management by allowing companies to: evaluate their own processes effectively and compare their performance with the performance of other partners, pursue their competitive advantages, utilise best practice information to prioritise their activities, quantify the benefits of what-if scenarios and identify the most suitable IT support tools for their business [63,64].

The connection between product and process design with supply chain decisions was investigated and the dependencies between these activities are highlighted in [12]. The supply chain design and redesign problem with minimal costs and demand satisfaction at the same time is tackled in [13]. The method also allows the identification of unnecessary actors in order for them to be eliminated from the supply chain typology. A mixed integer linear programming formulation is presented in [14] for the design and planning of closed-loop supply chains that include the phases of production, distribution and reverse logistics. The demand profiles used in the study modelled diverse conditions of market requirements through optimistic, pessimistic and realistic scenarios. Gumus et al. [15] calculated the optimal product flow between the factories, warehouses and distributors of a globalised supply chain network. The uncertainty of cost and capacity in the supply chain was tackled through a neuro-fuzzy approximation that calculated these variables. Multi-echelon decentralised manufacturing network structures were modelled in [16] and were compared to traditional centralised networks typologies, depicting their superiority for satisfying cost, time and environmental footprint objectives optimisation. Another study focused on the redesign of an existing network [17]. The redesign decisions are supported by a Tabu Search algorithm and comprise of the relocation of existing facilities to new sites under budget and time restrictions and the flow of commodities through the network among others. Another recent approach dealing with the integration of the planning of the production and distribution activities presented a capacitated plant that produced multiple products based on a steady market demand [18]. The approach included two Tabu Search variants, one creating solutions and storing them in a short-term memory and the other integrating path relinking to the first using a longer-term memory. In Subramanian et al. [19], a closed loop supply chain design problem formulated using Integer Linear Programming, was addressed through a constructive heuristic for acquiring high quality solutions. Good initial solutions were created through the Vogel's approximation method and were fed to a priority based Simulated Annealing heuristic for accelerating the algorithm's convergence. A genetic algorithm with a novel encoding mechanism and a new crossover operator was used for addressing the problem of multi-stage, multi-product, multiple objective supply network design optimisation [65]. Moreover, hybrid approaches that utilise combinations of optimisation methods are common. A hybrid metaheuristic combining a genetic algorithm with a local improvement search and a shortest path augmenting path method were proposed in [20]. The objective was to