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Ref.
Customised Order Fulfillment in a Machine Tool Supply Network

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Abstract. The research presented in the paper attempts to help globalised organisations to identify alternative supply network configurations and management strategies, to respond to different customised order fulfillment demand scenarios within existing cost and time restrictions. A case study of a machine tool manufacturer is presented. The company has a global multi-plant network and imperative requirements for introducing flexibility in a market demanding products with a high degree of customisation. Machine tools have a total production lead time longer than the market time. Therefore, the machine manufacturing process has to start before customers orders arrive. When an order arrives, a machine that is in process must be allocated to it. Some relevant information is collected and reviewed to carry out this allocation. The path across the manufacturing network that the allocated machine is going to follow is generated, the point where customisation will be executed to reconfigure the machine to the specific order requirements is identified and the delivery time is communicated to the customer. The research shows how this information is managed to make the allocation and how a simulation tool is used as a decisional support system to identify better network design alternatives for the location of new plants, warehouses, or logistics platforms, under mass customisation scenarios.

1. Introduction

Market globalisation, world-wide procurement, geographically distributed plants, more sophisticated customer requirements, increases in product variety, the rapid entry of new technologies and greater uncertainty due to the reduction in product life cycles, (Frey, 1994; Christensen, 1997), are hardening global competition in general, creating a new dynamic environment for supply networks. Spina et al. (1996), based on the study of 600 companies worldwide (IMSS database), found evidence that this new dynamic environment has led to the development of new managerial approaches, due mainly to the transformation of competitive forces, with the appearance of responsiveness to demands, with a greater degree of customisation, as a key factor (Kidd, 1994).

High value added manufacturing companies, like the ones of the machine tool industry, that make very large, heavily engineered, stand-alone products that are customized at the beginning of their production process face a unique challenge. The reason is that their production processes are often characterized by a delivery lead time that is substantially shorter than the production lead time, commonly about half, and also the units’ large size, and their high market value, limit a company's ability to keep units in inventory until a matching customer order is received (Raturi et al., 1990; Meredith and Akinc, 2006, 2009).

The research developed in this paper aims to gain understanding on how to design and manage customised order fulfillment strategies to better meet today's competitive pressures for faster delivery without increasing costs in machine tool supply networks. To do so, an engineering research approach for performance enhancement of systems has been taken, which combines case study research and simulation modelling.

The outline of this paper is organised as follows. Section 2 presents a brief literature review of different production strategies in operations management in the context of mass customization. In section 3, the research aim and research approach are specified. Section 4 presents MACTO case study; market context, products, production processes, supply network configurations, as well as the customer order fulfilment strategy and the machines allocation process and criteria. In Section 5, the simulation analyses driven, to evaluate the potential benefits of implementing different MACTO multi-plant network configurations for introducing mass customisation strategies, are shown. Finally, section 6 shows some preliminary conclusions and mentions future research working areas.

2. Literature review

The strategy adopted in this research to bring together, under the same production system, the competitive advantages of product “customisation”
(economies of scope), and the efficiencies associated with “mass production” (economies of scale), is Mass Customisation (Pine, 1992; Tseng and Jiao, 1998). Quoting Pine (1992): “Mass customisation denotes the ability to provide customised products and services at a comparable price and speed of equivalent standardised offerings”.

Steger-Jensen and Svensson (2004) classified different generic levels of Mass Customisation (MC), in relation with different MC approaches, strategies, stages, and types of customisation (Figure 1). The eight generic levels of MC occupy an asymmetric position within the mass production – individual product manufacturing (one-of-a-kind) axis, and can be associated with either Engineer to Order (ETO), Manufacture to Order (MTO), Assemble to Order (ATO), and Manufacture to Stock (MTS) strategies.

Figure 1: Taxonomy of MC that embrace both, the variety of products, and the stability of processes. Source: Steger-Jensen and Svensson (2004)

In the capital goods sector, companies also face the trend toward greater product customization in the context of reduced response times. When products are highly customized and competition requires manufacturers to deliver it with lead times significantly shorter than the manufacturing lead time, the scheduling practice first suggested in the literature was to release the manufacturing order before the customer order is released and subsequently match incoming customer orders to units in progress. This strategy was firstly referred, by Raturi et al (1990) as the Build-to-Forecast (BTF) approach, and more recently has been slightly reviewed as Make-to-Forecast (MTF) by Meredith and Akinc (2006, 2007): “For large engineered equipment, a relatively recent but increasingly common production strategy has arisen to better meet today’s competitive pressures for faster delivery of more customized products without increasing costs. A hybrid of

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the make-to-order (MTO) and make-to-stock (MTS) production strategies, manufacturers launch major product models to a demand forecast (MTS) and then modify the partially completed products as the actual orders arrive (MTO), a production strategy we refer to as make-to-forecast (MTF).”

In the automotive sector, Brabazon and MacCarthy (2004) have used a Virtual-Build-to-Order (VBTO) approach. VBTO is an emerging order fulfilment system that is intended to improve fulfilment performance by taking advantage of integrated information systems. The primary innovation in VBTO systems is the ability to make available all unsold products that are in the production pipeline to all customers. As these authors state: “In a conventional system the pipeline is inaccessible and a customer can be fulfilled by a product from stock or having a product Built-to-Order (BTO), whereas in a VBTO system a customer can be fulfilled by a product from stock, by being allocated a product in the pipeline, or by a build-to-order product.”

3. Research approach

The aim of the research is to gain understanding on how to design and manage customised order fulfillment strategies in a machine tool supply network, in order to make the network more flexible and efficient under changing demand scenarios.

The research approach adopted can be classified as an engineering approach for performance enhancement of systems (Pritsker, 1997). For developing the research we have based on: (1) Previous studies identified in the literature; (2) A case study research of a machine tools manufacturer, denoted in this paper as MACTO, with a global multi-plant network, and requirements for flexibility in their response to markets which demand products with a high degree of customisation; (3) A simulation environment which allows to conduct, for diverse conditions, systematic testing of the structure and operation of this type of supply network.

It is a combination therefore of case study research and simulation modelling research. Case studies are frequently used for exploratory and theory building research (Yin, 1994). The simulation modelling research approach is also fundamental to this research due to the high levels of interdependence between constituent elements of these supply networks, their inherent feedback loops, non-linearities, and delays, make network behaviour in the face of market demand variations a dynamic process which generally produces counterintuitive behaviours over time (Sterman, 2000), and therefore makes purely analytical approaches to the problem inadequate due to the fact that they generally require too many assumptions and also lack de la ability of effective communication (Fowler, 1998).
4. Case description

4.1. Company and market

MACTO is a Spanish SME that manufactures and sells machine tools, specifically, milling machines and milling centres. It has an extensive catalogue that includes several families depending on the machine size, bed type and column type. The machines have different levels of customisation, ranging from very special machines that are manufactured based on customer specifications to more standard machines that the customer decides on by selecting from a menu of options established beforehand by the company. This allows MACTO to satisfy a wide range of customers from sectors as diverse as aerospace, capital goods, railways, subcontractors or mould & die manufacturers.

For the case study presented in this paper the MC-1 product family was selected, which is basically made up of standard, small milling machines of the fixed bed and fixed column type. This product is principally sold in three markets: Spain, Germany and Turkey.

Over the last few years a continuous increase in market pressure on manufacturers has been detected, with demand for greater product customisation capability, shorter delivery times and increasingly competitive costs. An example of this is what has happened with the products in the family selected for the case study: the market demands delivery times of about 14 weeks, which is clearly shorter than the production time which is 30 weeks.

4.2. Product attributes and options

The MC-1 milling machines are small machines with a complex structure made up of thousands of different items. These items are grouped together in functional units known as attributes. An attribute can be fixed or belong to a range of values called options. As customers configure their order by selecting for each attribute the option best suited to the machine they need, a combinatorial problem is generated which could be in the order of billions, as in the case of the family selected.

For this family, MACTO has established the attributes and options given in table 1.
Table 1: Attributes-options for the MC-1 milling machine family

The way these attributes and options are dealt with is different if the machine is manufactured on the basis of a customer order, Build-to-Order (BTO) machine, when all the options available can be selected, or based on forecasts, Build-to-Forecast (BTF) machine. In this case, the number of BTF machine variants is reduced, limiting the options available for certain attributes or establishing a fixed value for others which, in some cases, can take the value ‘no’. In this way, the number of product variants is drastically reduced from a theoretical figure of 2,548,039,680 possible combinations to a figure of 384 variants when the launch was planned. Actually, the main aim of this strategy is to manufacture a set of basic BTF machine skeletons which will be subsequently completed when they are allocated to customer orders. This strategy gives the product great adaptation potential so that, quickly and easily, it can be adapted to the huge product variability generated by the combination of attributes and options available.

4.3. Production process

The manufacturing process for any milling machine in the MC-1 family takes about 30 weeks. This time only takes into account the planning, launch and manufacturing activities for the machines, but not the shipping, transport and clients’ in house installation (Figure 2).
The process starts with the order planning stage. This activity is carried out regularly every 2 weeks and consists of determining the amount and characteristics of the machines that are going to be manufactured. Once planning has been completed, launch takes place and orders are placed with suppliers. The materials ordered are received during practically the whole machine assembly process. However, a procurement stage has been established that covers all the materials that have to be in the plants before assembly of the machine starts. This phase takes about 14 weeks coinciding with the procurement time for cast-iron and machined parts, e.g. the XYZ traverses.

The procurement phase is followed by the initial assembly of the machine which takes 7 weeks. In this stage the assembly of the XYZ traverses takes place, together with the preliminary mechanical assembly operations, the assembly of the common modules in a milling machine and the first fine tuning of the electronics.

Once initial assembly has been completed two situations can occur: (1) The machine has not been allocated to a customer order so it remains in the assembly location as “stock” until an order will be allocated to it; (2) The machine has a customer order allocated and goes onto the final assembly stage in order to carry out the machine reconfiguration operations, adapting it to the customer order requirements, fine tuning of the electronics and mechanical part, installation of the shrouding, in-plant testing, painting of the machine and customer reception. This stage takes approximately 7 weeks.

Finally, the machine is dispatched and taken to the specified place where it is installed and handed over to the customer. Between 1 and 2 weeks are necessary for this.

### 4.4. Supply Network configurations

The MACTO Supply Network has three assembly plants, two of which are located in Spain and the third in Hungary.
For supplying all the commercial components necessary for the machines assembly, there is a Central Warehouse in Spain (MCW) in which all the purchases are centralized. Commercial components are distributed to the assembly plants depending on the needs generated by the assembly planning system.

Assembly operations corresponding to MC-1 machines only they take place in the assembly plant 1 of Spain (MAP 1) and in the assembly plant 3 in Hungary (MAP 3). Initial assembly stages are done in Hungary which has its own supplier network for cast-iron and machined parts. Finished the initial assembly, machines are transported to Spain where customisation operations, electrical and mechanical assemblies, careenage, tests and painting are done. In the same plant takes place the machine inspection and approval for the customer before shipping to the destination where final installation in house will be done.

At present, MACTO is evaluating the possibility of introducing a new global strategy maintaining current strategy for the Spanish market and assembling completely the whole MC-1 machines family in MAP 3 (Hungary) for the German and Turkish market. To materialize this strategy it is necessary to invest in the Hungarian plant facilities and to increase the technological training of its staff. This investment has to compare with the production cost reduction due mainly to lower Hungarian staff costs and lower transport costs for the proximity of the plant to German and Turkish market.

4.5. Customer order fulfillment strategy

In order to try and adapt to the 14-week delivery time demanded by the market for MC-1 milling machines, MACTO starts manufacturing machines that have no customer order allocated in the expectation that as the company receives orders these will be allocated to the machines which have started to be manufactured. To implement this strategy, the design of the product enables the characteristics of BTF machines to be specified in two stages. In the first stage, the planner builds the generic skeleton of each BTF machine, establishing only those characteristics that are essential to start manufacturing, e.g. the lengths of the XYZ traverses or the type of head. For the rest of the machine specifications the default values are
taken from the options available. The second stage takes place when the company receives a customer order and tries to allocate it to one of the BTF machines with no order allocated in any of the stages of the manufacturing process. Aspects like coinciding functional nature, delivery date, reconfiguration cost and the importance of the customer are assessed. When allocation is possible, the attributes of the BTF machine selected take the values indicated on the order, which is why the service strategy is going to be called Switch To Order (STO).

The use of the STO strategy, postponing the final configuration of the BTF machines, has several advantages:

- Drastic reduction in the number of variants to be taken into account in the planning operation.
- Increase in the probability of allocating BTF machines to customer orders reducing the financial costs of keeping BTF machines in stock waiting to be allocated.
- Reduction of the average delivery time to the customer as the times will be shorter than the production lead time depending on the position in the supply network when/where allocation takes place.

When it is not possible to find a viable allocation in terms of the functional nature required, delivery time or costs, the machine will be a Build To Order (BTO). In this case, the delivery time is the maximum possible, 30 weeks.

4.6. Machines allocation process and criteria

When MACTO receives an order for an MC-1 milling machine, a search is carried out for the one that best meets the customer’s requirements. This search it is done among all the BTF machines previously launched to the SN and which still have not been allocated. Due to the high number of machine variants that can result from the customer order configuration and the fact that the number of BTF machines in the SN is limited, the probability of finding an exact match between orders and BTF machines is practically zero. For this reason, a set of criteria have been established to tackle this problem. These criteria, used in the allocation process, are the following ones:

1. *Technical compatibility*: Allocation can only take place if the values for certain attributes considered critical (e.g. lengths of the XYZ traverses) coincide and certain options are not selected (e.g. Siemens CNC). Otherwise the machine has to be manufactured on a BTO basis.

2. *Economic margin*: The margin $M_i$ for the BTF$_i$ machine at the moment $t$ of allocation has to be equal to or greater than the minimum margin $M_{\text{min}}$ of profitability set by the company.

$$M_i(t) \leq M_{\text{min}}$$

$$M_i(t) = \text{SSP}_i - \Delta FC_i(t) - RC_i(t) - PC_i$$

where

- $\text{SSP}_i$: Standard selling price of the BTF machine $i$. 
\[ \Delta FC_i(t): \text{Additional financial cost accumulated in the BTF machine } i \text{ up to the moment } t \text{ of allocation.} \]

\[ RC_i(t): \text{Reconfiguration cost for the BTF machine } i \text{ at the moment } t \text{ of allocation.} \]

\[ PC_i: \text{Production cost of the BTF machine } i. \]

(3) **Delivery time:** Period of time \( DT_i \) from the moment \( t \) of allocation of the BTF machine \( i \) to the completion of the manufacturing process.

(4) **Customer profile:** Aspects like the importance of the customer for the company, the probability of them not accepting the resulting delivery time or the probability of admitting functional modifications with a moderate additional cost or with more competitive delivery times have to be evaluated for each BTF machine.

A process has been established to carry out efficient allocations of orders to BTF machines. The process aims for an effective balance between the best conditions which the customer can be offered in terms of delivery time and cost and the highest possible margin that can be generated for the company reducing the financial and reconfiguration costs. The allocation criteria mentioned above are used following the following evaluation process:

1. If the delivery time for the customer order (\( DT_i \)) is longer than the production time, the machine requested is manufactured on a BTO basis. If the delivery time is shorter, the machine ordered is compared with each of the BTF machines not allocated in the SN.

2. All the BTF machines that are not technically compatible are ruled out. If there is no BTF machine that can be allocated to the customer order, the machine ordered has to be manufactured on a BTO basis.

3. Margins and delivery times are obtained for all the remaining BTF machines at the moment \( t \) of allocation and those whose margin \( M_i \) is lower than the \( M_{\text{min}} \) are ruled out. This margin can be for all the BTF machines depening on how important the customer is for the company or for each individual BTF machine depending on how urgent it is to sell it.

4. An order of priority for the allocation of the candidate BTF machines is drawn up, ordering them from higher to lower margin and, if it is the same, from shorter to longer delivery time.

5. The probability of the customer accepting the delivery time and the introduction of modifications to the machine ordered is evaluated. The selling price and the delivery time to be offered are determined for each of the candidate BTF machines.

6. The candidate BTF machines, in the established order, are presented to the customer. If there is acceptance by the customer the BTF machine selected is allocated to the customer order. Otherwise, the customer is offered the possibility of manufacturing the machine on a BTO basis. If this is not accepted the customer order is classified as a failed order.
The time that the BTF machine expects to be allocated to a customer order, increases the financial cost and delays the assembly of other machines that need free space to do it. In some cases, it is possible to offer additional functionality if the cost increase is lower than the reconfiguration cost needed to match the customer requirements.

5. Simulation analysis

MACTO wanted to evaluate the potential benefits of implementing the new strategy (see Figure 3) over its supply network performance metrics. To do so, a developed simulation tool was used (Castellano et al., 2007, 2008). This tool implements a conceptual model that allows to analyze multi-plant networks configurations for introducing mass customisation strategies. That model is described in detail in Saiz et al. (2006, 2008). MACTO Supply Network configurations have been modeled with this tool, and different simulation runs have been executed to evaluate the new strategy viability.

All the simulations have been done on the basis of the same demand series; 66 customer orders for MC-1 milling machines, obtained from the real annual sales sequence. The configuration of each demanded machine was determined from real customer orders statistics: (i) Local strategies, meaning that replenishment, restocking procedures, were the same for each plant in both simulation runs; (ii) And also neither component purchasing costs nor supply network management costs were modified in either run.

Table 2: Simulation runs outputs

<table>
<thead>
<tr>
<th>Present SN Configuration - KPIs values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ongoing Machines: 0</td>
</tr>
<tr>
<td>SN Lead Time</td>
</tr>
<tr>
<td>165</td>
</tr>
<tr>
<td>Purchasing: 9,397,679 €</td>
</tr>
<tr>
<td>Production: 2,563,900 €</td>
</tr>
<tr>
<td>Transport: 576,497 €</td>
</tr>
<tr>
<td>Holding: 107,805 €</td>
</tr>
<tr>
<td>Management: 73,128 €</td>
</tr>
<tr>
<td>Total SN Cost: 13,669,006 €</td>
</tr>
<tr>
<td>Machine Cost: 205,894 €</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>New SN Configuration - KPIs values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ongoing Machines: 0</td>
</tr>
<tr>
<td>SN Lead Time</td>
</tr>
<tr>
<td>150</td>
</tr>
<tr>
<td>Purchasing: 9,397,679 €</td>
</tr>
<tr>
<td>Production: 1,966,150 €</td>
</tr>
<tr>
<td>Transport: 345,896 €</td>
</tr>
<tr>
<td>Holding: 870,732 €</td>
</tr>
<tr>
<td>Management: 73,128 €</td>
</tr>
<tr>
<td>Total SN Cost: 12,553,567 €</td>
</tr>
<tr>
<td>Machine Cost: 190,306 €</td>
</tr>
</tbody>
</table>

Table 2 shows the results of both simulation runs. It can be highlighted an important reduction in each MC-1 machine total cost; from €205.894 with present strategy to
€190,206 with the new one. For all the 66 MC-1 machines, the improvement goes beyond the €1 million, which means a 7.62% cost reduction. Taking into account that purchasing and management costs were kept identical for both simulation runs, 69% of the improvement is down to the manufacturing costs reduction derived from lower personnel workforce costs, and the 22% transport costs reduction is due to the proximity of assembly plants to the customers’ locations. Also, a decrease of inventory level is recorded, which means a 9% costs saving in stock management activities, 5 days of average delivery time cutting and an improvement of 7% in customer service level.

6. Conclusions

The use of some simulation techniques and tools constitutes a valuable decision support approach in the strategic design of supply networks with mass customisation challenges. The decision making process in this kind of scenarios has high levels of complexity. A simulation tool like the presented in this paper, can help managers to estimate more precisely the impact in costs, lead times, and inventory levels of a service strategy like STO in the case of MACTO, in front of different alternatives of supply network configurations and compare results.

The mix of products, manufacturing processes or staff technical competences that should be assigned at each supply network plant, as far as the possibility of creating a new warehouse to improve customer service, typical strategic decisions for a efficient supply network configuration, should be aligned with company customisation strategy. Risky decisions related to the type of products that are going to be served to each market, the strategy needed for each of them, the level of customisation offered, the location of the decoupling point for each order in the supply chain, etc, require tools that can take a systemic and dynamic perspective and capabilities for processing high amounts of databases.

Deepen knowledge in the relationships between customization strategies and supply network configurations, in improved allocation criteria to use in STO strategies or in the comparison of this strategy with others like ATO (Assembly To Order), are challenges that open a wide and interesting work area for the research community.

7. References


